Effects of Meteorological and Site Parameters on the Health Status of Beech (*Fagus sylvatica* L.) Forests in Hungary

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Abstract – The influence of meteorological parameters on the health status of beech (*Fagus sylvatica* L.) was analyzed using long term datasets (1989-2010) collected in 15 sample plots located in Hungary's main beech regions. Leaf loss values were correlated with different meteorological parameters as explanatory variables. Analysis was performed by the CReMIT (Cyclic Reverse Moving Intervals Techniques) method. Weather, stand, and site parameters were also examined with PCA for comparison. Leaf loss levels showed stronger correlations with maximum monthly temperatures than with monthly precipitation sums. The monthly number of summer days and monthly number of hot days displayed a similar correlation to leaf loss as the maximum monthly temperature did. The correlations were regularly stronger and more frequent on more arid sites where the climate is less favorable for beech. Temperature affected leaf loss more than precipitation did. Our results show that beech forests may suffer heavy damage if climate change continues as projected.

beech /*Fagus sylvatica* L. / leaf loss / climate change / CReMIT / Hungary

Kivonat – Meteorológiai és egyes termőhelyi tényezők hatása a bükk (*Fagus sylvatica* L.) egészségi állapotára Magyarországon. A meteorológiai tényezők bükkösökre gyakorolt hatásait 15 mintaterületen gyűjtött hosszútávú (1989-2000) adatsorokon vizsgáltuk. A lombvesztés értékét különböző meteorológiai tényezőkkel korreláltattuk, a CReMIT (Cyclic Reverse Moving Intervals Techniques) mozgó időablakos módszer segítségével. Ezután az időjárási, termőhelyi és erdőállomány-jellemzőket is bevonva PCA analízist is végrehajtottunk. A lombvesztés erősebb kapcsolatot mutatott a havi maximum hőmérséklettel, mint a havi csapadék-összeggel. A havi nyári napok és hőségnapok összegei a maximum-hőmérséklethez hasonló összefüggéseket mutattak. A korrelációk erőssége nagyobb volt a szárazabb klímájú, bükknek kevésbé alkalmas mintaterületeken. Eredményeink alátámasztják, hogy a jövőben a bükkösök súlyos károknak lehetnek kitéve, ha a klímaváltozás az előrejelzett forgatókönyvek szerint alakul majd.

bükk / *Fagus sylvatica* L. / lombvesztés / klímaváltozás / CReMIT / Magyarország

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1 INTRODUCTION

Although the ratio of European beech (*Fagus sylvatica* L.) forests is relatively low in Hungary (112,603 ha; 6.0% of total forested area – NFK 2020), the species still possesses ecological and economic importance. Hungarian beech forests are situated on low to mid-mountain elevations, and on extrazonal occurrences in lower, hilly areas. Due to its distinct climatic needs, beech is considered a forest-climate indicator species in Hungary. Optimal montane/submontane sites with preferable climate for beech have a restricted extent in Hungary; hence, beech forests often grow in suboptimal sites.

Beech has significant precipitation needs and weak drought tolerance (Arend et al. 2016), which makes it vulnerable to climate change (Geßler et al. 2007). This is especially true in conditions and sites where beech forests thrive in Hungary today. Nonetheless, climate change appears to have the opposite effect in other north-eastern European provenances where suitable areas for beech are expanding (Augustaitis et al. 2015).

Climate change scenarios project worsening conditions for beech forests in Southern and Eastern Europe, particularly in the Carpathian Basin (Berki et al. 2007). Some researchers suggest beech may even disappear from Hungary altogether in the next century (Mátyás et al. 2010, Führer et al. 2011). Central and Southern European beech stands have suffered incremental reduction during drought and warm years since 1980 (Jump et al. 2006, Zimmermann et al. 2015, Giagli et al. 2016). A reduction in suitable habitat for beech due to climate change is also projected for the Iberian Peninsula (del Río et al. 2018).

