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ORIGINAL ARTICLE

Assessment of regional climate change impacts on Hungarian landscapes

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Abstract The assessment of regional climate change impacts combined with the sensitivity of landscape functions by predictive modelling of hazardous landscape processes is a new fundamental field of research. In particular, this study investigates the effects of changing weather extremes on meso-regional-scale landscape vulnerability. Climatic-exposure parameter analysis was performed on a predicted climate change scenario. The exposure to climate change was analysed on the basis of the original data of the meso-scale IPCC A1B climate scenario from the REMO and ALADIN regional models for the periods of 2021–2050 and 2071–2100, and the regional types of climate change impacts were calculated by using cluster analysis. Selected climate exposure parameters of the REMO and ALADIN models were analysed, in particular, for extreme events (days with precipitation greater than 30 mm, heat waves, dry periods, wet periods) and for daily temperature and precipitation. The landscape functions impacted by climate change are proxies for the main recent and future problematic processes in Hungary. Soil erosion caused by water, drought, soil erosion caused by wind, mass movement and flash floods were analysed for the time periods of 1961–1990, 2021–2050 and 2071–2100. Based on the sensitivity thresholds for the impact assessments, the landscape functional sensitivity indicators were interpreted, and an integrative summary of the five indicators was made, differentiating the regions facing only a few or multiple sensitivities. In Central Hungary, the increasing exposure and sensitivity to droughts will be a serious problem when following the REMO scenario. In several regions, most indicators will change the sensitivity threshold from a tolerable risk to an increased or very high risk.

Keywords Climate change · Sensitivity of landscape · Impact of hazardous landscape processes · Carpathian basin · Regionalisation

Introduction

The assessment of regional climate change impacts is a new fundamental field of research, especially when investigating the effects of changing weather extremes, exposure at a landscape scale, sensitivity and vulnerability.

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To assess regional climate change impacts, this study uses the IPCC greenhouse-gas emission scenario A1B that was calculated for Central Europe by Bartholy et al. (2008) and Pongrácz et al. (2009) by applying the REMO, ALADIN or PRECIS regional climate model. These results on the climate change exposure for Hungary predict (1) an increased average temperature, mainly in the summer, and a higher variability of rainfall, especially in the summer and winter; (2) an increased number of tropical days; (3) an increased length of heat periods; (4) changes in the summer and winter precipitation; and (5) a slightly increased number of days with heavy rains (more than 30 mm).

Rannow et al. (2010) have developed a multifunctional assessment framework to create a model for Germany by varying the regional priorities of adaptation activities in spatial planning, using 11 "impacts of primary relevance for spatial planning on a regional level". The methodology used by Meyer et al. (2009) and Rannow et al. (2010) is applied for the regionalisation of the impacts when calculating the simple predictive risk assessment and combining the modelled changes of the climate variables with maps and statistics. The results are potential regional hazard sensitivities at the scale of German administrative districts and natural regions.

It is obvious that several scientific problems should be considered when using coarse-grained pixel information from regional climate modelling on a landscape or ecosystem level with the aim to apply a sound approach and to investigate future climate change impacts that are relevant for planning and risk prevention, especially in the case of extreme events. A multitude of interesting research discussions and investigations have occurred in recent years; some notable examples include the following: Jentsch and Bayerkuhnlein (2008) on the effects of extreme meteorological events on ecosystems; Opdam and Washer (2004) on the interlinkage of climate change and habitat fragmentation; Martens et al. (2010) on the institutional and multisectoral perspectives of abrupt and extreme climate changes; Pielke et al. (2007) on the changing role of agriculture in the climate system; and Metzger et al. (2008) with a spatially explicit and quantitative vulnerability assessment of the ecosystem changes in Europe.

The investigation of the multifunctional assessment of climate change impacts on Hungarian landscapes should help meet the public demand for research results regarding sensitivity assessments using landscape functions and landscape processes as indicators to clarify "relevant direct and indirect impacts of climate change with a special focus on the regional differentiation of its effects" (Meyer et al. 2010). Information about the regional and local impacts of climate change is of interest to several branches of planning and risk prevention (Meyer et al. 2009).

For Hungary, the coarse-grained climate information of the available regional modelling (of 11 min × 11 min or approx. 25 km × 25 km) leads to a regional approach. The overlay of the A1B climate scenario by the REMO and ALADIN regional climate models with the regional landscape types in Hungary is employed to assess the crucial changes in exposure, sensitivity and landscape vulnerability. Problematic landscape processes are investigated in this study by analysing the changes in soil erosion by water, droughts, wind erosion, mass movements and flash floods by comparing three periods: 1961–1990, 2021–2050 and 2071–2100. The aim of the research is to determine the main climate change factors (exposure), the affected earth-surface processes (sensitivity) and the critical impacts on the landscapes in the next century as a result of the predicted climatic tendencies.

In the following, the methodological and data-driven steps of the analysis regarding (1) the climate exposure in Hungary based on regional models emphasising extreme events, (2) the landscape types of Hungary and (3) the methods of sensitivity risks analysis and assessments are described. This part is followed by an integrative impact assessment to predict the climate change–induced changes of the landscape sensitivity for the mentioned time periods. The discussion leads to open questions about the vulnerability assessment and the application of the results in policy and adaptive land management in the face of the problems of the data, scale and accuracy of the scenario methods.

Data and methods

Landscape types of Hungary

The usage of landscape units has a long scientific history in Hungary. Pécsi and Somogyi (1967) have differentiated a map of landscape micro-regions. These micro-regions are defined by using the geomorphologic characteristics of the land forms for the regional and local typifications. The regional climatic models used in this study did not include enough data for a micro-region (sometimes only one or two data points fall into one micro-region). Therefore, it was practical to analyse at the aggregated hierarchical level of meso-scalic landscape units (see Fig. 1). Two main methods are generally suitable for the delimitation of landscape units when scaling up microscale information to the mesoscale: integration or segmentation techniques. A segmentation process was used in LANMAP (European Landscape Typology and Map) by Mücher et al. (2010). The Hungarian part of the LANMAP map is not scientifically validated. The segmentation process employed in LANMAP on raster information resulted in meso-scale landscape units that are not yet interpretable by the Hungarian microscale data, especially because of the resulting small units that are not explainable on a microscale level.

Fig. 1 The 18 meso-regions of Hungary (made up of 230 micro-regions) differentiated into plains, hilly and mountainous landscapes. The meso-region is an integration of geomorphologic characterisation and landscape types

Therefore, the integration of the micro-regions was used to aggregate the meso-regions based on the map of Pécsi and Somogyi (1967; see Fig. 1). It was derived from geomorphologic (mountain, hills, plains) and land cover-/landscape-type characteristics. Because the present paper is focused on the determination of land use and the hazardous consequences of climate change usable in regional planning, it was reasonable to define 18 meso-regions with an area of several thousands of square kilometres each, made up of an integration of 230 micro-regions. These regions are defined as homogeneous at the regional-scale level.

Climate change in Hungary

It is difficult to sketch a valid picture of climate change for the entire area of Hungary. Pinning down tendencies is hindered by multiple factors. One initial basic problem was the choice of the climate change scenario to be considered (IPCC 2007; Bartholy and Pongrácz 2010). In our analysis, only the data from the A1B scenario are used following a balanced storyline that does not belong to a single energy-source change as described by IPCC (2007). Another essential aspect is the selection of the regional climate change model that is employed. These models are different, not only in terms of the applicability of scale (global, regional) but also in their basic model assumptions. The results have been tested from four regional models (ALADIN, REMO, PRECIS, RegCM), out of which the REMO and ALADIN models are employed here because these models are the most reliable for Central Europe.

