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

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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).

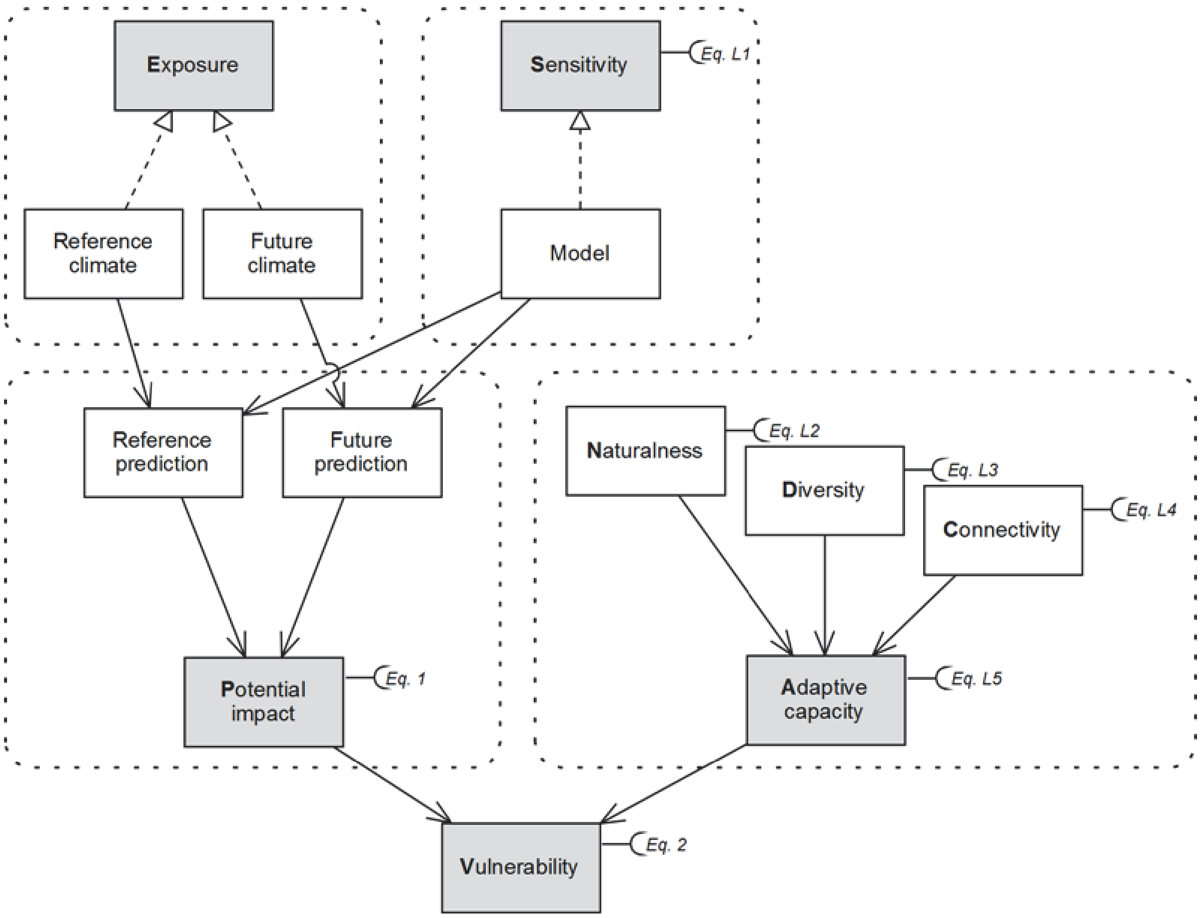

Fig. 1. Methodological flowchart of our research. Elements of climate change impact, adaptation and vulnerability (CCIAV) concept are shadowed, initial letters used hereinafter as abbreviations are typed bold, and equations/sources of calculation of sensitivity, potential impact, adaptive capacity, and 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 CCIAV 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	E	degree of change in the bioclimatic variables at a given location for a specific time horizon	timeline, climate model, location
Sensitivity	S	degree to which climate-related factors influence the natural distribution of the habitat	habitat type
Potential impact	P	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	A	capacity of the site and its landscape context to support successful adaptive processes for the studied habitat	habitat type, location
Vulnerability	V	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 V 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 × 2 climate models).