Hungarian forests already face direct or indirect damage related to extreme weather conditions, particularly drought damage (Csóka et al. 2009, Lakatos – Molnár 2009, Rasztovits et al. 2014, Janik et al. 2016). In Hungary, beech is close to its xeric limits, which makes it more susceptible to climate change.

As in many other European countries, severe beech declines were recorded at several locations in Hungary in the late 1980s. This the FRI (Forest Research Institute) to launch the beech health monitoring plot network in 1989 (Koltay 2004). The initiative was based on the experiences of the ICP-Forests network (Michel – Siedling 2014), and its aim was to closely monitor the health trends of Hungarian beech stands and, subsequently, analyze the collected data. In this paper we processed the dataset on beech monitoring plots, and used statistical methods to identify correlations between meteorological, forest site, forest stand, and leaf-loss parameters.

Our starting hypothesis predicted direct positive correlations between temperature-related parameters and leaf loss, and negative correlations between precipitation and leaf loss. We also expected delayed and/or cumulative effects of weather from previous years.

2 MATERIALS AND METHODS

2.1 Location and main parameters of the sample plots

Altogether, 32 beech monitoring plots have been established in Hungary since 1989. Individual sample trees were marked and numbered on the monitoring plots. The stands in which the plots are located were managed by state forest companies, according to normal management plans. All the plots were established with 100 sample trees; over time, the number of trees gradually decreased due to mortality, intermediate cutting, etc. In our present analysis, we selected 15 plots that fulfilled the criteria listed below:
- The time series was at least 15 years in duration,
- The number of sample trees in 2010 was at least 50,
- The decrease of the number of sample trees during the examined period did not exceed 30%.

2.2 Site and stand parameters

The ages of the monitored stands varies between 64 and 135 years. *Table 1* provides other basic information about the monitored stands. The sample trees were surveyed once a year, in early September. NARIC FRI researchers completed the assessments. The visual survey was executed according to ICP methodology, and the surveyors regularly participated in international calibration workshop events (ICP Forests.net). For this study, we used the assessed leaf-loss values of the sample trees within 5% accuracy, but we scored several other parameters as well. Leaf loss is an important health indicator, and it is also comparable to other results. Only sample trees in Kraft classes 1 (outstanding/dominant) and 2 (codominant) (Kraft 1884) were included in the analysis since the trees in other social classes are too strongly influenced by competition for light.

Forest stand data involving our plots were obtained from the "Hungarian forest inventory", from the National Land Center, Department of Forestry. This database contains detailed information (including site and stand parameters) about the location of the monitoring plots in the forest compartments.

Table 1. Basic data about the 15 selected monitoring plots included in the study

Forest subcompartment	Coordinates	First year	N (pcs) (first year)	N (pcs) (2010)	Age (2010)	Altitude (m)
Bőszénfa 12E	N46 15.727 E17 47.470	1992	100	98	128	300
Felsőtárkány 140D	N48 02.394 E20 28.986	1994	100	98	101	600
Felsőtárkány 55A	N48 01.515 E20 24.938	1994	100	99	95	700
Füzér 86F	N48 34.248 E21 25.785	1992	97	81	86	700
Füzér 86G	N48 34.123 E21 25.707	1992	99	80	81	700
Gyöngyössolymos 41B	N47 52.918 E19 57.480	1992	100	98	108	700
Kislőd 4B	N47 11.512 E17 38.402	1996	90	61	117	500
Kőszeg 43H	N47 22.103 E16 27.902	1992	76	64	133	800
Nagyhuta 10C	N48 28.157 E21 25.580	1995	89	66	89	400
Orfű 21B	N46 07.610 E18 10.292	1992	69	62	62	500
Répáshuta 11C	N48 03.288 E20 32.060	1994	100	100	83	700
Répáshuta 12G	N48 03.135 E20 32.290	1994	99	97	78	800
Szentpéterfölde 20A	N46 36.055 E16 44.973	1989	68	42	119	300
Ugod 31A	N47 17.534 E17 39.765	1992	120	84	101	500
Zselickislak 8E	N46 15.617 E17 48.380	1995	100	99	126	400

