

# IDŐJÁRÁS

*Quarterly Journal of the Hungarian Meteorological Service*  
*Vol. 121, No. 4, October – December, 2017, pp. 393–414*

## **Vulnerability of natural landscapes to climate change – a case study of Hungary**

**Ákos Bede-Fazekas**<sup>1,2\*</sup>, **Bálint Czúcz**<sup>1,3</sup>, and **Imelda Somodi**<sup>1,2</sup>

<sup>1</sup>*MTA Centre for Ecological Research, Institute of Ecology and Botany  
Alkomány u. 2-4., H-2163 Vácraátót, Hungary*

<sup>2</sup>*MTA Centre for Ecological Research, GINOP Sustainable Ecosystems Group  
Klebensberg Kuno u. 3., H-8237 Tihany, Hungary*

<sup>3</sup>*European Topic Centre on Biological Diversity,  
Muséum national d'Histoire naturelle  
57 rue Cuvier, FR-75231 Paris, Paris Cedex 05, France*

*\* Corresponding author E-mail: [bede-fazekas.akos@okologia.mta.hu](mailto:bede-fazekas.akos@okologia.mta.hu)*

*(Manuscript received in final form October 2, 2017)*

**Abstract**—Climate change is expected to exert considerable influence on natural ecosystems all over the world, though not all ecosystems are equally vulnerable to the changes. In this paper, an assessment framework of vulnerability of natural habitats to future climate change is presented, examining Hungary, Central Eastern Europe as a case study. A climate change impact, adaptation and vulnerability (CCIAV) assessment following IPCC traditions was applied, which operationalizes the concepts of exposure, sensitivity, potential impact, adaptive capacity, and vulnerability for natural ecosystems. Potential impact was quantified for the periods 2021–2050 and 2071–2100 based on regional climate models ALADIN-Climate and RegCM. Although the potential impact of future climate change was predominantly negative on the most climate sensitive forested habitat types of Hungary, for some of the grassland types we experienced positive predicted responses. Loess steppes and annual saline vegetation may thus partially benefit from climate change. The most climate vulnerable Hungarian regions are the Transdanubia (West Hungary) and the Northern Mountains (North Hungary) in terms of natural vegetation.

*Key-words:* climate vulnerability assessment, potential natural vegetation, habitat distribution model, global climate change, potential impact, habitat, prediction

## 1. Introduction

Vegetation is highly vulnerable to the predicted climate change both globally (Berry *et al.*, 2014) and in the Carpathian Basin (Kovács-Láng *et al.*, 2008, Czúcz, 2010; Mátyás *et al.*, 2010; Czúcz *et al.*, 2011b; Móricz *et al.*, 2013). By 2080, half of the 1350 European plant species studied by Thuiller *et al.* (2005) will become endangered by climate change. According to Hickler *et al.* (2012), the impact will be so great that also forestry and nature conservation will be significantly affected. It has also been proven that climate change detected during the last decades affected the distribution of species and survival of populations (Parmesan, 1996; Walther *et al.*, 2002; Moore, 2003; Parmesan and Yohe, 2003; Edwards and Richardson, 2004).

Based on the classification of Hughes (2000), Walther *et al.* (2002), Rosenzweig *et al.* (2007), the impacts of, and responses to, climate change are: 1) physiological and morphological changes; 2) phenological changes; 3) changes in the distribution; 4) changes in the composition and internal interactions of communities (including the food network), ecosystem structure and dynamics (including succession), ecosystem stability, ecosystem services; 5) genetic adaptation; 6) extinction. In this paper, we study changes in the potential distribution (3) of natural habitats, which expresses potential impact of climate change.

For assessing vulnerability to climate change, several methodological /conceptual frameworks have been developed (Füssel and Klein, 2006; Polsky *et al.*, 2007; Cheng, 2013; Fritzsche *et al.*, 2014), including the climate change impact, adaptation and vulnerability (CCIAV) assessment framework based on the terminology and concept of the Intergovernmental Panel on Climate Change (IPCC) as defined for the 3rd and 4th assessment reports (Parry and Carter, 1998; Carter *et al.*, 2007). The framework is sometimes called climate impact and vulnerability assessment scheme (CIVAS, e.g., Csete *et al.*, 2013). The CCIAV assessment adapted in this paper for natural habitats is a 2nd generation vulnerability assessment according to the classification by Füssel and Klein (2006), and is applied in several fields and regions (e.g., Allen Consulting Group, 2005). The implemented vulnerability concept is compatible with the risk concept of the 5th assessment report of IPCC (Hoffmann *et al.*, 2017). Although based on the three main components of the CCIAV (exposure, sensitivity, and adaptive capacity), the concept of vulnerability scoping diagram (VSD) of Polsky *et al.* (2007) and vulnerability framework of Turner *et al.* (2003) differ, since they suggest more permissive combination logic of the three components than the CCIAV concept implemented in this paper.

According to the framework, vulnerability to climate change is measured as the degree to which geophysical, biological, and socio-economic systems are susceptible to, and unable to cope with the adverse impacts of climate change (Schneider *et al.*, 2001). The vulnerability of an object is determined by the

potential impact of climate change and by the capacity of the object to adapt to the changing conditions. Potential impact is further determined by the exposure of the object to climate change, as well as by its sensitivity (Fig. 1). This framework can be applied to any object exposed to climate change. In our case, the objects include both natural and semi-natural ecosystems (habitat types). They have several relevant physical and biological properties determining their sensitivity, as well as adaptive capacity, which dependencies enable us to explore the climatic vulnerability of ecosystems using a modeling approach (Czúcz *et al.*, 2009, 2011a).

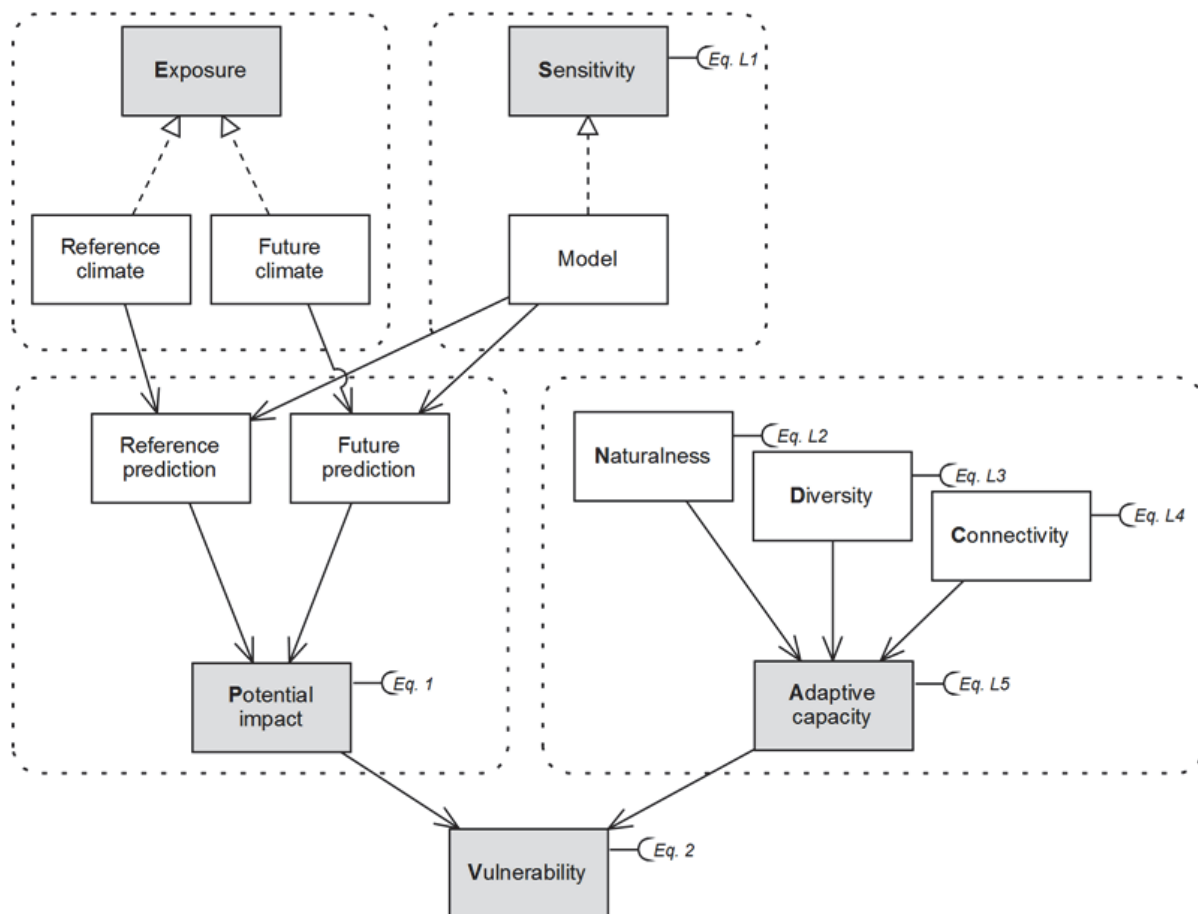


Fig. 1. Methodological flowchart of our research. Elements of climate change impact, adaptation and vulnerability (CCIAV) concept are shadowed, initial letters used hereinafter as abbreviations are typed bold, and equations/sources of calculation of sensitivity, potential impact, adaptive capacity, and vulnerability are also marked. For equation numbered with an initial L, please refer to Lepesi *et al.* (2017, in this issue, Section 2.2 and 2.3).