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

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 Ps (unfavorable climate impact) were considered (Eq. (2)).

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

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°) 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 *Typha* 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

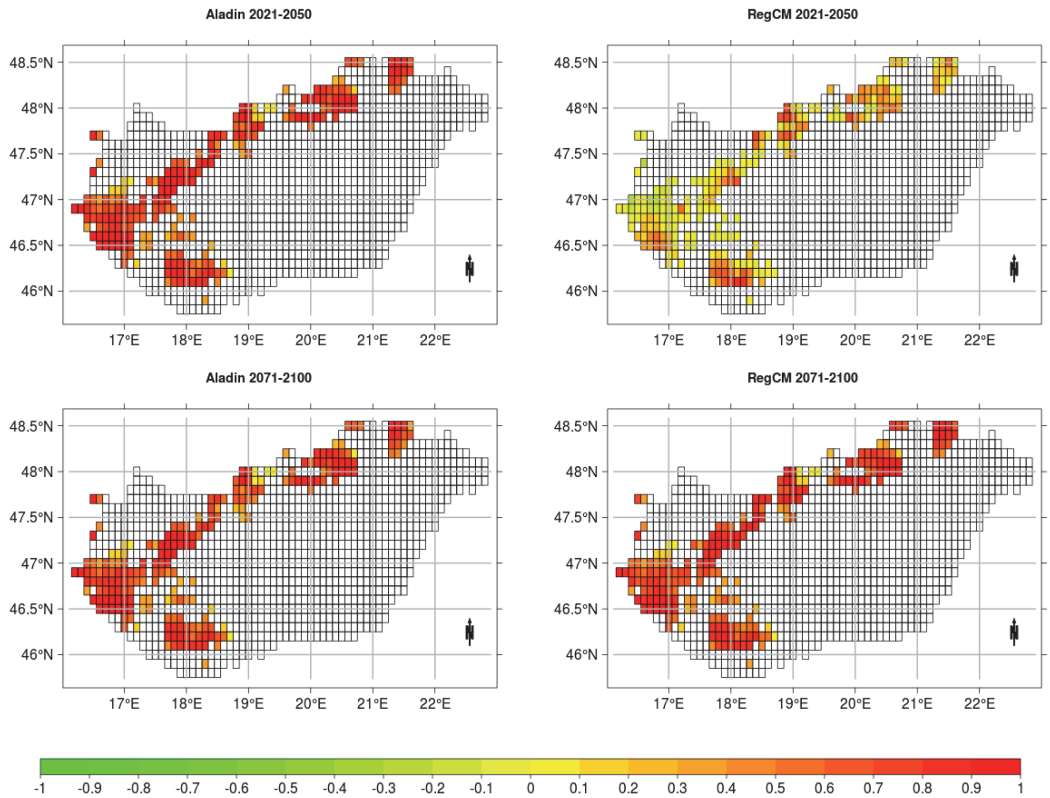

Fig. 2. Potential impact (*P*) of climate change to existing stands of beech forests (K5_K7a). Subfigure titles refer to the climate model and the future period in relation to which *P* was examined. Unfavourability of *P* increases from green to red.