2.3 Meteorological parameters

Data was provided by the Hungarian Meteorological Service as a 10 km x 10 km grid interpolated data set from standard weather station measurements by the MISH method (Szentimrey et al. 2005). We used the following monthly weather parameters from the data series: maximum monthly temperature; monthly precipitation sum; monthly number of hot days, monthly number of summer days. We chose monthly maximum temperature instead of average temperature because extreme weather events are generally more damaging to tree health. Defined meteorologically, hot days are those in which the maximum daily temperature reaches/exceeds 30 °C. Summer days are those in which the daily maximum temperature reaches/exceeds 25 °C. The meteorological dataset was available between 1961 and 2010.

2.4 Statistics

Leaf loss data collected in a long-term monitoring network was correlated with different meteorological indices using CReMIT (Cyclic Reverse Moving Intervals Techniques). This is a special moving-window based method implementing moving averages and moving interval techniques (Pödör et al. 2014). The method makes it possible to systematically increase the number of used dependent or independent variables by creating new, derived time series from the basic dataset in a systematic way. Next, linear regression was used to examine the relationships between the derived meteorological parameters as independent variables, and the health status (indicated by leaf loss) as dependent variables. The significance of the results was examined by Student's t-test. To see the effects of the two previous years' weather on forest health, we examined correlations dating back 36 months. In our CReMIT analysis, the time windows did not extend beyond five months. We examined the year of the leaf loss assessment, the previous year's damage, and the leaf loss assessments from two years ago.

With temperature, precipitation, and number of summer days as parameters, we chose May, June, July, August, and September as the time windows for the three examined years. We omitted winter precipitation amounts since we decided to present results that were comparable to all weather indices.

Only the time windows from June to September were feasible for the number of hot days; thus, the length of the input time series was not exactly even. Nevertheless, through our selection of method and sample plots, we endeavored to ensure the differences would not significantly impact the results.

Forest health data was correlated with all of the derived meteorological parameters. This data was available for all the sample trees, so it was possible to stratify the results into Kraft-classes (1 – predominant, 2 – dominant, 3 – codominant and partially dominated, 4 – overtopped) (Kraft 1884, in Assmann 1968).

The CReMIT method created all of the continuous time series from the previous three years with the above-mentioned different window sizes ranging from one to five months.

Once the CReMIT results were achieved, the sample plots were examined according to forest site, meteorological, and stand parameters to determine if these results were similar to the CReMIT results. Principal Component Analysis (PCA) was chosen to perform this examination, mainly because the method can also be used if the parameters are not (or not fully) independent (Pearson 1901). Forest site parameters were included: in the case of forest soil, topsoil layer thickness and slope are crucial as both affect soil water dynamics. Exposure (0 = north slope; 180 = south slope) and altitude define the mesoclimate.

Forest stand parameters were also used in PCA: species mixture, canopy closure, and social position (Kraft classes). Stem diameter and stand height can be complex variables due to site conditions; hence, these variables were excluded from our examinations. *Table 3* contains the 14 examined environmental parameters.

Basic database management was performed with Libreoffice and Microsoft Office software. We also used R software environment and PAST v.2.17c (Hammer et al. 2001) software for statistical analysis.

3   RESULTS

The significant CReMIT results were rather diverse. On some occasions, neighbouring sample plots with extremely similar site conditions (and with the same interpolated meteorological datasets) surprisingly exhibited different responses. Only results with 90, 95, and 99% significance levels of individual time windows were summarized in *Table 2*.

Positive correlations were expected between "maximum monthly temperature" and leaf loss. Four plots gave consistently strong relationships; as a result, the expected correlations appeared. Unexpected negative correlation values emerged for plots located at higher elevations. These results occurred sporadically in six plots, but with one plot (Orfű 21B), the negative correlation was remarkable between the given year's leaf loss and also with the temperature values from two years prior. In Kraft class 2, the results were usually similar, with the exception of the Kislőd plot.

As expected, "summer days" gave results similar to "maximum monthly temperature". Although the number of plots with significant correlations were lower, the significance levels were usually stronger. In five plots, unexpected negative results occurred, which were similar to the maximum temperature results.