With respect to natural habitats, we define exposure ( $E$ ) as the projected degree of change in the bioclimatic variables at a given location for a specific time horizon (*Table 1*). A separate study in this journal issue deals with the determination of climate sensitivity ( $S$ ) for our calculations (*Lepesi et al.*, 2017, in this issue, Section 2.2), where we defined  $S$  of a habitat type as the degree to which climate-related factors influence the natural distribution of the habitat. In our study, exposure and sensitivity were directly determined from climate data and habitat distribution models, respectively (*Fig. 1*). Although the sensitivity of a habitat is best represented by the multivariate habitat distribution model itself, sensitivity to a certain exposure dimension, i.e., to climate in our case, can be characterized by its partial derivatives for communication purposes. Nonetheless, potential impact ( $P$ ) measurement should be based on the original multivariate models.  $P$  is expressed by the difference of predicted probabilities of presence given the climate of the reference period and under climate change scenarios in a given location (logically, within the occurrence locations of the habitat). Adaptive capacity ( $A$ ) is a relatively independent element of the modeled system, which should always be treated and communicated separately from the main impacts (*Hoffmann et al.*, 2017). We defined  $A$  as the capacity of the site and its landscape context to support successful adaptive processes for the studied habitat, which we describe in detail in a separate study in this issue (*Lepesi et al.*, 2017, in this issue, Section 2.3). While exposure is related to changes in climatic system, sensitivity and adaptive capacity is attributed to the natural/physical environment (*Fritzsche et al.*, 2014) and the inherent characteristics of the habitat. Vulnerability ( $V$ ) is defined as the combination of potential impact and adaptive capacity. In this paper, we focused on the detrimental effects of climate change only and interpreted vulnerability in case of a negative impact only. The term 'vulnerability' can be resolved in several ways (*O'Brien et al.*, 2007). It is context-specific, and the factors that make a system vulnerable depend on the nature of the system and the type of effect in question (*Brooks et al.*, 2005; *Fellmann*, 2012).

In this paper we aimed at 1) implementing the CCIAMV scheme of IPCC to natural habitats; 2) predicting the potential impact of future climate change on the distribution of the most climate sensitive climax and subclimax natural habitats of Hungary; 3) assessing the vulnerability of the habitats to future climate change according to two prediction periods and two climate models.

*Table 1.* The key elements of the CCIAV assessment framework and the definition and practical implementation of them followed in this study

Key element	Abbreviation	Definition	Dependence
Exposure	<i>E</i>	degree of change in the bioclimatic variables at a given location for a specific time horizon	timeline, climate model, location
Sensitivity	<i>S</i>	degree to which climate-related factors influence the natural distribution of the habitat	habitat type
Potential impact	<i>P</i>	difference of predicted probabilities of presence given the climate of the reference period and under climate change scenarios in a given location	habitat type, timeline, climate model, location
Adaptive capacity	<i>A</i>	capacity of the site and its landscape context to support successful adaptive processes for the studied habitat	habitat type, location
Vulnerability	<i>V</i>	combination of potential impact and adaptive capacity (only negative impact considered in this study)	habitat type, timeline, climate model, location
Overall vulnerability of natural vegetation	$\bar{V}$	maximum of the <i>V</i> of the most climate sensitive habitats at each location	timeline, climate model, location

## 2. Materials and methods

### 2.1. Potential impact

Our case study is based on our previous findings on potential distribution of climax and subclimax habitats of Hungary in the reference period (1977–2006) and two prediction periods (2021–2050, 2071–2100), according to two regional climate models (ALADIN-Climate 4.5; *Csima and Horányi, 2008*; RegCM 3.1; *Torma, 2011*; *Torma et al., 2011*). Please refer to *Somodi et al. (2017)* and *Bede-Fazekas (2017)* for details of the data used and the habitat distribution models applied. Based on expert decision, a minimum threshold of relative importance of climate predictors was chosen to select the most climate sensitive habitats.

Further analyses were conducted for only on these 12 selected habitats. Please refer to *Lepesi et al.* (2017, in this issue, Section 3.1) for further details of the most climate sensitive habitats. The presented vulnerability assessment framework can, however, be applied to any habitat/species whose potential distribution can be predicted to a reference and a future period, based on any kind of environmental predictor data and any kind of modeling approach.

The first step to assess vulnerability is to quantify the potential impact ( $P$ ) of climate change on the distribution of the climate sensitive habitats.  $P$  was defined as the difference between the probability of potential presence of the habitat in the future and that in the reference period (Eq. (1)), where  $f$  is the model function that returns predicted probability based on hydrological ( $H$ ), topographical ( $T$ ), edaphic ( $E$ ), and climatic ( $C$ ) predictors. To assess  $P$ , habitat distribution models (*Somodi et al.*, 2017) were applied to the reference and future environmental settings given both time periods and climate models separately. Thus,  $P$  is available in four combinations for each of the habitats investigated (2 periods  $\times$  2 climate models).

$$P = f(H, T, E, C_{reference}) - f(H, T, E, C_{future}) \quad (1)$$

Since the codomain of  $f$  is the interval of  $[0; 1]$ ,  $P$  ranges from  $-1$  to  $1$  with  $-1-0$  representing positive impact of climate change on the habitat, while  $0-1$  represents adverse impact. This representation was chosen so that the target of this study, the negative climate impact receives large values.

## 2.2. Vulnerability

Vulnerability ( $V$ ) depends both on  $P$  and adaptive capacity ( $A$ ). The larger the  $P$ , the more vulnerable the habitat. This is in accordance with the core of the CCIAV concept: systems that are highly exposed, sensitive, and less able to adapt are vulnerable (*Allen Consulting Group*, 2005). High  $V$  can be mitigated with high  $A$ . The operationalization of the adaptive capacity concept is detailed in *Lepesi et al.* (2017, Section 2.3) in this issue. Codomain of  $A$  is the set of  $\{0; 1; 2; 3; 4\}$ , where  $4$  indicates the highest capacity to adapt to changing climate. Hence, the lack of adaptive capacity is defined as  $5-A$ . During our vulnerability analysis, we concentrated on the detrimental effects of climate change only, therefore only positive  $P$ s (unfavorable climate impact) were considered (Eq. (2)).

$$V = \begin{cases} 0, & \text{if } P \leq 0, \\ P * (5 - A), & \text{if } P > 0. \end{cases} \quad (2)$$

This formula ensured that lower  $A$  and higher negative impact (higher  $P$ ) lead to higher  $V$ . Range of  $V$  is the interval of  $[0; 5]$ . Values were calculated separately for climate models and periods in the future, since potential impact and vulnerability can vary over time (i.e., they are dynamic) by climatic stimuli (Smit and Wandel, 2006; Adger *et al.*, 2007; Fellmann, 2012). High level aggregated indicators for the two studied time periods and the two climate models, i.e., the overall vulnerabilities ( $\bar{V}$ ) of natural vegetation were estimated as the maximum of the  $V$  of the most climate sensitive habitats (Lepesi *et al.* 2017; in this issue, Section 3.1). This applied to each location where one or more of such habitats are present according to the MÉTA habitat database (Molnár *et al.*, 2007; Horváth *et al.*, 2008) in the reference period. To be consistent with the input data, all the layers of the vulnerability assessment, including the maps of  $P$ , were aggregated (upscaled) to the horizontal resolution of the climate models ( $0.1^\circ$ ) by calculation of the maximum values within the coarse cells. All calculations were performed in the R statistical programming environment (R Core Team, 2017).

### 3. Results

#### 3.1. Potential impact of climate change

As expected, the potential impact of future climate change is predominantly negative on the twelve most climate sensitive habitats (Table 2). Sensitive forests are likely to be negatively affected (Fig. 2). The exception is L5 (closed lowland steppe oak woodlands), where climate models highly disagree regarding the outcome. A similar pattern emerged for forest steppe meadows (H4). Results for these two habitats have to be handled with care therefore. The two wetland types are likely to benefit at least partially from climate change. The most likely reason for this is an increased winter precipitation with climate change. Loess steppes (H5a) also have the potential to benefit from climate change. A benefit is especially striking for annual saline vegetation (F5), which is in good accordance with its adaptation to soil salinity, typical for arid climates (Fig. 3). Potential impact maps are available at NATÉR (2017).