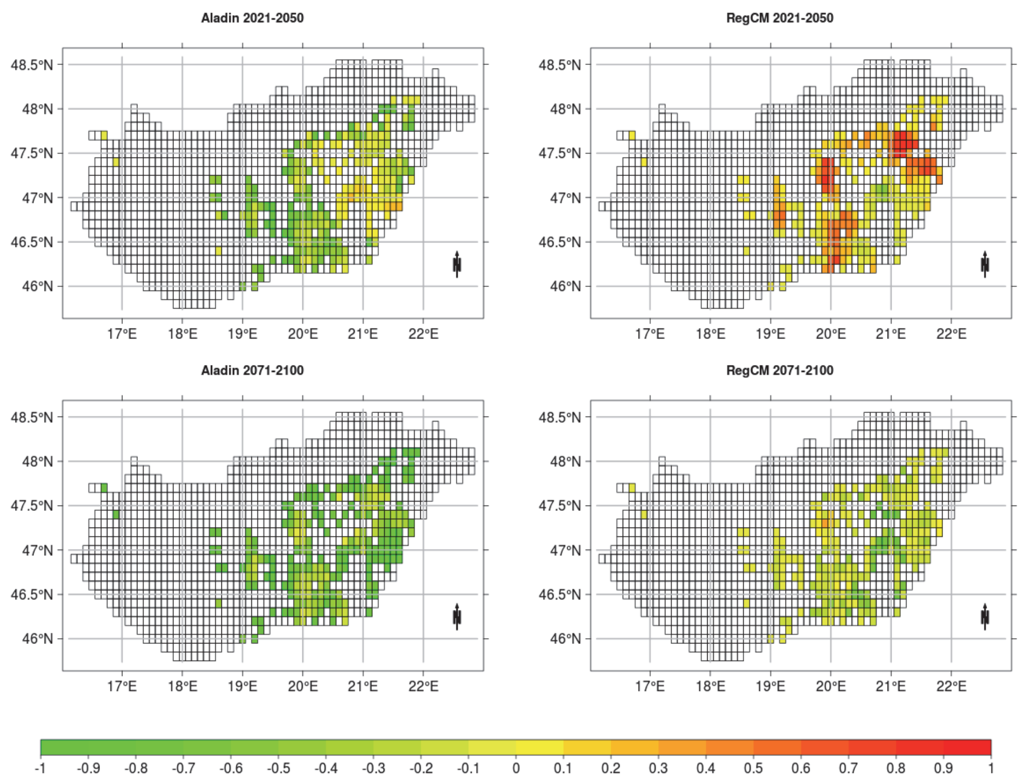

Fig. 3. Potential impact (*P*) of climate change to existing stands of annual salt pioneer swards of steppes and lakes (F5). Subfigure titles refer to the climate model and the future period in relation to which *P* was examined. Unfavourability of *P* increases from green to red.