Table 1 The average change in temperature (°C) and precipitation (mm) and the variation of the predictions in the Carpathian Basin using the REMO and ALADIN models' A1B scenario compared to period 1961–1990, Szabó et al. (2011)

Period	Years	Spring	Summer	Autumn	Winter
2021–2050	1.4–1.9	1.1–1.6	1.4–2.6	1.6–2.0	1.3
2071–2100	3.5	2.3–3.1	4.1–4.9	3.6–3.8	2.5–3.9

Based on these prerequisites in the choice of scenario and model and by following a similar rate and tendency as observed between 1961 and 1990, our investigation resulted in a continuous but uneven temperature increase focused on the summer period in the Carpathian Basin for this century (Table 1). The temporal distribution of precipitation will become increasingly variable, likely more than the annual sum in the scenario periods of 2021–2050 and 2071–2100 predicted (Table 1). The analysis of the REMO and ALADIN model scenario runs resulted in daily averages, monthly extreme temperatures and similar trends for the precipitation parameters and daily precipitation rates higher than 30 mm or in the length of heat waves. In Table 1, the differences in the predictions in the temperature and precipitation of the two models are given as averages of REMO and ALADIN, including the range of the predicted outcomes. These results are the main conclusions of the Hungarian Meteorological Service for our study. The details are also described for the other models, such as those by Pieczka et al. (2011) and Szabó et al. (2011), which are predicted by similar trends.

The model's estimate for 2021–2050 precipitation is not significant, but the results indicate a significant increase in the single-event intensity. Bartholy et al. (2007) have emphasised a potential autumn/wintertime precipitation increase but no increase for the summer.

The simulations of the weather extremes project more intense rainfall as well as longer warm and more frequent dry periods in the Carpathian Basin. The number of frost days will decrease by 30 and 50 % in the middle and end of the century, respectively. In the meantime, the number of hot days will double and triple (Szépszó 2008). The projection of the precipitation is, however, less straightforward because the models predict changes at different scales following the several incorporated methodological weaknesses in the modelling architecture. A sensitivity analysis was applied in detail describing the ranges of the change of the different climate change scenarios of the REMO and ALADIN models for the Carpathian Basin by Csima and Horányi (2008) and Szépszó and Horányi (2008).

Distinguishing climate-region types for Hungary

The REMO and ALADIN simulations have provided results that show differences in certain regions (particularly in the east and south), depicting the uncertainty range by applying different climate models. Multivariate statistical analysis and classification have been performed considering the climate change trends in the Hungarian climate regions and including the uncertainty range of the model simulations. The objective was to distinguish the region types with similar climate change characteristics. Hungary has a rather homogenous terrain, whereas larger or mountainous/alpine countries show a broader variation of local climates. As the landscape diversity in Hungary is—when described by statistics—relatively narrow, distinguishing the climate regions was a somewhat challenging task that was performed by applying factor and cluster analyses (Loibl and Aubrecht 2011). Factor analysis was used for reducing the number of variables and generating a few distinct and integrated "super-indicators" out of (via factor loadings) weighted input variables—the factor coefficients. Cluster analysis was used to group the Hungarian regions by the climate characteristics of the current and future climate by applying multivariate statistics. To conduct the clustering task, climate and climate change indicators were extracted from raster sets of precipitation, temperature and extreme-event indicators by averaging the indicators for the 18 Hungarian meso-regions.

Therefore, the 20 km × 20 km grid-cell results as derived from the climate simulations were transferred to the small Hungarian meso-regions by calculating the spatially weighted spatial averages, ranges and standard deviations of the climate data for those regions. A set of factor analyses were performed to derive the appropriate integrated "super-indicators" for the regions.

Finally, the factor analysis results were obtained for the temperature and precipitation data subsets individually. The factor analysis using the temperature data integrates the "current temperature" (1961–1990), the temperature from 2021 to 2050 and the temperature from 2071 to 2100 of the ALADIN and REMO scenarios and the current-to-future temperature change. The temperature subsets contain absolute numbers for the current and future temperature (the regional average and range within the region) and the averages of frost days (≤ 0 °C Tmin) and summer days (>25 °C Tmax) by scenario version. The factor analysis using the precipitation data integrates the "current precipitation" (1961–1990), the precipitation from 2021 to 2050 and the precipitation from 2071 to 2100 of the ALADIN and REMO scenarios. The precipitation subsets contain current and future rainfall absolutes (totals and range within the regions), the numbers of extreme rainfall days (>20 mm and >30 mm per day) and the average daily rainfall sum on precipitation days (>1 mm) by scenario.

The factor analyses deliver the factor coefficients for the meso-regions as "super-indicators". The coefficients of those factors whose eigenvalues explain more than 10 % of all variables' variance (usually 2 factors per analysis) were selected. These factor coefficients of the few important factors describe the current and future climates from the ALADIN and REMO scenario results.

Using those factor coefficients, cluster analyses were performed with alternative linkage approaches and metrics to identify the regions of similar characteristics by detecting the natural groupings in the data. Hierarchical clustering, which records the tightness of linkages between the factor coefficients by observing the similarity or "distance" between the values by (region) case, is typically applied. Several distance metrics and linking methods are available with hierarchical clustering. Ward's linkage method was applied, which averages all the distances between pairs of objects in different clusters, with adjustments for the covariance, to determine how far apart the clusters are. As a distance metric, the normalised Euclidean distance (root-mean-squared distance) was used.

The cluster analysis results that are ultimately selected to delineate the climate regions are based on the factor coefficients of the 2 highest factors of the 4 different factor analyses for the temperature and the precipitation considering the scenario results for 2021–2050 and 2071–2100 and integrating the temperature and precipitation ranges of the meso-regions.

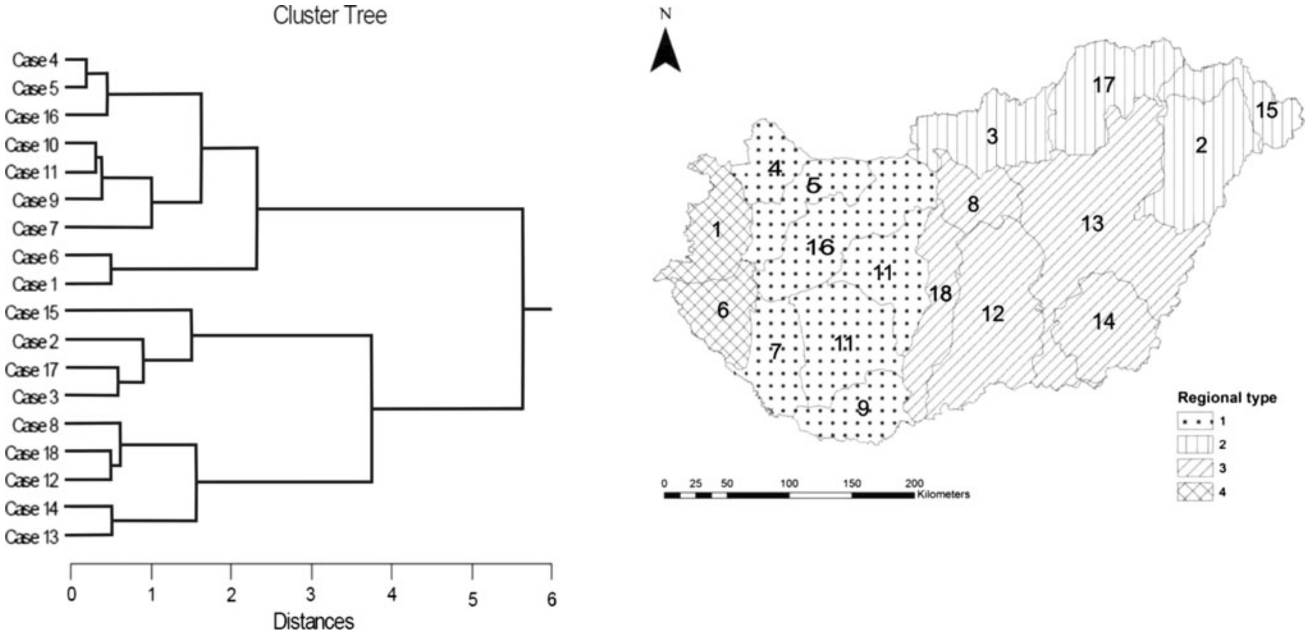

Fig. 2 The regional types of climate change exposure as a result of cluster analysis using all factors