The number of "hot days" were obviously fewer than the number of "summer days", but the results were similar. The significant correlations were even stronger, but fewer in number. Negative correlation values occurred only in one plot, in two time windows, in the Kraft class 2.

In the case of "monthly precipitation sum", negative correlation values were presumed. The expected negative correlations occurred in eight plots; five of these had remarkably strong significant correlations. Unexpectedly, positive correlations occurred in five plots. Orfű 21B had a remarkable and unexpected correlation with the values from two years before the actual leaf loss values. The Kraft 2 class also shows similar but weaker correlations. The main results of the CReMIT analysis are summarized in *Table 2*.

Table 2. *Evaluation of the CReMIT results by scoring the strength according to the frequency of significant (above 90%) time windows (1, 2, 3) and direction ("−" = negative correlation; "+" = positive correlation) of correlations between leaf loss and weather parameters in a given year (0) and the previous two years (−1; −2)*

Parameter	Maximum monthly temperature			Monthly precipitation sum			Summer days			Hot days		
Location/Year	**0**	**−1**	**−2**	**0**	**−1**	**−2**	**0**	**−1**	**−2**	**0**	**−1**	**−2**
Bőszénfa 12E	3	0	0	−2	0	0	3	0	0	3	0	0
Felsőtárkány 140D	0	0	2	0	0	0	−1	0	1	0	0	0
Felsőtárkány 55A	0	0	0	0	0	0	0	0	1	0	0	0
Füzér 86F	2	0	0	−3	0	−1	3	0	0	0	0	0
Füzér 86G	2	0	0	−2	0	−2	3	0	0	0	0	0
Gyöngyössolymos 41B	0	0	0	0	−1	0	0	0	0	0	2	0
Kislőd 4B	2	1	0	−2	0	0	2	1	0	3	1	0
Kőszeg 43H	1	0	−1	0	0	0	2	0	0	3	0	0
Nagyhuta 10C	−1	−2	−1	−2	−2	0	−2	−2	0	0	0	−1
Orfű 21B	3	0	−2	0	0	2	3	0	−1	3	0	0
Répáshuta 11C	0	−1	0	0	2	0	0	0	0	1	0	0
Répáshuta 12G	0	−1	0	0	1	0	0	0	0	3	0	0
Szentpéterfölde 20A	1	1	−1	0	1	1	0	0	−1	1	1	0
Ugod 31A	0	0	3	2	1	0	0	−1	3	0	0	1
Zselickislak 8E	3	0	0	−2	0	0	3	1	0	3	0	0

Furthermore, CReMIT results (based on leaf-loss data series) were compared with forest site data collected via PCA analysis, which was performed in 15 (meteorological, site-dependent, and stand-dependent parameters all together) variables. This resulted in four new variables (4 Axes) that together account for 85% of the variation in forest site variables of the

sample plots (*Table 3*). Meteorological parameters were represented in the PCA analysis by their averages for all sample plots and for the whole examination period. Axis 1 is strongly positively correlated with the topsoil layer thickness and temperature variables, and negatively correlated with altitude. This relationship is obvious since average temperature normally increases as altitude decreases. Similarly, on lower altitudes, topsoil layers are usually thicker. The second component (Axis 2) is negatively correlated with slope, crown closure, and the proportion of Kraft class 1 and 2; it is also positively correlated with precipitation. As can be observed in the variance values of the components, temperature, and topsoil layer thickness are the main parameters. It is also clear that temperature is more relevant than precipitation sum. These support the results derived from time series analysis (CReMIT). Similar to weather, temperature has the most influence on health status at the long term level.

The third component (Axis 3) is determined by mixing ratio, and the fourth (Axis 4) contains exposure/facing and the age of trees. Only the mixing ratio determines the third component.