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 –

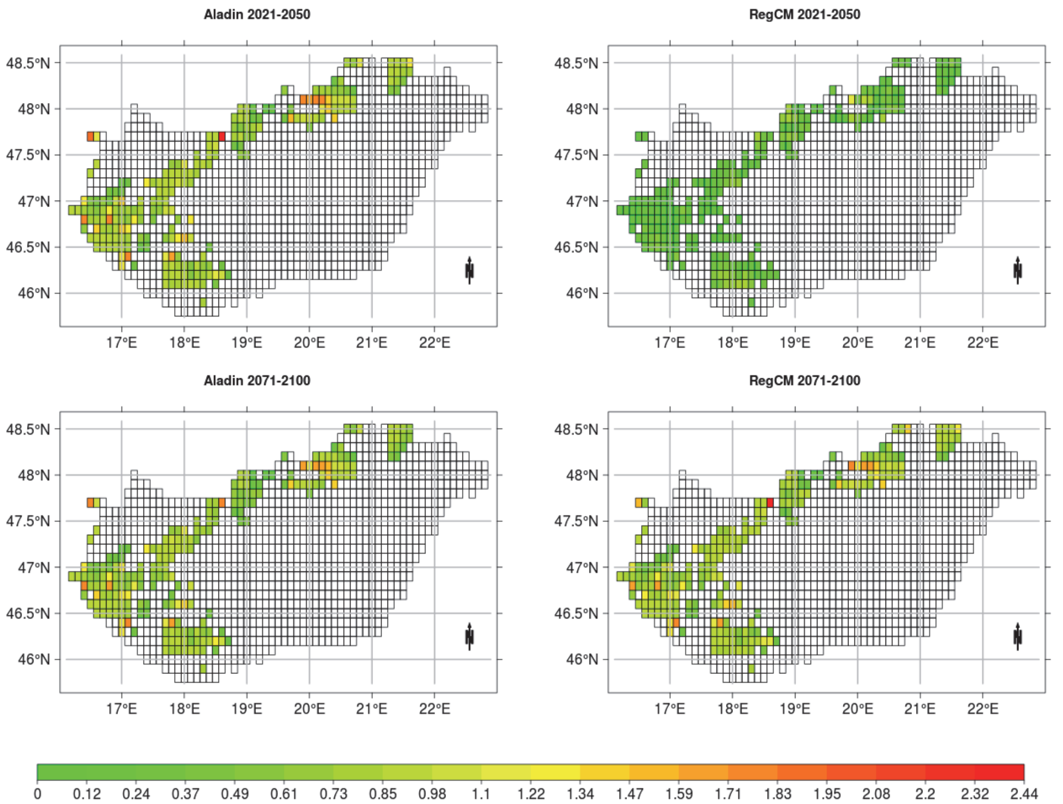

Fig. 4. Vulnerability (*V*) of the existing stands of beech forests (K5_K7a). Subfigure titles refer to the climate model and the future period in relation to which *V* was examined. *V* increases from green to red.

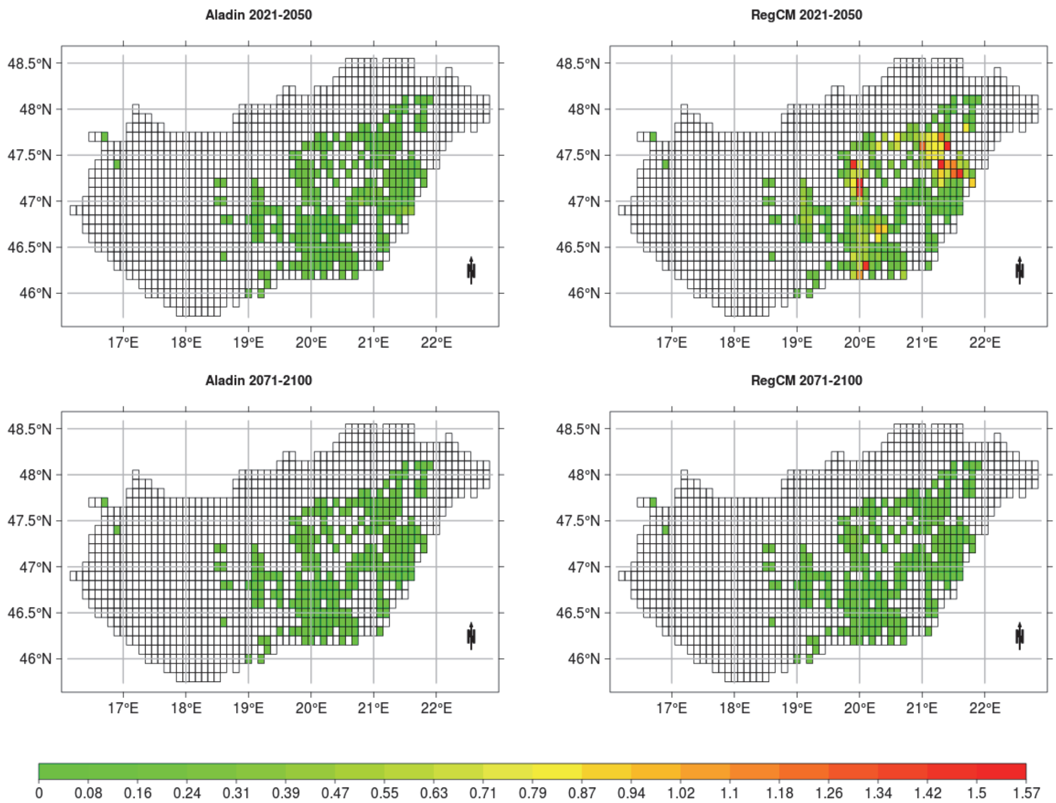

Fig. 5. Vulnerability (*V*) of the existing stands of annual salt pioneer swards of steppes and lakes (F5). Subfigure titles refer to the climate model and the future period in relation to which *V* was examined. *V* increases from green to red.