The analysis delivers four main climate-region types (Fig. 2):

- Region type 1 covers 2 meso-regions contained in cluster 1 in the western hilly area. This type is characterised by lower temperatures, less temperature increase and less change in the temperature extremes. The type is expected to be more humid, with higher precipitation totals but smaller precipitation-change ratios and smaller change rates regarding heavy rain events.
- Region type 2 indicates a moderate temperature increase and more distinct changes in extreme temperature events. The precipitation totals are moderate; the future precipitation increase is expected at higher rates but with moderate changes in extreme rainfall events. The meso-regions of this type are located along a west central corridor from the north to the south of Hungary.
- Region type 3 is characterised by a flat topography, with the highest temperatures, the highest temperature increase and significant changes in the extreme temperature events (increase of the summer days and decline of the frost days). This type suffers from the lowest annual precipitation totals and can expect the highest precipitation decline (or, at least, the lowest precipitation-increase ratios). The increase in heavy-rainfall days indicates a growing concentration of rainfall and thus longer drought periods. This region type covers a large area of Hungary, ranging from the centre to the south-east.
- Region type 4 covers the north-eastern meso-regions along the Slovakian border, with the lowest annual mean temperatures, the highest intraregional temperature variation and moderate precipitation totals resulting in more humidity when compared with the other continental regions. The moderate increase in the precipitation sum and the (few) extreme-event days may have positive effects on agriculture and nature evolution.

In Table 2, the regional differentiation of climate change exposure is summarised for the regional landscapes of Hungary, including the data for the periods of 1961–1990, 2021–2050 and 2071–2100 (projections based on the REMO & ALADIN simulations). Differentiation refers to the temperature and precipitation totals for summer days, tropical days and days with precipitation greater than 30 mm.

Investigations of the landscape sensitivity in Hungary due to climate change assessments of landscape hazards

In order of their actual importance in Hungary, the following natural processes were considered during the analysis: soil erosion by water, droughts, soil erosion by wind, flash floods and mass movements. These processes represent the most important environmental hazards for land use in Hungary (Szabó et al. 2008). The flood problem was not included into our analysis because the increase in this process is not primarily a consequence of the climate impacts (influencing factors are the capacity of water-deduction of the floodplain, the land use of the catchment and the construction of dams in the upper section), and the floods are difficult to predict in Carpathian Basin at a regional scale without an enclosure of the surrounding mountains.

Table 2 The landscape regions of Hungary and the impacts of climate change (REMO and ALADIN) for the periods of 1961–1990, 2021–2050 and 2071–2100

Code	Name	Temperature (°C) 1961–1390	Temperature (°C) 2021–2050	Temperature (°C) 2071–2100	Precipitation (mm) 1961–1990	Precipitation (mm) 2021–2050	Precipitation (mm) 2071–2100	SU 1961–1990	SU 2021–2050
1	Western part of the Carpathian basin	9.9	11.4	13.3	603	626	626	49.8	68.9
2	Loess and sand plain of Nyírség and Hajdúság	10.0	11.7	13.6	571	552	549	55.3	79.4
3	Western part of the North Hungarian Mountains	9.6	11.1	13.1	536	535	516	48.6	71.2
4	Little Hungarian Plain	10.3	11.7	13.7	530	552	545	52.8	70.6
5	Marcal basin and Komárom plain	10.1	11.6	13.5	541	559	555	51.7	70.7
5	Zala hills	10.0	11.5	13.5	656	671	659	60.5	80.9
7	Hilly region of inner Somogy	10.4	11.5	13.5	625	648	637	70.5	90.1
8	Gödöllő hills	10.4	12.1	14.0	506	500	487	61.9	83.7
9	Dráva plain and Mecsek Mountains	10.7	12.4	14.3	576	569	569	77.3	98.7
10	Mezőföld plain	10.5	12.1	14.0	524	527	529	60.9	81.3
11	Transdanubian hills	10.5	12.1	14.0	567	577	572	66.4	87.0
12	Danube-Tisza Interfluve	10.7	12.4	14.3	493	478	47	72.7	94.3
13	Central part of die Great Hungarian Plain	10.4	12.1	14.0	497	474	466	65.4	88.7
14	Körös-Maros Interfluve	10.6	12.3	14.2	488	461	458	75.1	98.1
15	Plain of Upper Tisza	9.7	11.3	13.2	659	653	641	50.8	74.3
16	Transdannubian Mountains	10.1	11.6	13.5	556	569	567	53.3	74.4
17	Eastern part of hie North Hungarian Mountains	9.1	10.7	12.6	564	565	549	44.8	67.9
18	Danube plain	10.7	12.4	14.3	508	503	501	69.6	90.2

Code	Name	SU 2071–2100	HEAT 1961–1990	HEAT 2021–2050	HEAT 2071–2100	RR30 1961–1990	RR30 2021–2050	BR30 2071–2100
1	Western part of the Carpathian basin	95.9	4.6	15.3	40.0	1.1	1.5	1.7
2	Loess and sand plain of Nyírség and Hajdúság	103.8	7.1	23.4	47.4	0.5	0.6	0.9
3	Western part of the North Hungarian Mountains	98.9	3.4	14.1	36.4	0.6	1.0	1.2
4	Little Hungarian plain	96.5	7.4	21.1	45.4	0.6	1.1	U
5	Marcal basin and Komárom plain	96.0	6.2	13.4	43.7	0.6	1.0	1.3
5	Zala hills	106.0	6.1	13.6	46.6	1.2	1.5	1.6
7	Hilly region of inner Somogy	113.1	10.0	27.8	55.4	0.7	1.3	1.4
8	Gödöllő hills	107.8	9.2	25.2	51.3	0.4	0.7	1.0
9	Dráva plain and Mecsek Mountains	119.5	11.9	32.3	59.2	0.6	0.8	1.1

Table 2 continued

Code	Name	SU 2071–2100	HEAT 1961–1990	HEAT 2021–2050	HEAT 2071–2100	RR30 1961–1990	RR30 2021–2050	BR30 2071–2100
10	Mezőföld plain	104.7	9.2	25.4	51.3	0.5	0.9	1.1
11	Transdanubian hills	109.9	3.2	24.1	52.7	0.6	1.0	1.2
12	Danube-Tisza Interfluve	115.0	14.1	34.3	60.4	0.4	0.5	0.7
13	Central part of die Great Hungarian Plain	112.0	11.0	30.0	56.0	0.5	0.6	0.8
14	Körös-Maros Interfluve	119.2	14.4	36.1	62.4	0.4	0.4	0.7
15	Plain of Upper Tisza	99.6	5.6	19.8	43.3	0.8	0.8	1.4
16	Transdannubian Mountains	100.0	5.3	17.0	41.2	0.5	1.0	1.2
17	Eastern part of hie North Hungarian Mountains	96.3	2.9	12.3	33.0	0.7	1.0	1.2
18	Danube plain	111.9	12.9	31.6	58.1	0.4	0.7	1.0

SU summer days, *HEAT* tropic days, *RR30* days with precipitation greater than 30 mm, *code* region number

Following these processes, a number of landscape function–based sensitivities have been spatially assessed using predictive models and diverse geo-data (Table 3) from multiple sources. The main aims are (1) the exploration of the status quo of the indicators' assessment on the regional scale for Hungary and (2) the assessment of the usage of the climate change parameter predictions modelled by REMO and ALADIN and typified by cluster analysis in the sensitivity assessments.