Table 2. Potential impact (*P*) of climate change on the twelve most climate sensitive habitats (Lepesi et al. 2017; in this issue, Section 3.1) ordered according to their sensitivity. The table summarizes the spatial pattern of potential impact within the country (–: negative, 0: neutral, +: positive). We also indicate if any conflict between predictions of climate models has been identified, and if a change in trends was discernible between the two periods. Habitats are encoded according to Bölöni et al. (2011). For actual distribution of the habitats, please refer to Bölöni et al. (2008, 2011) and Molnár et al. (2008).

Habitat code	Descriptive habitat name	2021–2050, Aladin	2021–2050, RegCM	2071–2100, Aladin	2071–2100, RegCM	Conflict	Trend change
N13	mixed coniferous forests	–	–	–	–	no	no
LY2	mixed forests of slopes and screes	–	–	–	–	no	no
F5	annual salt pioneer swards of steppes and lakes	+ or 0	mostly +, sometimes –	+ or 0	+ or 0	no	no
K5_K7a	beech woodlands	–	–	–	–	no	no
B1b	oligotrophic reed and <i>Typka</i> beds of fens and floating fens	– at the edges, + in the center	– at the edges, + in the center	– in the West, + elsewhere	– in the West, + elsewhere	no	yes
L5	closed lowland steppe oak woodlands	0 or + in the East, – in the West	–	0, sometimes +	0 or –	yes	inconsistent
H5a	closed steppes on loess, clay, tufa	variable, but + in the East	variable, but – in the East	+ or 0	+ or 0	yes	inconsistent
L2x_M2	steppe oak woodlands on foothills and on loess	–	–	–	–	no	no
L2a_L2b	Turkey oak woodlands	–, 0 in the South	–, 0 in the South	–, 0 in the South	–, 0 in the South	no	no
H4	forest steppe meadows	0 or –	+	+ in Central Hungary, 0 or – elsewhere	variable, – in the East	yes	yes
J1a	willow mire shrubs	– in the East, 0 or + in the center	– in the East, 0 or + in the center	+ or 0	+ or 0	no	yes
K1a_K2_K7b	oak-hornbeam woodlands	–	–	–	–	no	no



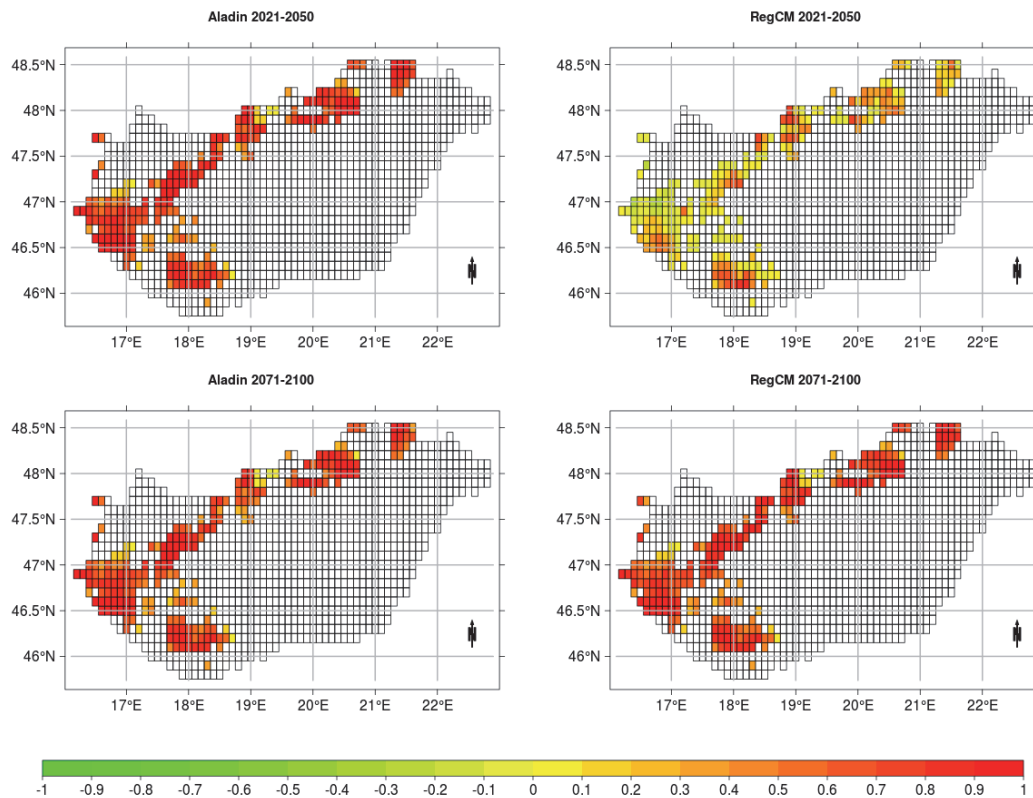


Fig. 2. Potential impact ( $P$ ) of climate change to existing stands of beech forests (K5\_K7a). Subfigure titles refer to the climate model and the future period in relation to which  $P$  was examined. Unfavourability of  $P$  increases from green to red.

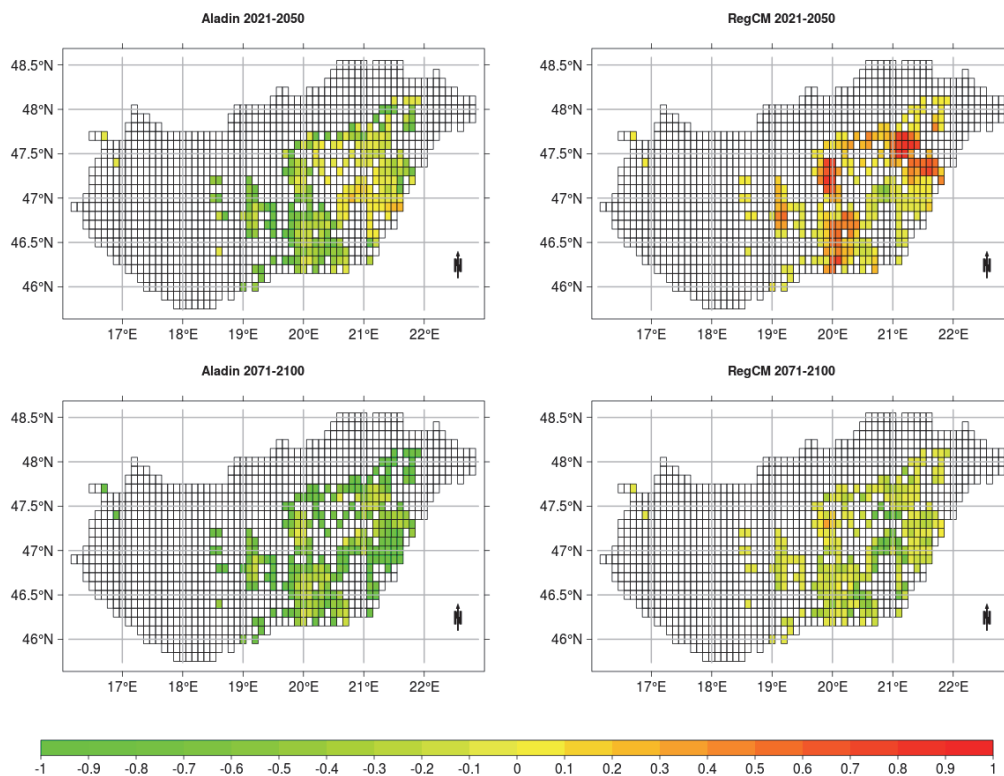


Fig. 3. Potential impact ( $P$ ) of climate change to existing stands of annual salt pioneer swards of steppes and lakes (F5). Subfigure titles refer to the climate model and the future period in relation to which  $P$  was examined. Unfavourability of  $P$  increases from green to red.

### 3.2. Vulnerability of habitats

The estimated vulnerability to future climate change has high variance across the habitats, periods, regional models and regions (*Table 3*). An agreement between the two models indicates robust results. Some habitats seems to be consequently vulnerable (N13) or vulnerable in most of the periods/models/regions (L2a\_L2b, K5\_K7a, K1a\_K2\_K7b; *Fig. 4*), while others may not be remarkably vulnerable (F5, B1b, H5a, H4, *Fig. 5*). Although RegCM shows higher *V* in general, long-term (2071–2100) vulnerability of natural habitats is consistent given the two climate models. Natural vegetation appears most vulnerable in Western and Northern Hungary, as well as in the easternmost corner of Hungary. This is probably in connection with forests being the dominant natural vegetation there. Models disagree, however, in the degree of short-term (2021–2050) *V*.

*Table 3.* Vulnerability (*V*) to climate change of the twelve most climate sensitive habitats ordered according to their sensitivity. The table summarizes the spatial pattern of vulnerability within the country (0: low, --: medium, -: high; relative to the highest value). Habitats are encoded according to *Bölöni et al. (2011)*. For the name of habitats please consult to *Table 2*.

