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# Climatic threats determining future adaptive forest management – a case study of Zala County

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**Abstract—** Research of future climate tendencies is a precondition for appropriate climate change adaptation strategies in forestry and agriculture. The aim of this paper is to investigate the expected probability and magnitude of threatening climate conditions that are of primary importance in terms of forest management. Until 2100, precipitation and temperature results of an ensemble of 12 regional climate model simulations as well as derived indicators (e.g., Forestry Aridity Index and Ellenberg's climate quotient) have been analyzed for the A1B emission scenario. For the case study area in Southwest Hungary (Zala County), projections indicate an increasing tendency of warming and drying of summers towards the end of the 21st century. In the period 2071–2100, decrease of summer precipitation sum may exceed 25% compared to 1981–2010. Both extreme droughts and heavy precipitation events are expected to be more frequent. Consequently, the already observed climate change impacts and damages in forestry are very likely to occur with higher probability and severity. Including these results, a GIS-based "Agroclimate" decision support system is under development that contains a coherent data chain from climate change simulations, through impact assessments to adaptation support in order to provide quantified information on the possible yield potential and production risk for sustainable forest management.

*Key-words:* regional climate modeling, climate change impact, forest ecosystem, adaptation, decision support

## 1. Introduction

### 1.1. Climatic extremes threatening forests in the Carpathian Basin

The Carpathian Basin is considered to be highly sensitive and vulnerable to climate change and the related increase of the probability and intensity of extreme events. Droughts are recurrent features in the climate of the region, and relatively high amounts of precipitation is required to recover from a severe dry period (*Antofie et al.,* 2015). For the high drought risk, climate change, land cover changes, and intensive land use jointly are responsible (*Spinoni et al.,* 2013).

Precipitation is the determining and limiting factor of the distribution of climate dependent tree species in the forest/grassland transition zone ("xeric limits"; *Mátyás,* 2009) in Eastern-Central Europe and Southeast Europe. Primarily consecutive drought periods threaten the survival and adaptation of forest ecosystems (*Mátyás,* 2009; *Mátyás et al.,* 2010). In the last 50 years, the frequency, severity, and duration of extremely dry and warm weather events have increased (*Szinell et al.,* 1998; *Spinoni et al.,* 2013), their impacts on the most sensitive tree species are already visible.

Summer droughts of the last decades (especially in 1983–1995 and 2000–2003) have led to vitality loss of beech forests and to the drastic reduction of their climatically suitable niche in Hungary (*Berki et al.,* 2009). Health status decline has been observed also in sessile oak stands (*Berki et al.,* 2014). Under drier climate conditions, *Führer et al.,* (2013) found less organic matter production of above-ground dendromass. Climatic extremes are being observed to affect the water uptake of forests from groundwater and the whole water balance of forested catchments (*Gribovszki,* 2014). As result of a drought induced damage chain, increasing number of pests and diseases has been detected in beech and oak forests (*Lakatos* and *Molnár,* 2009; *Csóka* and *Hirka* 2011). Lack of adaptation may lead to increasing forest die-back and mortality (*Mátyás et al.,* 2010; *Czúcz et al.,* 2011; *Rasztovits et al.,* 2014; *Hlásny et al.,* 2014).

### 1.2. Projected climate tendencies

Regional climate change projections largely agree in a statistically significant warming in all seasons over Europe (*Christensen et al.,* 2007; *Jacob et al.,* 2008; *van der Linden* and *Mitchell,* 2009). The annual precipitation sum shows an increase in the northern and a decrease in the southern regions towards the end of the 21st century. In the transition zone, changes are smaller and statistically not significant (*Kjellström et al.,* 2011). This zone is projected to shift northwards in summer resulting in a decrease of the precipitation amount in the Carpathian Basin, whereas the southward shift of the transition zone in winter may lead to precipitation increase (*Bartholy et al.,* 2007, 2008; *Jacob et al.,* 2008). Projected increase of warm extremes as well as of drought frequency, magnitude, and length are statistically the most significant in the Southern European regions, whereas the risk of wet extremes is the most pronounced in the northernmost areas of the continent (*Heinrich* and *Gobiet,* 2011). In the Carpathian Basin, more irregular rainfall can lead both to more frequent heavy precipitation events and severe droughts (*Gálos et al.,* 2007; *Szépszó,* 2008; *Pongrácz et al.,* 2014). Recently, in the frame of the World Climate Research Program Coordinated Regional Downscaling Experiment (EURO-CORDEX) initiative, new regional climate projections have been provided for Europe in higher horizontal resolution (*Jacob et al.,* 2013). The results of the multi-model ensemble confirm the above introduced tendencies, the magnitude and the main spatial patterns of the expected climate change, however, they show more spatial details (*Jacob et al.,* 2013; *Vautard et al.,* 2013, 2014).

### *1.3. Decision support system development*

In Hungary, silvicultural technologies and species preferences are prescribed by binding regulation based on climate conditions that are assumed to be constant over time. Severe droughts of the last decades and observed tree mortality shed light on the need to rethink forest management planning. Reliable projections of health status, production, growth, and yield are essential for the next decades in order to decide about sustainable tree species preference and to assess the economic impacts of possible species changes. The "Agroclimate" decision support system will provide coherent, GIS-supported information about the most important regional and local risks and adaptation options for three climate-dependent sectors (forestry, rainfed agriculture, and animal husbandry on nature-close pastures; *Mátyás et al.,* 2013). In the first step, Zala County in Southwest Hungary was selected as pilot region.