In the following, the main landscape processes, the models employed to predict the landscape indicators and the thresholds used for the sensitivity assessment are described (Usher 2001). An overview of the parameters, the calculation steps of the predictive models and the methods used to model the landscape hazard indicators, including the thresholds for the sensitivity assessment, are given in Table 4.

Soil erosion by water considers the physical soil degradation processes at today's largest spatial extent in Hungary. It affects 2 million ha of productive land on Late Tertiary and Quaternary alluvial and lacustrine clays, silty sediments and loess (Stefanovits 1981). The erosion sensitivity was calculated on a micro-regional scale following the universal soil loss equation (USLE) of Wischmeier and Smith (1978) adapted for Hungary. The parameters determining the soil sensitivity (K), length of slope (L) and steepness (S) are relatively stable; the rainfall erosivity factor (R) has the closest link to climate change. The vegetation and crop factor (C) and the measures against erosion (P) have a high degree of unpredictability because of changing land-use systems and also due to potential protective adaptive measures in the future. In our modelling example, the average RR30 value in the winter half-years was used for the calculations of extreme rainfall events (the RR30 values were calculated from REMO and ALADIN model).

Droughts, in general, are natural phenomena, though human activity can have a high indirect influence on them, especially via land use. As a consequence, the estimates of the drought sensitivity include high data uncertainties compared with the other natural disaster predictions. The sensitivity map in this study was developed using the Pálfai Drought Index (PaDI). The PaDI was calculated as the ratio of the mean temperature of the summer months (April–August) and the annual sum of precipitation. As a proxy for the sensitivity changes induced by climate change exposure, the regional types of climate change exposure are applied (Fig. 2) as a result of the cluster analysis using all climatic factors.

Wind erosion in the Carpathian Basin is not usually an issue in sand-covered areas but frequently has an effect on the degradation of arable soils. The wind erosion sensitivity is primarily determined by the granulometry of the soil; for

Table 3 The main data sources for the calculation of the sensitivity indicators for Hungary

Sensitivity indicator	Source of basic data
Soil erosion by water	USLE map (Kertész and Centeri 2006)
	Results of cluster analysis (sensitivity values were confronted to climate change indicating parameter clusters (Loibl and Aubricht 2011)
Drought	Daily/monthly average temperature (from REMO and ALADIN models)
	Daily/monthly precipitation from REMO and ALADIN models)
	Results of cluster analysis (sensitivity values were confronted to climate change indicating parameter clusters (Loibl and Aubricht 2011)
Wind erosion	Map on potential wind erosion risk (Lóki 2011)
	Soil type (Agrotopographical database 1991)
	Results of cluster analysis (sensitivity values were confronted to climate change indicating parameter clusters (Loibl and Aubricht 2011))
Flash floods	Slope map (SRTM 2000)
	Soil type (Agrotopographical database 1991)
	Forest categories (European Environment Agency 2000)
	Results of cluster analysis (sensitivity values were confronted to climate change indicating parameter clusters (Loibl and Aubricht 2011))
Mass movements	Mass movements of last decades (1965–2005) (Juhász 2004, Fodor and Kleb 1986)
	The precipitation sum of the winter season (from REMO and ALADIN models)
	Results of cluster analysis (sensitivity values were confronted to climate change indicating parameter clusters (Loibl and Aubricht 2011))

example, if a great amount of fine sediment is available on the surface, deflation will be more intense as lower and more frequent wind velocities will be adequate to reach the critical entrainment force. The characteristic yearly average wind velocities close to the surface are 3 m/s in Hungary, though the values are 15–20 % higher in the NW and central parts of the basin. The Lóki (2011) map of the potential wind erosion hazard was used in this study, and the climatic parameter affected by climate change for the prediction of the sensitivity was associated with the regional types of climate changes as result of the cluster analysis shown in Fig. 2.

Flash flooding is one of the most frequent hazards in Hungary (Czigány et al. 2010; Estrela et al. 2001). In the past decades, the most important hydrometeorological parameters have been clarified (Grundfest and Rips 2000). Monitoring systems have been set up to help mitigate this hardly predictable hazard (Carpenter et al. 1999). A point-based calculation was applied in this study by using the classification given in Table 3. The climatic parameter that was taken as the climatic-exposure climate change for the flash flood prediction is the temporal frequency of the extreme precipitation events higher than 30 mm (Szépszó 2008).

Mass movements were evaluated according to their present-day activity. The endangered areas were predicted in the mountains and hilly regions where the natural conditions are able to mobilise the processes by using the recorded information about recent significant landslide events (Juhász 2004; Fodor and Kleb 1986), geology, the granulometric type of the sediment, relief and the actual precipitation data for Hungary. Hilly regions with only ancient quaternary mass movement have not been considered. The climatic parameter affected by climate change is the sum of the precipitation in the winter season.

Thresholds for sensitivity assessment

The sensitivity was assessed by using the threshold values for the classification of the hazard for each of the indicators in the sensitivity classes of the regional landscape in qualitative terms of low/tolerable (class 1), increased (class 2) and high (class 3). The thresholds are identified for each indicator as described in Table 4. The usage of qualitative classes is a standard procedure for an equal-weighted integration of different factors in impact assessment. The applied method is simple because the uncertainty of the models (climatic and hydrological) and the limited amount of verification do not enable highly precise calculations. Practically, a matrix-based assessment was made to link the climatic exposure of the region to its sensitivity to the problematic processes.

Results: regionalised climate change impacts and sensitivity assessments

The aim of the study was not to verify the quality or scaling of different regional climate modelling. The data of REMO

Table 4 The parameters, calculation steps, methods and sensitivity thresholds used for the climate change impact ON the landscape hazard indicators