Habitat code	2021–2050, Aladin	2021–2050, RegCM	2071–2100, Aladin	2071–2100, RegCM
N13	–	–	–	–
LY2	variable, mainly 0 and --, – in the South	variable, mainly 0 and --, – in the South	variable, mainly 0 and --, – in the South	variable, mainly 0 and --, – in the South
F5	0	Variable	0	0
K5_K7a	--	0	--	--
B1b	0, -- and – in the West	0, -- and – in the West	0, -- and – near Lake Balaton	0, -- and – in the West
L5	0	Variable	0	0, -- and – in the East
H5a	0	variable, mainly 0 and --	0	0, -- in the West
L2x_M2	0, sporadically --	Variable	0, sporadically --	variable
L2a_L2b	–, 0 and – in the Southwest	– in the North, 0 in the Southwest	–, 0 and – in the Southwest	–, 0 and – in the Southwest
H4	variable, mainly 0 and --	0	0	variable, mainly 0 and --
J1a	0, -- and – in the East and Southwest	0	0, -- and – in the East and Southwest	0
K1a_K2_K7b	--, sporadically –	0 and --, – in the Northwest	--, sporadically –	--, sporadically –

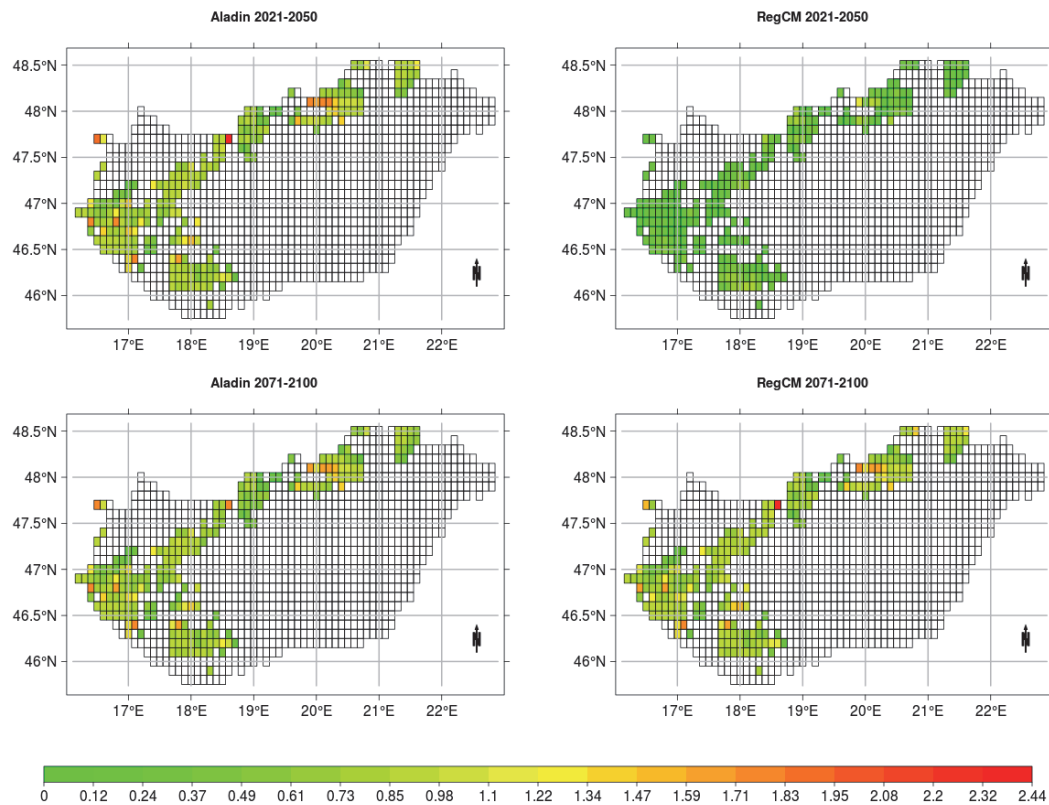


Fig. 4. Vulnerability ( $V$ ) of the existing stands of beech forests (K5\_K7a). Subfigure titles refer to the climate model and the future period in relation to which  $V$  was examined.  $V$  increases from green to red.

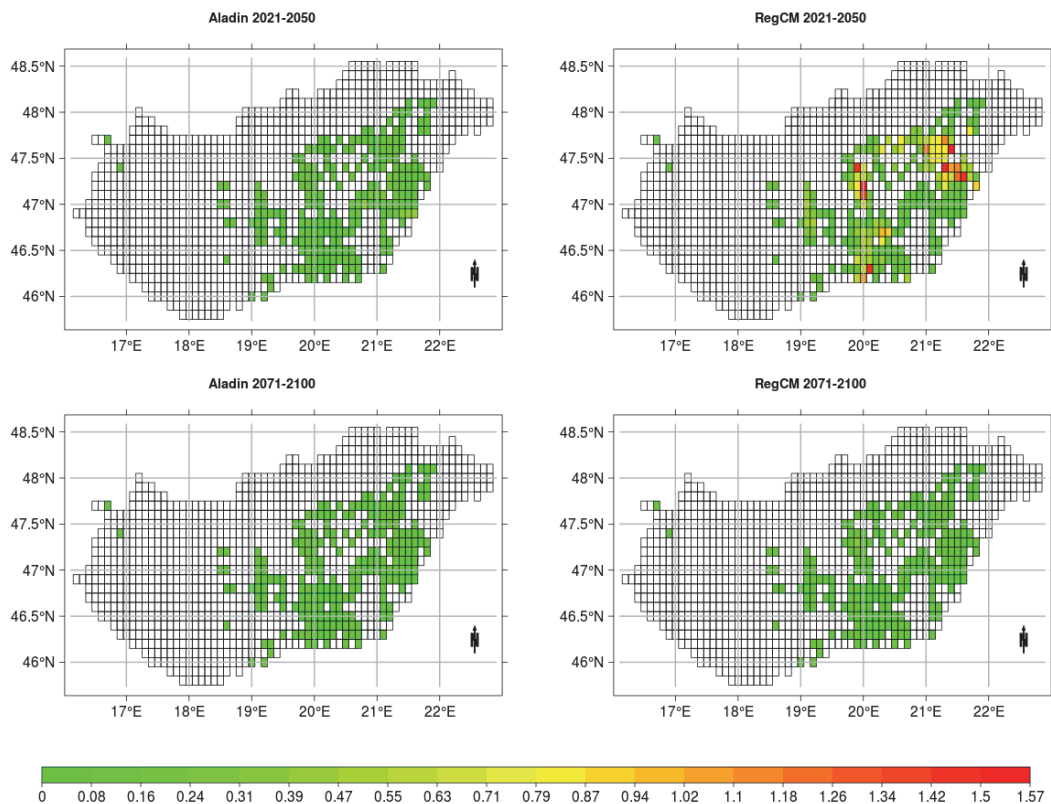
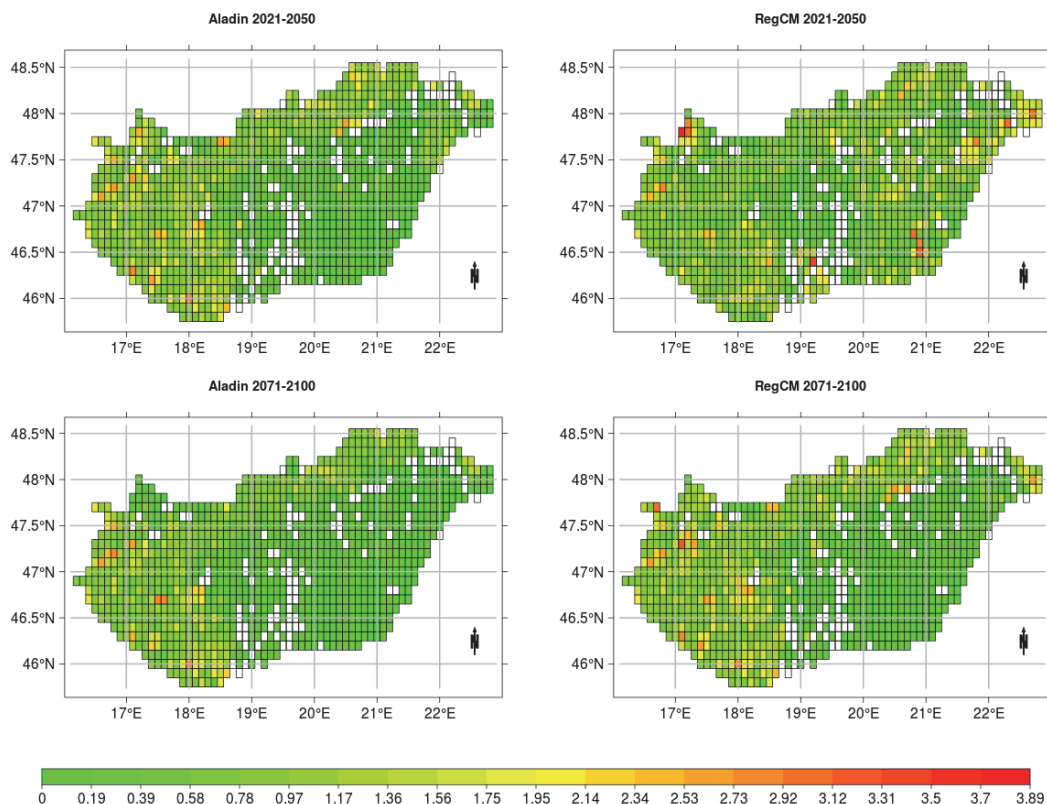


Fig. 5. Vulnerability ( $V$ ) of the existing stands of annual salt pioneer swards of steppes and lakes (F5). Subfigure titles refer to the climate model and the future period in relation to which  $V$  was examined.  $V$  increases from green to red.