Table 3. Eigenvalues, proportion of variance and environmental variable loadings for the first 4 principal components in PCA

Axes	Axis 1	Axis 2	Axis 3	Axis 4
Statistical parameters				
Eigenvalue	6.0	2.6	1.8	1.4
Explained variance	43.0%	18.9%	13.0%	10.2%
Cumulated variance	43.0%	61.9%	74.9%	85.1%
Environmental variables				
Altitude	**–0.809**	–0.070	0.264	0.161
Exposure/Facing	0.324	0.210	–0.510	**–0.516**
Slope	–0.441	**–0.539**	–0.447	0.460
Topsoil layer thickness	**0.904**	0.059	0.250	0.064
Mixture ratio	–0.138	0.357	**0.873**	–0.094
Age	0.425	0.328	–0.081	**0.638**
Crown closure	–0.346	**–0.636**	0.378	–0.483
Average temperature	**0.937**	0.159	0.068	0.166
Maximum temperature	**0.955**	–0.206	–0.013	0.104
Sum of hot-days	**0.924**	–0.068	0.241	–0.151
Sum of summer-days	**0.974**	–0.126	0.047	–0.047
Precipitation sum	–0.122	**0.934**	–0.022	–0.014
Precipitation sum between May-Aug.	–0.559	**0.581**	0.213	0.208
Proportion of Kraft class 1/2	0.088	**–0.601**	0.447	0.412

The PCA detected three groups among the sample plots (*Figure 1*). These groups are colored red, yellow, and green. The red group contains the sample plots that had the strongest correlation between leaf loss and weather parameters according to CReMIT. The other plots in PCA also show an order similar to the results of CReMIT.
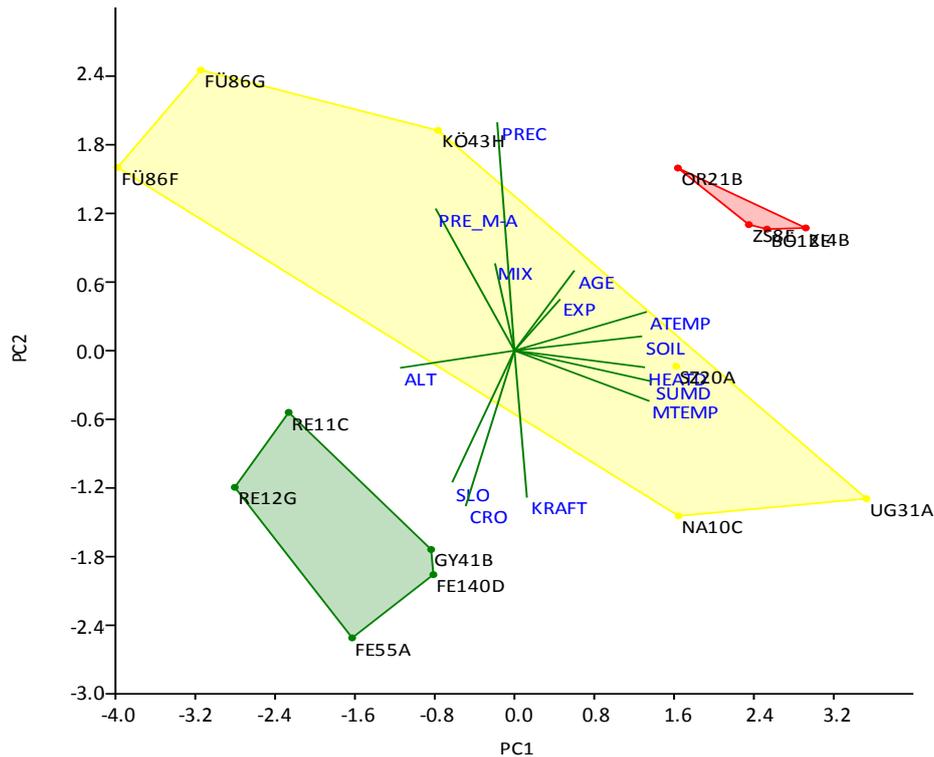
Figure 1. Scatter biplot of PCA. The diagram displays both the loadings (correlations between the original environmental variables and the components) as labelled vectors and the component scores of survey plots as labels and colored points. Survey plots with similar parameters are grouped together and linked with colored convex hulls. Plot names are abbreviated with the first 2 and the last 3 characters.