Indicator	Parameters	Calculation	Method/climate change affection	Indicator sensitivity threshold
Soil erosion by water	Rainfall erosivity factor (*R*), Soil erodibility factor (*K*), Length of slope (*L*), Steepness (*S*), Crop factor (*C*) Protective measures (*P*)	Universal soil loss equation (USLE) $E = RK(LS)CP$ (t/ha) E = soil erosion by water	USLE; Wischmeier and Smith (1978) was used for risk calculation The climatic parameter effected by climate change: Extreme rainfall events and winter precipitation were considered for the assessment of climatical effect (R-Faktor change)	1. Tolerable: 0–2 t/ha 2. Increased: 2–8 t/ha 3. High: >8 t/ha
Drought	Precipitation Temperature	$\mathrm{PaDI} = \sum_{(i\,=\,\mathrm{Apr–Aug})} T_i \times 0.05 / \sum_{(\mathrm{Oct–Sept})} P_i$ T—monthly average temperature P—monthly precipitation PaDI—Palfai drought index	Pálfai (2004) drought index calculation (PaDI) was used for drought sensitivity mapping The climatic parameter affected by climate change: sensitivity values were confronted to climate change indicating parameter clusters (Loibl and Aubricht 2011)	1. Tolerable: <6 2. Increased: 6–8 3. High: >8
Wind erosion	Granulometry of the sediment/soil cover Climatologic characters (starter velocity, precipitation) Vegetation cover; Wind speed	GIS based calculation using WEQ (2000), Klik (2004) and Lóki (2011) map on potential wind erosion risk	The wind erosion calculations, based on Chepil formula, and on Agro-topographical maps (1991) The climatic parameter affected by climate change: The sensitivity values were confronted to regional types of climate changes as result of the cluster analysis Fig. 2 (Loibl and Aubricht 2011)	1. Tolerable: WE processes starts on loamy and silty soil by a wind speed of 8.6 and 10.5 m/s 2. Increased: WE starts at sandy loamy soils at wind speed between 6.5 and 8.5 m/s 3. High: WE starts on sandy and peat bog soils with high amount of organic material by a wind speed of around 6.5 m/s
Flash flood	Slope categories (area based) Granulometry (area based) Forest surfaces (area based)	Classification: Slope: <0.1 % 0; 0.1–5 % 1; 5–30 % 2; 30 % <3 Silt/clay: 0–40 % 1; 40–80 % 2; 80 % < 3 Forest: 0–20 % 3; 20–50 % 2; 50 % < 1 Calculation: FF index = [(Class of Slope × 2) + Class of SiltClay + (Class of Forest/2)]/3.5	Point-based calculation was used by GIS using on classification and formula The climatic parameter affected by climate change: temporal frequency of extreme precipitation events higher 30 mm was taken as the climatic indicator	1. Tolerable: <1.43 2. Increased: 1.44–2.21 3. High: >2.22–(3.00)
Mass movement	Most recent and significant landslide events Geological, mechanical type of the sediment Relief Precipitation	Assessment: If the region is affected by mass movements less than 5 % of the total area, then a value of 1 is given; if the affected area is between 5 and 25 %, then a value of 2 is given; if the mass movements occurred on more than 25 % of the total area; then a value of 3 is given	Additive sensitivity calculation based on observed actual mass movements (Juhász 2004; Fodor and Kleb 1986) earlier events was used The climatic parameter affected by climate change: the precipitation sum of the winter season	1. Tolerable: <5 % 2. Increased: 5–25 % 3. High: >25 %

Table 5 The sensitivity assessment results for the Hungarian meso-regions based on the REMO scenario (1–18 = name of micro-region; see code in Table 3)

Meso-region indicator	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Soil erosion																		
Basic	2	1	3	1	2	3	2	2	2	2	3	1	1	1	1	2	3	1
2021_2050_REMO/ALADIN	3	1	3	1	3	3	3	1	1	2	3	1	1	1	2	2	3	1
2071_2100_ REMO/ALADIN	3	1	3	1	3	3	3	2	2	2	3	1	1	1	2	3	3	1
Drought																		
Basic	1	2	1	2	2	1	1	3	2	3	1	3	1	3	2	2	1	3
2021_2050_REMO/ALADIN	1	3	1	1	2	1	1	3	2	3	1	3+	1	3+	2	2	1	3
2071_2100_REMO/ALADIN	2	3+	1	2	2	1	1	3+	2	3	1	3++	1	3++	2	2	1	3
Wind_erosion																		
Basic	2	3	1	2	3	2	3	3	2	2	2	3	1	2	1	2	1	2
2021_2050_REMO/ALADIN	1	3	1	1	3	1	3	3	2	2	2	3+	2	3	1	2	1	2
2071_2100_REMO/ALADIN	2	3+	1	2	3	2	3	3+	2	2	2	3++	3	3+	1	2	1	2
Flash_flood																		
Basic	2	1	3	1	2	3	2	2	3	2	3	1	1	1	1	3	3	1
2021_2050_REMO/ALADIN	3	1	3	2	3	3	3	1	2	2	3	1	1	1	2	2	3	1
2071_2100_REMO/ALADIN	3	1	3	1	3	3	3	2	3	2	3	1	1	1	2	3	3	3
Mass movement																		
Basic	2	1	3	1	2	3	2	2	3	2	3	1	1	1	1	2	3	1
2021_2050_REMO/ALADIN	3	1	3	2	3	3	3	1	2	2	3	1	1	1	2	2	3	1
2071_2100_REMO/ALADIN	3	1	3	2	3	3	3	2	3	2	3	1	1	1	2	3	3	1

Sensitivity classes 1 = tolerable, 2 = increased, 3 = high; 3+ (3++) indicates that the regional sensitivity has strongly (very strongly) increased

and ALADIN have been used in our study at the meso-regional level. These data on the climate change scenarios have been employed by using single parameters on the temperature, precipitation or extreme events and also by typifying the four main categories of regional climate change exposure by cluster analysis in the different assessments on the regional sensitivities. The data scale levels of the climate models and the regional landscape units fit together well due to the data accuracy. The combination is a step towards breaking down the climate change exposure variations to a local-scale level.

Hungary is affected by several naturally driven environmental hazards, which can modify the functioning and the households of the regions and limit the use of resources. The relevance of the different hazards is assessed in this study by the sensitivity to the main problematic processes. A balance or a resilient status of the processes, in terms of the economy and society, relates mostly to damages of material value. The present investigation used an environmental hazard assessment perspective of nature-driven hazards. To a certain extent, these hazards are also affected by human factors.

In the following, we describe some of the outcomes of the sensitivity change analysis from a large number of results of the sensitivity assessments on soil erosion by water, drought, wind, flash floods and mass movement. A resilient status of the assessments and sensitivity changes and the results calculated by the models using the thresholds shown in Table 4 for the three periods of investigation are given in Table 5. A three-category system (tolerable, increased, high) was used for an integration analysis; therefore, 3+ and 3++ were taken into consideration as 3 when the sensitivity indicators have strongly or very strongly increased and when the critical limits of change were reached.

The *soil erosion* hazards in response to climate change are expected to affect similar areas in both of the time periods of 2021–2050 and 2071–2100. The USLE calculation shows an increasing sensitivity in both periods. The only significant difference is found in the period of 2021–2050 in the regions of the Dráva Plain, the Mecsek Mountains and the Gödöllő Hills, where a decrease in rains higher than 30 mm is expected in winter. The Fig. 3a–c gives examples of the results for the soil erosion sensitivity assessments for the actual situation and the two periods of prediction for the A1B scenario.