Overall vulnerability of the twelve most sensitive habitats is only sporadically striking (*Fig. 6*). Except for the 2021–2050 period according to RegCM model, in which case the vulnerable spots are not arranged systematically, Western and Northern part of Hungary is more vulnerable than the Southeastern one. While Aladin shows a similar overall pattern in case of the two prediction period, RegCM shows considerable differences. According to the short-term estimations using RegCM,  $\bar{V}$  is lower in Central Transdanubia and higher in the Southeast part of the Great Hungarian Plain than at the long term. Additionally, to the broader pattern we see an increased  $\bar{V}$  South to Lake Balaton and in the North-western area. South to Lake Balaton, there are closed forests at the edge of their environmental tolerance, therefore they are particularly vulnerable to climate change.



*Fig. 6.* Overall climatic vulnerability of the most climate sensitive habitats of Hungary ( $\bar{V}$ ). Subfigure titles refer to the climate model and the future period in relation to which  $\bar{V}$  was examined.  $\bar{V}$  increases from green to red.

## 4. Discussion

### 4.1. Discussion of the framework

The analysis presented shows that the elements of the CCIAV framework can be effectively interpreted in, and adapted to, specific sectorial contexts, such as natural habitats. The specific solutions (components of *A*, aggregation schemes etc.) can be used as an orientation in further similar studies. Furthermore, the entire analysis can be reused as an embedded part of a large multi-sectoral CCIAV assessment.

Potential impact (P) of climate change was estimated, in any location, as the difference of future and reference probability of presence (Eq. (1)). In methodological terms, calculation of the difference of habitat suitability indices (for species) results in the same approach (e.g., *Vallecillo et al.*, 2009). The presented method is more detailed than the widespread gain/loss/turnover calculations (e.g., *Hamann and Wang*, 2006; *Harrison et al.*, 2006; *Benito Garzón et al.*, 2008; *Ogawa-Onishi et al.*, 2010; *Robiansyah*, 2017) and their aggregated form, the change of climate envelope richness (e.g., *McKenney et al.*, 2007; *Attorre et al.*, 2011), since it estimates P on a continuous scale instead of the binary output of gain/loss method (or the sum of the gains/losses in case of the change climate envelope richness. Furthermore, the latter ones can only be used in case of binary presence/absence output of distribution models that need a threshold often specified unfoundedly and subjectively (*Jiménez-Valverde and Lobo*, 2007; *Lobo et al.*, 2008; *Liu et al.*, 2015). Some researchers present P by simply displaying current and future potential distributions side by side (e.g., *Kriticos et al.*, 2003; *Guo et al.*, 2016), or partly (e.g., *Trájer et al.*, 2014) or fully (e.g., *Bede-Fazekas et al.*, 2014) overlapping each other, instead of calculating the difference. Since those methods pass the responsibility to the reader to draw conclusions, we suggest calculating and presenting P in a difference map, possibly next to the current and future distribution maps (similarly to maps presenting potential impacts on environmental factors, e.g., *Blanka et al.* (2013), *Mezősi et al.* (2014)). Calculation of P, and therefore V, is not inextricably linked to climate change (*Glick et al.*, 2011); the proposed framework can be applied in, inter alia, land cover change assessments as well.

The most central part of a CCIAV assessment is quantifying vulnerability (V). Although some researchers consider V simply as the inverse of resilience (*De Wrachien et al.*, 2008), we argue that V is essentially a (set of) high-level aggregated indicator(s), which establish a balanced information over all of the individual CCIAV components. The main goal of V is to give a quick but insightful overview of the assessment outcomes for decision makers, policy uses and the general public. As there are many valid possible policy and decision-making contexts, there is no single default aggregation formula or V indicator either. The construction of a V indicator and the resulting vulnerability map

highly depends on the decisions taken during its construction, which should ideally be customized for a specific policy context and designed in a participatory process involving key stakeholders. The overall vulnerability index of the twelve most sensitive habitats presented in this paper is only one option, created for a general nature conservation-planning context. This unweighted statistic can be used for framing general policy discussions, but we encourage all users of our data sets to use custom weightings of  $V$  of the selected habitats, or, even more, aggregating strategies for  $P$  and  $A$  components tailored to their specific needs and the problem in focus. For country-wide assessments we suggest to develop a structured aggregation model (e.g., multi-criteria decision analysis, MCDA) with the involvement of all relevant stakeholders.

Although some authors (e.g., *Downing et al.*, 2001) have argued that vulnerability is a relative, rather than absolute, measure (*Füssel and Klein*, 2006), we developed in this paper an easy to use vulnerability index for an interval scale within  $[0; 5]$ . Note, however, that the calculated adaptive capacity index is relative (*Lepesi et al.*, 2017, in this issue, Section 4.2), hence, vulnerability is relative as well.

Although only positive  $P$ s (unfavorable climate impact) were considered during the calculation of  $V$  since we concentrated on the detrimental effects of climate change, if necessary, also negative  $P$ s can be used. This may result in negative  $V$ s, which is somewhat contradictory to the meaning of the word 'vulnerability' but nevertheless can be easily interpreted.

#### 4.2. Interpretation of the results

As most of the zonal habitats of Hungary can be found among the twelve most climate sensitive habitats (*Lepesi et al.*, 2017, in this issue, Section 3.1), our results give a reliable overview about the expected ecological impacts of climate change. As a general rule, the modeled  $P$  was predominantly negative for forested habitat types, but for grassland types we experienced at least partially positive predicted responses in most of the cases. This result is congruent with the expectation that Hungary, lying roughly at the biogeographic boundary between forest and steppe zones (*Zólyomi*, 1989; *Molnár et al.*, 2012), should experience a shift towards more open habitat types. Furthermore, the natural vegetation of mountainous areas, predominantly forests, appears to be more vulnerable than that of the lowlands. This foreshadows that maintaining forests in Hungary might become more difficult (*Czúcz et al.*, 2011b) and that more open habitat types may become more sustainable. It is also important to note that the lower level of  $P$  and  $V$  in the lowland landscapes applies only to the natural landscape elements there (i.e., space covered by natural or seminatural vegetation). The  $V$  of agricultural fields or settlements can greatly differ from this pattern.

We can be most confident in estimations if the results regarding all climate periods and climate models consistently suggests reliable results. This kind of consistence was experienced for all zonal forests and two of the grasslands, for example. Estimations should be handled with care however, when climate models disagree in outcome or when trends change between the two future periods. We did experience such patterns, as well. In such cases, future research should cover more climate models and wider time periods to reduce uncertainty. On the other hand, it is important to view uncertainty as a necessary component of any climate projections, as well as the impact assessments relying on them (*Heikkinen et al., 2006; Hanspach et al., 2011; Beale and Lennon, 2012; Thuiller, 2014*). Uncertainty should not be considered as a shortcoming of the analysis, rather as an informative warning that the behavior of some objects or subsystems is less predictable and their prediction is therefore less reliable (*Heuvelink et al., 2007; Gerharz et al., 2010*). This can be caused by several factors, including uncertainties in the input data, a limited understanding of system functioning, but also can be an inherent characteristic of the object in question, which cannot and should not be eliminated. Low prevalence of a habitat (e.g., steppe oak woodlands on foothills and on loess – L2x\_M2), therefore too few data records used for training of the habitat distribution model, can increase uncertainty of potential impact and vulnerability estimations. This may result in under or overprediction. Informed decisions need to be aware of the sources and magnitude of uncertainties.

Future research needs to be directed towards assessing a wider range of climate scenarios, time periods and habitats as well as providing detailed analysis of the *P* and *V* results for questions in the field of ecology.