4. DISCUSSION

In this paper we processed a previously gathered dataset on beech health, and searched for statistically detectable correlations with weather indices (in an available meteorological dataset). Our methods successfully detected known connections and demonstrated that these methods are serviceable even in extremely complex systems. That temperature affects leaf loss much more than precipitation sum is an important result from a forest protection perspective. If higher mean temperatures do occur (as they have in recent years), neither the same amount nor a slightly higher amount of precipitation will prevent beech trees from declining. We also could statistically support that beech forests in less suitable climatic conditions are more susceptible to weather extremities.

More specifically, most of the results supported our preliminary hypotheses: temperature and precipitation-type weather parameters have a consequential effect on beech health. Both of the used statistical methods supported these presumptions.

As we assumed, the CReMIT method resulted in a relatively low number of significant correlations. Since forest ecosystems are extremely complex, we could not expect simple linear correlations, as mentioned by Berki et al. (2014). Detecting statistical patterns in forests is often difficult (Granier et al. 1999). Even so, significant results could be detected with weather parameters two years before the actual leaf loss. Time windows in the damage year gave the strongest significant results. Additionally, as was the case in our work, studies examining the weather dependence of beech growth with different running window statistical methods also

detected correlations with various drought indexes (Manninger et al. 2011, Garamszegi – Kern 2014).

Monthly maximum temperature showed frequent and remarkable positive correlations with leaf loss, which is similar to conclusions many researchers have reached regarding average temperature (Siedling 2007, Zimmermann et al. 2015, Popa et al. 2017). In our analysis, this effect could even be detected with temperature values two years before the actual leaf loss. The number of hot days had a high significance in some cases, but the lower occurrence made patterns undetectable.

In our results, the effect of monthly precipitation sums on beech health was weaker than the effect of monthly maximum temperature. As expected, precipitation sums showed mostly negative correlations with leaf loss in our results. Precipitation sum values from previous years had some significant correlations on some time windows, as expected, but the actual year had the greatest effect (in particular sample plots most time windows had significant correlations) on the health status. These findings coincide with results of previous European studies, namely that higher amounts of precipitation have a positive effect on beech health (Meier – Lauschner 2008a, Seletković et al. 2009, Delaporte et al. 2016).

Although our input datasets were not optional (we had to use the available data from our sample plots), the weaker effects of precipitation compared to temperature and the unexpected correlations may raise a potential methodological issue: Using non-locally measured data (10x10 km grid interpolation in our case) may not be reliable enough to reveal the real correlations because the spatial variation of precipitation is very high (Manninger 2017). This may, at least partly, explain the controversial correlations. For every meteorological index, we detected that nearly the same plots had stronger correlations, while other plots had no responses or weak significant responses. The four plots showing the strongest responses kept this feature in almost every parameter and in both Kraft classes.

Sample plots situated in less favorable sites showed consistently stronger correlations with weather parameters. In fact, the plots are all situated in areas where the climate had become suboptimal for beech stands. According to Gálos and Führer (2018), this even applies to beech stands established from 1971-2010. The weather extremes in suitable sites affect health status less intensively. Although our plots are not situated on an ideal altitude for beech, many sample plots may remain relatively healthy. On the lower edge of the climate belt suitable for beech, the health statuses were generally worse.

It is known that many forest stand and forest site parameters impact beech health; for example: stands with higher canopy closure are less susceptible to health problems than those with low canopy closure (Csóka et al. 2009; Bošeľa et al. 2016). Mixed stands also appear to be more resistant and resilient than artificially grown monoculture beech forests (Mölder – Leuschner 2014, Metz et al. 2016). Nevertheless, seedlings and young trees in mixed forests are still vulnerable to extreme droughts (Lübbe et al. 2015).