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, 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 V South to Lake Balaton and in the North-western areae. South to Lake Balaton, there are closed forests at the edge of their environmental tolerance, therefore they are particularly vulnerable to climate change.

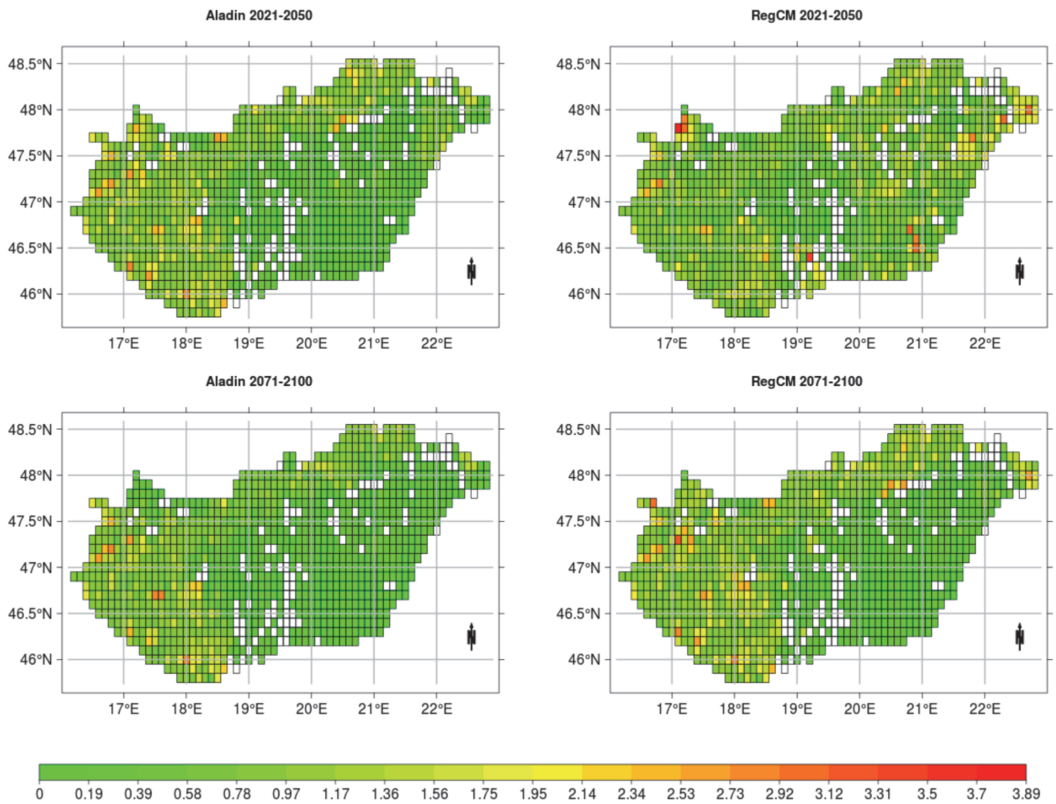

Fig. 6. Overall climatic vulnerability of the most climate sensitive habitats of Hungary ($\bar{V}$). Subfigure titles refer to the climate model and the future period in relation to which $\bar{V}$ was examined. $\bar{V}$ increases from green to red.

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 Ps (unfavorable climate impact) were considered during the calculation of V since we concentrated on the detrimental effects of climate change, if necessary, also negative Ps can be used. This may result in negative Vs, 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 areae, 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 (*Upgupta 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 areae, policy-driven land use change (e.g., afforestation, *European Environment Agency*, 2005), top-down designation of nature reserve areae (*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 CCIAV 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 vary 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.

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