### *4.3. Application of the results*

The maps produced allow a wide range of applications. There are several policy sectors where the final and intermediate results of a climatic vulnerability assessment on natural ecosystems can provide easily interpretable and relevant inputs (*European Environment Agency, 2005; Glick et al., 2011*). However, there is a great need for adaptation policy frameworks and effective result communication to incorporate the output of the assessments in adaptation strategies (*European Environment Agency, 2005*). Major applications of vulnerability assessments are expected in the field of nature conservation and restoration prioritization, as well as in landscape evaluations (*Loidi and Fernández-González, 2012*). Prioritizing requires the identification of vulnerable systems (*Allen Consulting Group, 2005*). Indeed, maps from a habitat-oriented vulnerability assessment can effectively support the prioritization of the different stands of a threatened habitat type for nature conservation (*Glick et al., 2011; McNeeley et al., 2017*). Locations, which are least vulnerable to climate change, are likely the ones that can be most cost-effectively conserved in their

current state. Hence, vulnerability assessments enable efficient allocation of financial resources (*Uppgupta et al.*, 2015; *McNeeley et al.*, 2017). On the other hand, high  $V$  does not mean that a stand should be given up by nature conservation (*Glick et al.*, 2011), it rather shows that in those location a nature conservation action should take the form of promoting natural processes, i.e., the natural transformation of a stand to a less sensitive habitat or even to a habitat that endures the new climate better. Emphasis is put on natural processes here, which can also be a target of conservation and may thus serve biodiversity protection, as well as ecosystem service maximization (*Prach and del Moral*, 2014; *Prach et al.*, 2016).

For restoration and forestry planning, it is also crucial to consider the future state of the location. Modern restoration theory and practice is moving away from restoring past vegetation and aims at creating self-sustainable stands (*Somodi et al.*, 2012; *Török et al.*, in press), which maintain themselves under the actual, as well as the future climatic conditions. To this end, it is important at each studied location to identify the list of habitats that find their requirements both now and in the future, and least vulnerable habitats should be selected as restoration targets. For example, according to our results and that of other studies (*Mátyás et al.*, 2010; *Czúcz et al.*, 2011b), beech forests (K5\_K7a) seem to be relatively inappropriate to become such restoration targets, and forestry decisions may have to weight in their vulnerability at places. However, ecosystems with natural species composition and dynamics generally need less maintenance efforts and provide a more balanced portfolio of ecosystem services than artificial green spaces, thus natural habitat types should be preferred as restoration targets wherever possible.

As our analysis was designed and restricted to existing stands, our results are not fully informative for local restoration periodization purposes. However, the messages that emerged from this vulnerability analysis are useful for restoration considerations as well. Grasslands (loess steppes and saline ones) that appeared to benefit from climate change in our analysis are among the potentially most promising (sustainable and cost-effective) restoration targets (c.f., the similar results of *Czúcz*, 2010). From forests, turkey oak woodlands (L2a\_L2b) appear to be the best candidates, because their high  $A$  balance the negative direct  $P$  that even this forest type seems to face.

Landscape evaluation and landscape planning can benefit from the use of our results (*Loidi and Fernández-González*, 2012; *Bede-Fazekas*, 2017). Any adjustment in the elements of ecological networks or green infrastructure has to consider whether the proposed change in the network will make it more or less vulnerable under climate change. Furthermore, restoration efforts may be efficiently directed to network elements with high vulnerability.

Broad-scale landscape architecture, i.e., spatial and regional planning, and landscape rehabilitation may gain information from our result that enables them to be more scientifically sound and to be more prepared for potential land use



conflicts (Golobič and Žaucer, 2010; Crist *et al.*, 2014). Those landscape architecture and rehabilitation projects that are informed by our results are able to reflect more on ecological processes and let the decision makers cost-effectively avoid conflicts and disasters that are connected to natural patterns and processes to a certain degree, including infrastructure investments on vulnerable areas, policy-driven land use change (e.g., afforestation, *European Environment Agency*, 2005), top-down designation of nature reserve areas (Glick *et al.*, 2011), etc. Recognizing the future perspectives on *P*, *A*, and *V* of (semi)natural habitats should significantly and essentially alter some widely used and non-informed landscape planning strategies (Bede-Fazekas, 2017).

## 5. Conclusions

Our results indicate that the CCIIV framework of IPCC can be effectively adapted to (semi)natural habitats. According to our simple and straightforward implementation of the framework, vulnerability of habitats and overall vulnerability of the vegetation can be assessed based on adaptive capacity and the potential impact of climate change calculated from predicted potential distribution maps. The results show that vulnerability highly varies across regions, climate models, prediction periods and habitats. Hence, detailed ensemble approach is always necessary when only one, easily interpretable vulnerability indicator of the vegetation is aimed to be developed and presented to decision makers.

**Acknowledgements:** The authors thank to the Hungarian Actual Habitat Database (MÉTA) Curatorium for allowing the use of the database, as well as to the field mappers for their contribution to the database. The study was supported by the Hungarian Scientific Research Fund (OTKA) grant no. PD-83522 (Imelda Somodi), by the Bolyai János research fellowship of the Hungarian Academy of Sciences (Bálint Czúcz) and by the GINOP-2.3.2-15-2016-00019 grant. Financial support was also received from Iceland, Liechtenstein and Norway through the European Environment Agency Grants and the Regional Environmental Center (National Adaptation Geo-information System (NAGiS) project).

## References

- Adger, W.N., Agrawala, S., Mirza, M.M.Q., Conde, C., O'Brien, K., Pulhin, J., Pulwarty, R., Smit, B., and Takahashi, K., 2007: Assessment of adaptation practices, options, constraints and capacity. In (Eds.: Parry, M.L., Canziani, O. F., Palutikof, J.P., van der Linden, P.J., and Hanson, C.E.) *Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK.
- Allen Consulting Group, 2005: *Climate Change Risk and Vulnerability. Promoting an efficient adaptation response in Australia*. Australian Greenhouse Office, Canberra, Australia.
- Attorre, F., Alfó, M., De Sanctis, M., Francesconi, F., Valenti, R., Vitale, M., and Bruno, F., 2011: Evaluating the effects of climate change on tree species abundance and distribution in the Italian peninsula. *Appl. Vegetat. Sci.* 14, 242–255.

- Beale, C.M. and Lennon, J.J., 2012: Incorporating uncertainty in predictive species distribution modelling. *Phil. Trans. Roy. Soc. London. Series B, Biol. Sci.* 367, 247–258.
- Bede-Fazekas, Á., 2017: Fás szárú dísznövények potenciális telepíthetőségi területének előrejelzése természetközeli élőhelyekre készített modellek alapján. PhD dissertation. Szent István University, Doctoral School of Landscape Architecture and Landscape Ecology, Budapest, Hungary. (in Hungarian)
- Bede-Fazekas, Á., Horváth, L., and Kocsis, M., 2014: Impact of climate change on the potential distribution of Mediterranean pines. *Időjárás* 118, 41–52.
- Benito Garzón, M., Sánchez de Dios, R., and Sainz Ollero, H., 2008: Effects of climate change on the distribution of Iberian tree species. *Appl. Veget. Sci.* 11, 169–178.
- Berry, P.M., Dawson, T.P., Harrison, P.A., and Pearson, R.G., 2002: Modelling potential impacts of climate change on the bioclimatic envelope of species in Britain and Ireland. *Glob. Ecol. Biogeogr.* 11, 453–462.
- Blanka, V., Mezösi, G., and Meyer, B., 2013: Projected changes in the drought hazard in Hungary due to climate change. *Időjárás* 117, 219–237.
- Bölöni, J., Molnár, Zs., and Kun, A., (eds.) 2011: Magyarország élőhelyei. A hazai vegetációtípusok leírása és határozója. ÁNÉR 2011. MTA ÖBKI, Vácrátót, Hungary. (in Hungarian)
- Bölöni, J., Molnár, Zs., Biró, M., and Horváth, F., 2008: Distribution of the (semi-)natural habitats in Hungary II. Woodlands and shrublands. *Acta Botanica Hungarica* 50, 107–148.
- Brooks, N., Adger, W.N., and Kelly, P.M., 2005: The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Glob. Environ. Change* 15, 151–162.
- Carter, T.R., Jones, R.N., Lu, X., Bhadwal, S., Conde, C., Mearns, L.O., O'Neill, B.C., Rounsevell, M.D.A., and Zurek, M.B., 2007: New assessment methods and the characterisation of future conditions. In (Eds.: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E.) *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press: Cambridge, UK.
- Cheng, C., 2013: Social vulnerability, green infrastructure, urbanization and climate change-induced flooding: A risk assessment for the Charles River watershed, Massachusetts, USA. Ph.D. dissertation. University of Massachusetts Amherst, Amherst, MA, USA.
- Crist, P., Maybury, K., Carr, S., and Hak, J., 2014: Tools for Landscape-Level Assessment and Planning. A Guide for the North Pacific Landscape Conservation Cooperative. NatureServe, Arlington, VA, USA.
- Csete, M., Pálvolgyi, T., and Szendrő, G., 2013: Assessment of climate change vulnerability of tourism in Hungary. *Reg. Environ. Change* 13, 1043–1057.
- Csima, G. and Horányi, A., 2008: Validation of the ALADIN-Climate regional climate model at the Hungarian Meteorological Service. *Időjárás* 112, 155–177.
- Czúcz, B., 2010: Az éghajlatváltozás hazai természetközeli élőhelyekre gyakorolt hatásainak modellezése. PhD dissertation. Corvinus University of Budapest, Doctoral School of Horticultural Sciences, Budapest, Hungary. (in Hungarian)
- Czúcz, B., Csecserits, A., Botta-Dukát, Z., Kröel-Dulay, Gy., Szabó, R., Horváth, F., and Molnár, Zs., 2011a: An indicator framework for the climatic adaptive capacity of natural ecosystems. *J. Vegetat. Sci.* 22, 711–725.
- Czúcz, B., Gálhidy, L., and Mátyás, Cs., 2011b: Present and forecasted xeric climatic limits of beech and sessile oak distribution at low altitudes in Central Europe. *Ann. Forest Sci.* 68, 99–108.
- Czúcz, B., Torda, G., Molnár, Zs., Horváth, F., Botta-Dukát, Z., and Kröel-Dulay, Gy., 2009: A spatially explicit, indicator-based methodology for quantifying the vulnerability and adaptability of natural ecosystems. In (Eds.: Filho, W.L., Mannke, F.) *Interdisciplinary Aspects of Climate Change.* Peter Lang Scientific Publishers, Frankfurt, Germany.
- De Wrachien, D., Mambretti, S., and Sole, A., 2008: Risk analysis and vulnerability assessment in flood protection and river basin management. In (Eds.: Proverbs, D., Brebbia, C.A., Penning-Rowsell, E.) *Flood Recovery, Innovation and Response.* WIT Press, Ashurst, UK.
- Downing, T.E., Butterfield, R., Cohen, S., Huq, S., Moss, R., Rahman, A., Sokona, Y., and Stephen, L., 2001: *Climate Change Vulnerability: Linking Impacts and Adaptation.* Report to the Governing Council of the United Nations Programme. United Nations Environmental Programme, Nairobi, Kenya.