PCA detected site and stand parameters, which allowed for the establishment of three identifiable groups among the plots. We could conclude that the differences in the correlations between forest health and weather indices (CReMIT results) in the different sample plots show the same variances, which can be obtained by the PCA examination of climate, forest stand, and site data. This fact implies that differences are caused by these climatic, site, and stand parameters. The importance ranking of these parameters on beech health in our results is monthly maximum temperature, altitude, topsoil layer thickness, monthly precipitation sum, tree social class, canopy closure, slope, species mixture, stand age, and exposure. The patterns of PCA and CReMIT results among the sample plots are almost identical, so the statistical variances caused by leaf loss and site parameters are also almost identical. This implies that the weather effect on beech health is influenced by forest stand and site parameters. Additionally,

it is influenced in the manner PCA calculated (*Table 3*). This also suggests that beech health risks can be projected based on forest site and stand data.

These results support earlier findings (Neirynck – Roskams 1999, Stribley – Ashmore 2002, Siedling 2007, Seletković et al. 2009). According to Potočić et al. (2008), during years without weather extremes, the correlation between weather and leaf loss is not particularly remarkable, but a strong connection can be detected in extremely droughty years when the correlation between leaf loss and temperature appears much stronger. Popa et al. (2017) also found different responses of beech health to the weather parameters. In areas where beech occurs naturally, temperature increase has a positive effect on the health status. Wherever beech grows outside this area, precipitation has a moderately positive effect on health, while temperature increase has a negative effect. On the upper edge of the beech area (in high mountains), temperature had a clearly positive effect. On optimal forest sites for beech, both temperature and precipitation had little effect on tree health (Popa et al. 2017). These findings are the logical results of the process of forest acclimatization to weather: the variability of environmental parameters in the long term established a natural range of a certain species that have low impact influence in the "core area". On the margins, these parameters either open a new frontier for the species, or reduce the area of the species.

Tree-ring analyses provided similar results and correlations between ring width and early summer temperatures than with late summer precipitations in Central Europe. With lower altitudes – which regularly means worsening climate for beech – the effects become stronger (Kolář et al. 2017).

There are many ways to improve the research of weather and forest health relationships. Permanent "on the spot" meteorological parameter measurements would be a major step forward. Applying health indicators other than leaf loss (i.e. measuring photosynthetic activity, sap flow, etc.) could also be a way forward.

Some weather parameters – those not included in our study – could also modify health responses. Cloudy weather (occurring often in mountain valleys) can greatly decrease leaf transpiration (Rozas et al. 2015). Air humidity can also be an important factor. Furthermore, the quantity of soil nitrogen can exacerbate the effects of drought (Dziedek et al. 2016). Measuring these parameters in the future would be extremely useful for understanding beech health responses.

Individual tree level differences in sensitivity and response are also considerable since intraspecific/intrapopulation diversity (i.e. phenological cycle) is typical in all populations and biological processes (Delpierre et al. 2017).

It would be very useful to forecast beech damage – possibly similarly to Italian researchers who found a fungal pathogen's presence or absence (*Biscogniauxia nummularia*) to be a suitable sign for indicating drought damage in Mediterranean areas (Luchi 2015).

Some opinions suggest that the southern provenances should be more adapted and, therefore, more resistant to a warmer and drier climate (Cavin – Jump 2016, Horváth – Mátyás 2016). Others believe this type of adaptation potential is not strong enough in the case of beech (Knutzen et al. 2015), or that genetic diversity affects the shoot and the leaf growth more than the root growth, which is crucial from a drought tolerance perspective (Meier – Leuschner 2008b).

The predictive site choice of a given tree species (or the tree species choice for a given site) is increasingly important. The climate tolerance of different tree species must be carefully considered since this significantly influences the stability of future forests (Hlásny et al. 2017).

Moreover, if climate change proceeds in the manner some projections predict, more frequent and severe damage events will occur. These events will be far more connected to weather conditions than they currently are (Gálos – Führer 2018). Clearly, a proactive sylviculture involving mixed

beech stands, increased structural diversity, and high canopy closure (avoiding large cutting areas) may considerably reduce the risks imposed by the changing climate.

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