The future change in the *drought* PaDI is also estimated by referring to similar trends in the periods of 2021–2050 and 2071–2100, independent of using the REMO or ALADIN data for the calculation. Only the south-western and northern peripheries of Hungary might not face a problematic drying tendency. The results show that mainly the

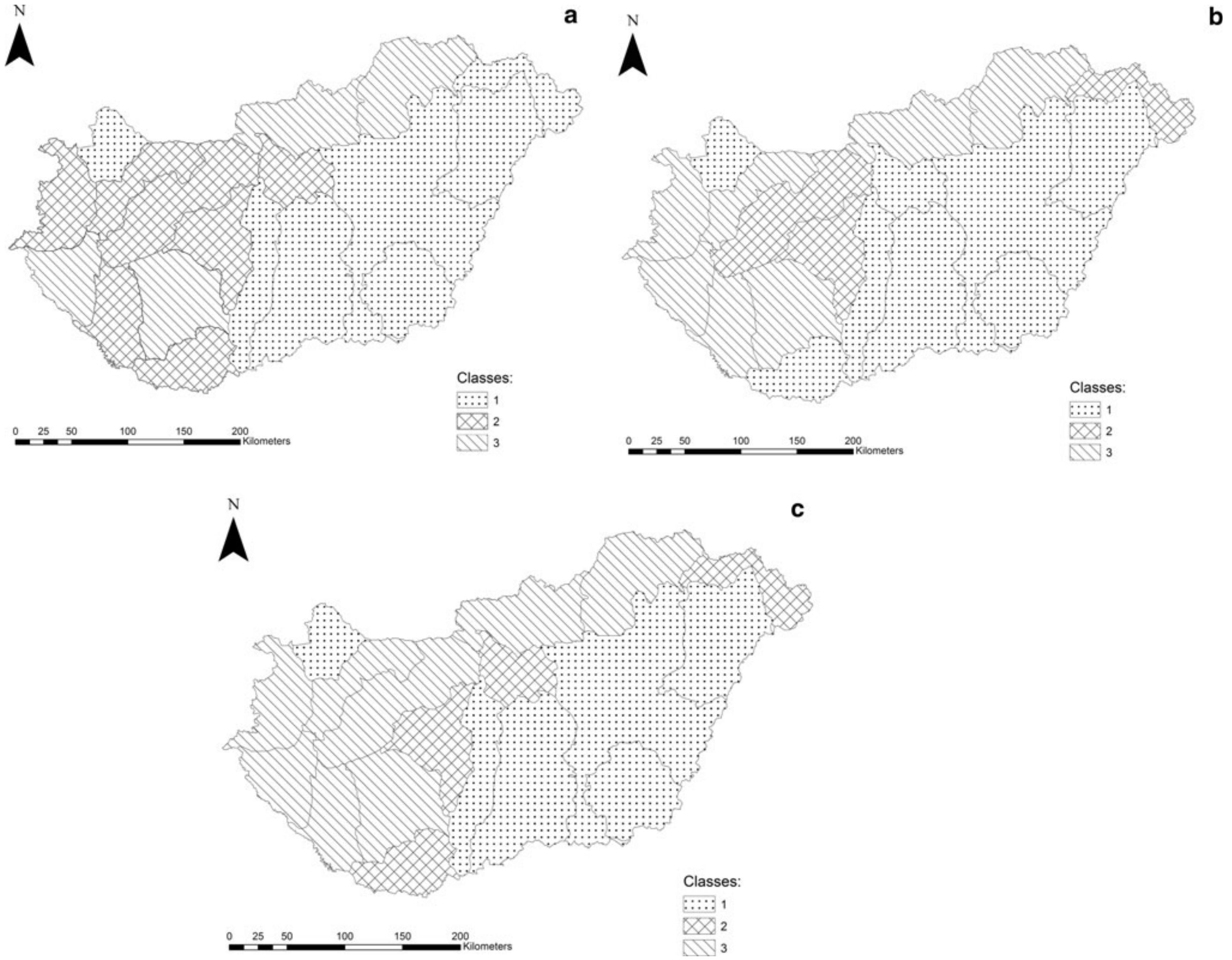

Fig. 3 **a** Sensitivity to soil erosion by water (actual assessment). **b** Sensitivity to soil erosion by water (Scenario A1B; 2021–2050). **c** Sensitivity to soil erosion by water (Scenario A1B; 2071–2100)

south-eastern part of the country is to expect serious problematic changes in the level of drought hazard. In the first period, the hazard assessment class increases in the Danube-Tisza Interfluves and in the loess and sand plain of Nyírség and Hajdúság by one class, and in the later period, by two classes towards problematic levels of aridity. The consequences are well known; in theory, when droughts increase due to a decreasing water supply, the groundwater table drops, agricultural productivity declines and soil degradation occurs.

The *wind erosion* sensitivity follows the drought sensitivity changes in the spatial distribution of Hungary, also with an increasing sensitivity. This is mainly caused by the soil and vegetation cover characteristics. We predicted a continued increase in the sensitivity and the hazards in both periods in two south-eastern regions, the Danube-Tisza Interfluve and the Körös-Maros Interfluve. A reduced drying of the soils in the first period will decrease the sensitivity in some western Hungarian regions.

A climate change-driven *flash flood hazard* increase can be expected in the Transdanubian Hills and in the Northern Mountains. The most sensitive areas are the regions of the Zala Hills and the Transdanubian Hills. The most critical areas are the region of the Zala River and the territory of the Transdanubian Mountains. With this phenomenon, the temporal frequency of the extreme precipitation events above 30 mm was taken as the climatic indicator.

An increased sensitivity is also given for the Mecsek Mountains and the Dráva plain; despite the medium relief and high vertical fragmentation, the *mass movements* on the slopes here are not frequent. Their increase is not highly probable. Hailstorms and sudden floods are already frequent in the area. Their frequency can increase due to high-intensity precipitation. Concerning the mass-movement hazard, those areas can be endangered by climate change-driven processes where the lithological, morphological and hydrological preconditions for mass

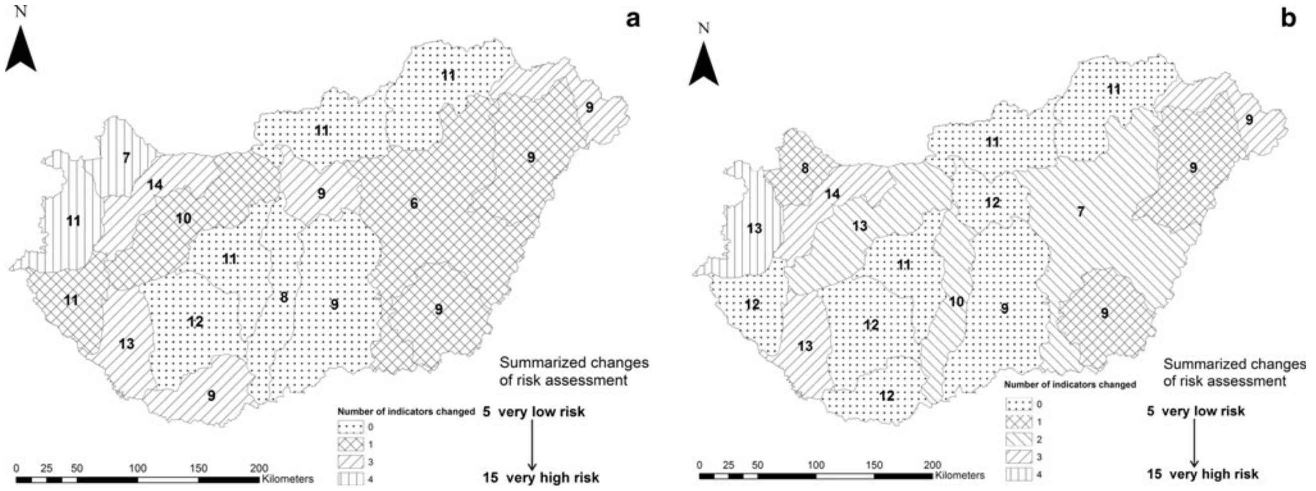

Fig. 4 **a** The number of hazard class changes in the indicators and the additive sensitivity assessment of the meso-regional hazard for 2021–2050 scenarios compared to period 1961–1990 for Hungary. **b** The number of hazard class changes in the indicators and the additive sensitivity assessment of the meso-regional hazard for 2071–2100 scenarios compared to period 1961–1990 for Hungary

movements are given. The expected regional distribution patterns are similar to flash floods.