- Edwards, M. and Richardson, A.J., 2004: Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature* 430, 881–884.
- European Environment Agency, 2005: Vulnerability and adaptation to climate change in Europe. European Environment Agency, Copenhagen, Denmark.
- Fellmann T., 2012: The assessment of climate change-related vulnerability in the agricultural sector: reviewing conceptual frameworks. In: (Eds.: Meybeck, A., Lankoski, J., Redfern, S., Azzu, N., Gitz, V.) Building resilience for adaptation to climate change in the agriculture sector. Proceedings of a Joint FAO/OECD Workshop 23–24 April 2012. Food and Agriculture Organization of the United Nations, Organisation for Economic Co-operation and Development, Rome, Italy.
- Fischlin, A., Midgley, G.F., Price, J.T., Leemans, R., Gopal, B., Turley, C., Rounsevell, M.D.A., Dube, O.P., Tarazona, J., and Velichko, A.A., 2007: Ecosystems, their properties, goods and services. In (Eds.: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E.): Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
- Fritzsche, K., Schneiderbauer, S., Bubeck, P., Kienberger, S., Buth, M., Zebisch, M., and Kahlenborn, W., 2014: The Vulnerability Sourcebook. Concept and guidelines for standardized vulnerability assessments. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Bonn, Germany.
- Füssler, H.M. and Klein, R.J.T., 2006: Climate change vulnerability assessments: An evolution of conceptual thinking. *Climatic Change* 75, 301–329.
- Gerharz, L., Pebesma, E., and Hecking, H., 2010: Visualizing uncertainty in spatio-temporal data. In (Eds.: Tate, N.J., Fisher, P.F.): Proceedings of the Ninth International Symposium on Spatial Accuracy Assessment in Natural Resources and Environmental Sciences. University of Leicester, Leicester, UK.
- Glick, P., Stein, B.A., and Edelson, N.A. (eds.), 2011: Scanning the Conservation Horizon. A Guide to Climate Change Vulnerability Assessment. National Wildlife Federation, Washington, DC, USA.
- Golobič, M. and Žaucer, L.B., 2010: Landscape planning and vulnerability assessment in the Mediterranean. Regional Activity Centre for the Priority Actions Programme, Split, Croatia.
- Guo, Y., Wei, H., Lu, C., Gao, B., and Gu, W., 2016: Predictions of potential geographical distribution and quality of *Schisandra sphenanthera* under climate change. *PeerJ* 4, e2554.
- Hamann, A. and Wang, T., 2006: Potential Effects of Climate Change on Ecosystem and Tree Species Distribution in British Columbia. *Ecology* 87, 2773–2786.
- Hanspach, J., Kühn, I., Schweiger, O., Pompe, S., and Klotz, S., 2011: Geographical patterns in prediction errors of species distribution models. *Glob. Ecol. Biogeogr.* 20, 779–788.
- Harrison, P.A., Berry, P.M., Butt, N., and New, M., 2006: Modelling climate change impacts on species' distributions at the European scale: implications for conservation policy. *Environ. Sci. Policy* 9, 116–128
- Heikkinen, R.K., Luoto, M., Araújo, M.B., Virkkala, R., Thuiller, W., and Sykes, M.T., 2006: Methods and uncertainties in bioclimatic envelope modelling under climate change. *Progr. Phys. Geography* 30, 751–777.
- Heuvelink, G.B.M., Brown, J.D., and van Loon, E.E., 2007: A Probabilistic Framework for Representing and Simulating Uncertain Environmental Variables. *Int. J. Geograph. Inform. Sci.* 21, 497–513.
- Hickler, T., Vohland, K., Feehan, J., Miller, P.A., Smith, B., Costa, L., Giesecke, T., Fronzek, S., Carter, T.R., Cramer, W., Kühn, I., and Sykes, M.T., 2012: Projecting the future distribution of European potential natural vegetation zones with a generalized, tree species-based dynamic vegetation model. *Glob. Ecol. Biogeogr.* 21, 50–63.
- Hill, J.K., Thomas, C.D., and Huntley, B., 2003: Modeling present and potential future ranges of European butterflies using climate response surfaces. In (Eds.: Bogs, C., Watt, W., Ehrlich, P.) Butterflies. Ecology and evolution taking flight. The University of Chicago Press, Chicago, IL, USA.
- Hoffmann, E., Rupp, J., and Harnisch, R., (eds.), 2017: Guidelines for Climate Impact and Vulnerability Assessments. Recommendations of the Interministerial Working Group on

- Adaptation to Climate Change of the German Federal Government. Umweltbundesamt, Dessau-Roßlau, Germany.
- Horváth, F., Molnár, Zs., Bölöni, J., Pataki, Zs., Polgár, L. Révész, A., Oláh, K., Krasser, D., and Illyés, E., 2008: Fact sheet of the MÉTA Database 1.2. *Acta Botanica Hungarica* 50, 11–34.
- Hughes, L., 2000: Biological consequences of global warming: is the signal already apparent? *Trends Ecol. Evolut.* 15, 56–61.
- Jiménez-Valverde, A., Lobo, J.M., 2007: Threshold criteria for conversion of probability of species presence to either–or presence–absence. *Acta Oecologica* 31, 361–369.
- Kovács-Láng, E., Kröel-Dulay, Gy., and Czúcz, B., 2008: Az éghajlatváltozás hatásai a természetes élővilágra és teendők a megőrzés és kutatás területén. *Természetvédelmi Közlemények* 14, 5–39. (in Hungarian)
- Kriticos, D.J., Sutherst, R.W., Brown, J.R., Adkins, S.W., and Maywald, G.F., 2003: Climate change and the potential distribution of an invasive alien plant: *Acacia nilotica* ssp. *indica* in Australia. *Journal of Applied Ecology* 40, 111–124.
- Lepesi, N., Bede-Fazekas, Á., Czúcz, B., and Somodi, I., 2017: Adaptive capacity of climate sensitive habitats to climate change in Hungary. *Időjárás* 121, 415–436.
- Liu, C., Newell, G., and White, M., 2016: On the selection of thresholds for predicting species occurrence with presence-only data. *Ecol. Evolut.* 6, 337–348.
- Lobo, J.M., Jiménez-Valverde, A., and Real, R., 2008: AUC: a misleading measure of the performance of predictive distribution models. *Global Ecol. Biogeogr.* 17, 145–151.
- Loidi, J. and Fernández-González, F., 2012: Potential natural vegetation: reburying or reborning? *J. Vegetat. Sci.* 23, 596–604.
- Mátyás, Cs., Berki, I., Czúcz, B., Gálos, B., Móricz, N., and Rasztoivits, E., 2010: Future of Beech in Southeast Europe from the Perspective of Evolutionary Ecology. *Acta Silvatica et Lignaria Hungarica* 6, 91–110.
- McKenney, C.W., Pedlar, J.H., Lawrence, K., Campbell, K., and Hutchinson, M.F., 2007: Potential Impacts of Climate Change on the Distribution of North American Trees. *BioScience* 57, 939–948.
- McNeeley, S.M., Even, T.L., Gioia, J.B.M., Knapp, C.N., and Beeton, T.A., 2017: Expanding vulnerability assessment for public lands: The social complement to ecological approaches. *Climate Risk Manage.* 16, 106–119.
- Mezősi, G., Bata, T., Meyer, B. C., Blanka, V., and Ladányi, Zs., 2014: Climate Change Impacts on Environmental Hazards on the Great Hungarian Plain, Carpathian Basin. *Int. J. Disaster Risk Sci.* 5, 136–146.
- Molnár, Zs., Bartha, S., Seregélyes, T., Illyés, E., Tímár, G., Horváth, F., Révész, A., Kun, A., Botta-Dukát, Z., Bölöni, J., Biró, M., Bodoncz, L., Deák, J. Á., Fogarasi, P., Horváth, A., Isépy, I., Karas, L., Kecskés, F., Molnár, Cs., Ortmann-né Ajkai, A., and Rév, Sz., 2007: A grid-based, satellite-image supported, multi-attributed vegetation mapping method (MÉTA). *Folia Geobotanica* 42, 225–247.
- Molnár, Zs., Biró, M., Bartha, S., and Fekete, G., 2012: Past Trends, Present State and Future Prospects of Hungarian Forest-Steppes. In (Eds.: Werger, M.J.A., van Staaldin, M.A.) *Eurasian Steppes. Ecological Problems and Livelihoods in a Changing World*. Springer, Dordrecht, Netherlands, Heidelberg, Germany, New York, NY, USA, London, UK
- Molnár, Zs., Biró, M., Bölöni, J., and Horváth, F., 2008: Distribution of the (semi-)natural habitats in Hungary I. Marshes and grasslands. *Acta Botanica Hungarica* 50, 59–105.
- Moore, P. D., 2003: Back to the future: biogeographical responses to climate change. *Prog. Phys. Geogr.* 27, 122–129.
- Móricz, N., Rasztoivits, E., Gálos, B., Berki, I., Eredics, A., and Loibl, W., 2013: Modelling the Potential Distribution of Three Climate Zonal Tree Species for Present and Future Climate in Hungary. *Acta Silvatica et Lignaria Hungarica* 9, 85–96.
- NATÉR, 2017: Nemzeti Alkalmazkodási Térinformatikai Rendszer. URL: [map.mfgi.hu/nater](http://map.mfgi.hu/nater) [Last accessed: 2017.07.12.]. (in Hungarian)
- O'Brien, K., Eriksen, S., Nygaard, L.P., and Schjolden, A., 2007: Why different interpretations of vulnerability matter in climate change discourses. *Climate Policy* 7, 73–88.

- Ogawa-Onishi, Y., Berry, P. M., and Tanaka, N., 2010: Assessing the potential impacts of climate change and their conservation implications in Japan: A case study of conifers. *Biol. Conservat.* 143, 1728–1736.
- Parmesan, C., 1996: Climate and species' range. *Nature* 382, 765–766.
- Parmesan, C., and Yohe, G., 2003: A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421, 37–42.
- Parry, M.L. and Carter, T.R., 1998: Climate Impact and Adaptation Assessment: A Guide to the IPCC Approach. Earthscan, London, UK.
- Polsky, C., Neff, R., and Yarnal, B., 2007: Building comparable global change vulnerability assessments: The vulnerability scoping diagram. *Glob. Environ. Change* 17, 472–485.
- Prach, K. and del Moral, R., 2014: Passive restoration is often quite effective: Response to Zahawi et al. (2014). *Restorat. Ecol.* 23, 344–346.
- Prach, K., Tichý, L., Lencová, K., Adámek, M., Koutecký, T., Sádlo, J., Bartošová, A., Novák, J., Kovář, P., and Šmilauer, P., 2016: Does succession run towards potential natural vegetation? An analysis across seres. *J. Vegetat. Sci.* 27, 515–523.
- R Core Team, 2017: R: A language and environment for statistical computing. Bécs, Ausztria: R Foundation for Statistical Computing. URL: [www.R-project.org](http://www.R-project.org) [Last accessed: 2017.07.12.].
- Robiansyah, I., 2017: Predicting the impact of climate change on the distribution of *Flindersia pimenteliana* F. Muell. in Indonesian Papua and Papua New Guinea. *Biotropia* 24, 59–70.
- Rosenzweig, C., Casassa, G., Karoly, D. J., Imeson, A., Liu, C., Menzel, A., Rawlins, S., Root, T.L., Seguin, B., and Tryjanowski, P., 2007: Assessment of observed changes and responses in natural and managed systems. In (Eds.: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E.) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
- Schneider, S., Sarukhan, J., Adejuwon, J., Azar, C., Baethgen, W., Hope, C., Moss, R., Leary, N., Richels, R., Van Ypersele, J-P., Kuntz-Duriseti, K., and Jones, R.N., 2001: Overview of impacts, adaptation, and vulnerability to climate change. In (Eds.: McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken D.J., White, K.S.): Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
- Settele, J., Scholes, R., Betts, R., Bunn, S. E., Leadley, P., Nepstad, D., Overpeck, J.T., Taboada, M.A., 2014: Terrestrial and inland water systems. In (Eds.: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L.) Climate Change 2014: Impacts, Adaptation, and Vulnerability Part A: Global and Sectoral Aspects Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA.
- Smit, B. and Wandel, J., 2006: Adaptation, adaptive capacity and vulnerability. *Glob. Environ. Change* 16, 228–292.
- Somodi, I., Molnár, Zs., Czucz, B., Bede-Fazekas, Á., Bölöni, J., Pásztor, L., Laborczi, A., and Zimmermann, N.E., 2017: Implementation and application of Multiple Potential Natural Vegetation models – a case study of Hungary. *J. Vegetat. Sci.* DOI: 10.1111/jvs.12564.
- Somodi, I., Molnár, Zs., and Ewald, J., 2012: Towards a more transparent use of the potential natural vegetation concept – an answer to Chiarucci et al.. *J. Vegetat. Sci.* 23, 590–595.
- Thomas, C.D., Cameron, A., Green, R.E., Bakkenes, M., Beaumont, L.J., Collingham, Y.C., Erasmus, B.F.N., Ferreira de Siqueira, M., Grainger, A., Hannah, L., Hughes, L., Huntley, B., Van Jaarsveld, A.S., Midgley, G.F., Miles, L., Ortega-Huerta, M.A., Peterson, A.T., Phillips, O.L., and Williams, S.E., 2004: Extinction risk from climate change. *Nature* 427, 145–148.
- Thuiller, W., 2014: Editorial commentary on “Patterns and uncertainties of species’ range shifts under climate change”. *Glob. Change Biol.* 20, 3593–3594.
- Thuiller, W., Lavorel, S., Araújo, M.B., Sykes, M.T., and Prentice, I.C., 2005: Climate change threats to plant diversity in Europe. *Proc. Nation. Acad. Sci.* 102, 8245–8250.

- Torma, Cs., 2011: Átlagos és szélsőséges hőmérsékleti és csapadék v0iszonyok modellezése a Kárpát-medencére a XXI. századra a RegCM regionális klímamodell alkalmazásával. PhD dissertation. Eötvös Loránd University, Faculty of Science, Budapest, Hungary. (in Hungarian)
- Torma, Cs., Coppola, E., Giorgi, F., Bartholy, J., and Pongrácz, R., 2011: Validation of a high-resolution version of the regional climate model RegCM3 over the Carpathian Basin. *J. Hydrom.* 12, 84–100.
- Török, K., Csecserits, A., Somodi, I., Kövendi-Jakó, A., Halász, K., Rédei, T., and Halassy, M.: Restoration prioritization for industrial area applying Multiple Potential Natural Vegetation modelling. *Restoration Ecology* (in press).
- Trájer, A., Bede-Fazekas, Á., Bobvos, J., and Páldy, A., 2014: Seasonality and geographical occurrence of West Nile fever and distribution of Asian tiger mosquito. *Időjárás* 118, 19–40.
- Turner, B.L., Kasperson, R.E., Matson, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Kasperson, J.X., Luers, A., Martello, M.L., Polsky, C., Pulsipher, A., and Schiller, A., 2003: A framework for vulnerability analysis in sustainability science. *Proc. Nat. Acad. Sci.* 100, 8074–8079.
- Upp Gupta, S., Sharma, J., Jayaraman, M., Kumar, V., and Ravindranath N.H., 2015: Climate change impact and vulnerability assessment of forests in the Indian Western Himalayan region: A case study of Himachal Pradesh, India. *Climate Risk Manage.* 10, 63–76.
- Vallecillo, S., Brotons, L., and Thuiller, W., 2009: Dangers of predicting bird species distributions in response to land-cover changes. *Ecol. Appl.* 19, 538–549.
- Walther, G.R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J.C., Fromentin, J-M., Hoegh-Guldberg, O., and Bairlein, F., 2002: Ecological responses to recent climate change. *Nature* 416, 389–395.
- Zólyomi, B., 1989: Magyarország természetes növénytakarója. In: (Ed.: Pécsi, M.) Nemzeti Atlasz. Kartográfia Vállalat, Budapest, Hungary. (in Hungarian)