An integrative analysis of the five sensitivity assessments of the landscape functional hazards in Hungary due to climate change is summarised in the Fig. 4a, b. The figures show the expected climate change impact on two levels of interpretation: (1) by the number of indicators changed for the scenarios for Hungary for the periods of 2021–2050 and 2071–2100 compared to the 1961–1990 period (out of the maximal 5 investigated in this study); and (2) the summarised changes in the hazard assessment of the meso-regional sensitivity for the same periods. The latter shows the increasing sensitivity on a scale from 5 (very low) to 15 (very high). The highest problematic increases in the processes are found in the Marcal Basin and Komárom plain in the north-west of Hungary for the first (and second) period when summarising all the sensitivity indicators. In this region, the actual processes are very active.

Considering the results of our study, we conclude that the vulnerability to climate change-induced natural process changes may not pose as serious and sudden a risk to human life as expected by Tobin and Montz (1997) because of the generally slow changes in the land-use system and the chance of adaptation activities of the society. Szabó et al. (2008) calculated that, on smaller units (landscape micro-region), the factors of potential environmental hazards are expected to be lower in the north-western part of Hungary compared to the south-eastern part. The calculation of Szabó et al. (2008) was based on investigations regarding a number of hazardous parameters, including floods and droughts. The natural hazards studied by this investigation give higher hazard predictions in the regions of Tisza, Danube and around the Körös River. Because of the diversity of the applied methods and a different time horizon of the predicted changes, it is difficult to compare the results of our study with the study of Szabó et al. (2008). Our study's results are interpreted as a step forward for a downscaling of climate change-induced impacts. The sensitivity assessments are strongly based on data and highly suitable for planning when compared to the overall nonspatialised results of the Hungarian VAHAVA-Project (Change, Impact, Reaction), which analysed the effects of climate change on the environment in general (Faragó et al. 2010).

Flooding and excess inland water are also significant in Hungary but have not been a subject of our study. The primary causes of flooding are linked to the mountains around the Carpathian basin. The interpretation of the changing climate parameters, for example, the increase of extreme precipitation events in the wintertime and of anthropogenic factors (the changes in land use by deforestation, crop rotation, and urbanisation impacts), is fairly determined. Based on the present state of knowledge, several local sites of future excess inland water problems can already be determined; however, their occurrence is still interpreted as random with regards to the climate (Pálfai 2004; van Leeuwen et al. 2008; Rakonczai 2011).

Discussion and conclusion

The integrative methods example resulted in some interesting outcomes when comparing the regional climatic models of REMO and ALADIN, in general and for coarse-grained meso-regional-scale levels of a number of landscapes in Hungary. The original climate data used in the regional models feature a resolution of 25 × 25 km, and a further downscaling to the Hungarian micro-region-scale level is not scientifically appropriate because of the lack of locally accurate data. Further investigation should aim to break down the climate change scenario modelling to local-scale applications when following the scientific potential of the results to link the climate change parameters of the temperature, precipitation and related extreme events (heat waves, drought periods, heavy rains and storms) to the scale level of land use and biotope types as proxies of the local ecosystems. This highlights the potential for the methods of landscape functions analysis and assessments to clarify the expected changes at the local-site-specific scale using planned and applied measures or projects proposed for climate change adaptation.

The aim of the study was not to apply our explorative methodological approach to the entire set of climate change scenarios provided by the IPCC (2007). The stability of the climate change variables of the scenario A1B chosen in this investigation is strongly linked to the societal success of the general environmental policy (for example, by the further activities following the Kyoto protocol) and to the unpredictable societal and economic changes in land uses following the same time horizon until 2100. The goal of our work lies in the regional differentiation of the expected functional sensitivities and the usage of a qualitative approach to clarify the hazards at an ordinal-data-scale level (from low to high). The qualitative entrance to the assessment is suitable, especially because of the diverse uncertainties of the climate change regional modelling data and prognosis. The regional environmental data and statistics of diverse sources have been used. The intrinsic uncertainty problems of the sensitivity assessment methods have not been subjects of our study. The aggregation of the heterogeneous site-specific data to the sensitivities of regional aggregates follows rule-based assessment methods.

The regional approach is suitable for general scenario applications, for example, in water management, in nature conservation policy (for example, for the management of FFH and Habitat networks) or for agricultural and forest policy and programme development. For Hungary, the hazard assessment scenario is compared with the expectations, needs and outputs of VAHAVA (Szabó et al. 2008—a programme of the Hungarian Academy of Sciences and the Ministry for Rural Development dealing with the future hazards of climate change for usage in governance issues. The main users of the regional-scale methodology for mass movements, soil erosion hazards by wind and water, flash floods and droughts are seen in regional and local land-use (landscape) planning, agricultural and water management planning, and governmental applications to reduce societal risks by reducing hazards in general. In these medium- or long-term planning measures, the potential climate change impacts will become integrated. The results might also be valuable in the insurance sector.

The authors applied a set of simple methods, appropriate largely on the basis of publicly available environmental and social data. The aggregation method is simple because of the methodological problems to integrate complex systems. The uncertainty of the meteorological and hydrological models and the limited validity of rules-based predictive modelling used in this study result in a differentiated view of the sensitivity of Hungarian regions to climate change. A detailed, in-depth analysis should be applied to further break down the climate change impact to the micro-regional scale of adaptation measurements.

The assessment results are integrated by a summation of assessment points—but the results are obviously also useful for sectoral indicator applications. From the scientific viewpoint, intensive future investigations based on integrative landscape and land-use models are required to deepen knowledge regarding the interlinkages of landscape maintenance for the investigated functions (for example, between wind erosion and drought, water erosion and flash floods) or the further development of methods for use with single landscape functions (for example, by an enhanced modelling of the processes of heavy rains and the hazards of mass movements).

Generally, the authors have investigated only a chosen set of landscape functions/landscape hazards by linking the climate change parameters of the temperature and precipitation to problems of drought, erosion, mass movement and flash flooding. Further investigations are seen in a widening of the lists of functions or ecosystem functions included in integrative methods and by a better reflection of the multifunctionality of land use, including its fast and dynamic changes. Future land-use changes may be more dynamic and led by the strong dynamics of the socioeconomic systems and the variable impacts of new technologies and markets. Such recent changes include the conflicting new usages of the landscape in the context of emerging bioenergy in concurrence with further-globalised food markets. In this context, the problem of the resilience of regional land-use systems is an open field of scientific methods development and investigation, as this resilience is strongly related to vulnerability and the adaptation capacity. The methods for hazard assessment of landscape functions or ecosystem services applied in our study provide results in a long-time perspective. Today, they are not applicable for integration of the daily and seasonal dynamics of weather and land-use systems in terms of farming system models. A step forward in this field could be, for example, the application of SWAT (soil water assessment tool) in sensitivity and vulnerability assessments when detailing the climate change impacts and the hazards of the extreme events due to local catchments for agricultural and water management purposes (Wisner et al. 1994).

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References

Agrotopographical Database (1991) Budapest, http://www.mta-taki.hu/en/departments/gis-lab/agrotopo_en

Bartholy J, Pongrácz R (2010) Analysis of precipitation conditions for the Carpathian Basin based on extreme indices in the 20th century and climate simulations for the 21st century. Phys Chem Earth 35:43–51

Bartholy J, Pongrácz R, Barcza Z, Haszpra L, Gelybó G, Kern A, Hidy D, Torma C, Hunyady A, Kardos P (2007) The regional consequences of the climate change: present status and expected trends. Földrajzi Közlemények 55:257–269 (In Hungarian)

Bartholy J, Pongrácz R, Gelybó G, Szabó P (2008) Analysis of expected climate change in the Carpathian Basin using the PRUDENCE results. Időjárás 112:249–264 (In Hungarian)

Carpenter TM, Sperfslage JA, Georgakakos KP, Sweeney T, Fread DL (1999) National threshold runoff estimation utilizing GIS is support of operational flash flood warning systems. J Hydrol 224:21–44

Csima G, Horányi A (2008) Validation of the ALADIN—Climate regional climate model at the Hungarian Meteorological Service. Időjárás 112(3–4):155–177

Czigány S, Pirkhoffer E, Balassa B, Bugya T, Bötkös T, Gyenizse P, Nagyváradi L, Lóczy D, Geresdi I (2010) Flash floods as a natural hazard in Southern Transdanubia. Földrajzi Közlemények 134:281–298 (In Hungarian)

Estrela T, Menéndez M, Dimas M, Marcuello C, Rees G, Cole G, Weber K, Grath J, Leonard J, Ovesen NB, Fehér J (2001) EEA Sustainable water use in Europe. Part 3: Extreme hydrological events: floods and droughts. http://www.eea.europa.eu/publications/Environmental_Issues_No_21

European Environment Agency (2000) CORINE land cover technical guide—Addendum 2000. EEA, Copenhagen

Faragó T, Láng I, Csete L (eds) (2010) Climate change and Hungary: mitigating the hazard and preparing for the impacts (The "VAHAVA" Report). http://www.unisdr.org/files/18582_thevahavareport08dec2010.pdf

Fodor T, Kleb B (1986) Engineering geological overview of Hungary. MÁFI, Budapest, p 199

Grundfest E, Rips A (2000) Flash floods. In: Parker DJ (ed) Floods 2002, vol 1. Routledge, London, pp 377–390

IPCC 2007 Climate Change 2007: The physical science basis. Working group I contribution to the fourth assessment report of the IPCC. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Cambridge University Press, New York, http://www.ipcc.ch

Jentsch A, Beierkuhnlein C (2008) Research frontiers in climate change: effects of extreme meteorological events on ecosystems. CR Geosci 340:621–628

Juhász Á (2004) Mass movement endangering human settlements and structures along the high bluff flanking Lake Balaton. Földrajzi Közlemények 52:19–30 (in Hungarian)

Kertész Á, Centeri C (2006) Hungary. In: Poesen J, Boardman J (eds) Soil erosion in Europe. Wiley, London, pp 139–153

Klik A (2004) Wind erosion assessment in Austria using wind erosion equation and GIS. In: OECD: Agricultural impacts on soil erosion and soil biodiversity: developing indicators for policy analysis, Paris, www.oecd.org/tad/env/indicators

Loibl W, Aubrecht Ch (2011) Hungary Climate Regions: Regional statistical analysis of selected Climate Change related indicators and classification of physiogeographic Meso-Regions to Climate Change region types. AIT – Austrian Institute of Technology Vienna, p 52

Lóki J (2011) Research of the land forming activity of wind and protection against wind erosion in Hungary. Riscuri Si Catastrofe 10:1–13 http://riscurisicatastrofe.reviste.ubbcluj.ro/Volume/X_Nr_9_2011/PDF/J%20Loki.pdf

Martens P, Aerts JCJH, Amelung SB, Bouwer LM, Huynen M, Chang CT, Ierland EC, Koppen CSA, McEvoy D, Mol APJ, Tatenhove JPM (2010) Imagining the unimaginable: synthesis of essays on abrupt and extreme climate change. Curr Opin Environ Sustain 2:347–355

Metzger M, Schröter D, Leemans R, Cramer W (2008) A spatially explicit and quantitative vulnerability assessment of ecosystem service change in Europe. Reg Environ Change 8:91–107

Meyer BC, Rannow S, Greiving S, Gruehn D (2009) Regionalisation of climate change impacts in Germany for the usage in spatial planning. GeoScape 1:34–43

Meyer BC, Rannow S, Loibl W (2010) Climate change and spatial planning. Landsc Urban Plan 98:139–140

Mücher CA, Klijn JA, Wascher DM, Schaminée JHJ (2010) A new European landscape classification (LANMAP): a transparent, flexible and user-oriented methodology to distinguish landscapes. Ecol Ind 10:87–103

Opdam P, Washer D (2004) Climate change meets habitat fragmentation: linking landscape and biogeographical scale levels in research and conservation. Biol Conserv 117:285–297

Pálfai I (2004) Undrained runoff and droughts in Hungary (Hydrologic Studies). KözDoc, Budapest p 492

Pécsi M, Somogyi S (1967) Magyarország természeti földrajzi tájai és geomorfológiai körzetei. Földrajzi. Közlemények 15: 285–304

Pieczka I, Pongrác R, Bartholy J, Kis A, Miklós E (2011) Estimated extreme climatical data in the Region of Carpathian-basin using results of the ENSEMBLES project. OMSZ, Budapest, pp 76–85 (in Hungarian)

Pielke RA Sr, Adegoke JO, Chase TN, Marshall CH, Matsui T, Niyogi D (2007) A new paradigm for assessing the role of agriculture in the climate system and in climate change. Agric For Meteorol 142:234–254

Pongrácz R, Bartholy J, Szabó P, Gelybó G (2009) Comparison of observed trends and simulated changes in extreme climate indices in the Carpathian basin by the end of this century. Int J Global Warm 1:336–355

Rakonczai J (2011) Effects and consequences of global climate change in the Carpathian Basin. In: Blanco J, Kheradmand H (eds) Climate change—geophysical foundations and ecological effects, pp 297–322

Rannow S, Loibl W, Greiving S, Gruehn D, Meyer BC (2010) Potential impacts of climate change in Germany—identifying regional priorities for adaptation activities in spatial planning. Landsc Urban Plan 98:160–171

Stefanovits P (1981) Pedology. Mezőgazdasági Kiadó, Budapest, p 376 (In Hungarian)

Szabó J, Lóki J, Tóth C, Szabó G (2008) Natural hazards in Hungary. In: Kertész Á, Kovács Z (eds) Dimensions and trends in Hungarian geography. MTA FKI, Budapest, pp 55–68

Szabó P, Horányi A, Krüzselyi I, Szépszó G (2011) The climate modelling at Hungarian Meteorological Survey: ALADIN and REMO. OMSZ, Budapest, pp 87–101 (In Hungarian)

Szépszó G (2008) Regional change of extreme characteristics over Hungary based on different regional climate models of the PRUDENCE project. Időjárás 112(3–4):265–284

Szépszó G, Horányi A (2008) Transient simulation of the REMO regional climate model and its evaluation over Hungary. Időjárás 112(3–4):203–231

Tobin GA, Montz BE (1997) Natural hazards: explanation and integration. Guilford Publishing, New York, p 388

Usher M (2001) Landscape sensitivity: from theory to practice. Catena 42:375–383

Van Leeuwen B, Tobak Z, Szatmári J (2008) Development of an integrated ANN—GIS framework for inland excess water monitoring. J Environ Geogr 1:1–6

WEQ 2000—http://www.weru.ksu.edu/nrcs/weqguidance062503.doc

Wischmeier WH, Smith DD (1978) Predicting rainfall erosion losses: a guide to conservation planning. Agriculture Handbook No. 537. USDA/Science and Education Administration, US. Govt. Printing Office, Washington, p 58

Wisner B, Blaikie P, Cannon T, Davis I (1994) At risk: natural hazards. People's vulnerability and disasters. Routledge, New York, p 447