This paper introduces the climate part of the decision support system. The aim is to analyze future climate projections that are providing input for the assessment of forest responses to climate change. Special focus is on the expected probability and magnitude of threatening climate conditions that are of primary importance in terms of forest management (Section 3). Examples are shown for application of regional climate model outputs for impact research in the GIS-supported system (Section 4).

## *2. Sources of climate information and methods for analyzing*

### *2.1. Applied climate data and models*

For the period 1961–2010, daily observation series of temperature and precipitation have been used. The gridded data are available from the CARPATCLIM EU-project (www.carpatclim-eu.org, *Lakatos et al.,* 2013) in

$0.1° \times 0.1°$ horizontal resolution. In the project, the MASH (Multiple Analysis of Series for Homogenization; *Szentimrey,* 2011) procedure has been used for homogenization of long-term observation series. Interpolation of the homogenized time series was carried out by applying the MISH (Meteorological Interpolation based on Surface Homogenized data basis; *Szentimrey* and *Bihari,* 2007) method. Since the target region of the CARPATCLIM project does not cover the whole Zala County, data from further stations of the Hungarian Meteorological Service were also involved in the investigations.

For the 21st century, results of 12 regional climate model simulations have been analyzed that were created in the frame of the ENSEMBLES EU FP6 project (www.ensembles-eu.org). The data are accessible at daily time scale, in $0.22° \times 0.22°$ spatial resolution. The models are already validated (*Jacob et al.,* 2008), their uncertainties (related to the model, scenario, boundaries, and the variability of the climate system; *Prein et al*., 2011) have been investigated and evaluated in many research projects (e.g., *Christensen et al.,* 2007). This ensemble of regional climate change projections for the SRES A1B emission scenario (IPCC, 2007) are considered as state-of-the-art for European climate impact assessments, so far.

### *2.2. Methods of analyzing*

Climate model results have been included in the GIS-based decision support system, transformed into a common grid applying the DigiTerra Map GIS software and its newly developed Climate Database Query Module (*Czimber,* 2014). Inclusion of all available information (e.g., elevation, hydrology, soil and climate conditions, and satellite images of land use, land cover, and forest inventory data) into a geoinformatic system allows the integrated data processing of the different raster and vector layers. It is possible to query data from the database and the map, and to make geostatistical analyses. For finding spatial correlations and developing functions for impact assessments, the latest image processing technologies (fuzzy membership functions based and maximum likelihood classifiers) has been used.

Applying the Climate Database Query Module, monthly, seasonal, and annual temperature means and precipitation sums as well as their means over the vegetation period have been determined using the daily time series of 12 different regional climate models. For calculating general extreme indices (e.g., total number of summer days, hot days, frost days, dry days, heavy precipitation days), minimum and maximum temperatures from 6 models are available. Moderate and severe dry summers have been defined based on *Gálos et al.* (2007). *Table 1* contains the variables and derived indices selected and investigated in this paper.

*Table 1.* Climate variables and indices analyzed in this study

| | |
|---|---|
| Temperature means ($T$) | • annual, seasonal, monthly, vegetation period |
| Derived extreme indices from daily temperature minima ($Tmin$) and temperature maxima ($Tmax$) | • extremely hot days ($Tmax \geq 35$ °C)<br>• hot days ($Tmax \geq 30$ °C)<br>• frost days ($Tmin < 0$ °C)<br>• ice days ($Tmax < 0$ °C) |
| Precipitation sums ($P$) | • annual, seasonal, monthly, vegetation period |
| Derived extreme indices from daily precipitation sums | • wet days ($P \geq 20$ mm day$^{-1}$) |
| Ellenberg's climate quotient (*EQ*; *Ellenberg,* 1988) | $EQ = \frac{T_{July}}{P_{Annual}} * 1000$ |
| Forestry aridity index (*FAI*; *Führer*, 2010) | $FAI = \frac{T_{July-August}}{P_{May-July} + P_{July-August}} * 100$ |

Projected climate conditions have been analyzed for three 30-year time periods in the 21st century: 2011–2040, 2041–2070, and 2071–2100, respectively. Expected changes of temperature and precipitation as well as of the probability and severity of climate extremes have been determined relative to the reference period 1981–2010.

Results of an ensemble of different regional climate model simulations have been considered rather than one single climate projection. In this way, the spread and robustness of the projections as well as the likelihood of the possible changes can be evaluated (it is not possible to state a concrete value for future climate change in a specific region). According to the IPCC, the change has been categorized as "likely" when 66% of all changes projected through the various models lie within this range.

## *3. Climate tendencies in Zala County*

### *3.1. Observed climate*

Based on meteorological observations, Zala County can be characterized by 10.4 °C annual mean temperature and 717 mm annual precipitation sum for the time period 1981–2010 that has been applied as reference of the projected climate change (*Table 2*). Summer is the warmest (19.7 °C) and wettest (241 mm), whereas winter is the coldest (0.5 °C) and driest (121 mm) among the seasons.

*Table 2.* Observed temperature and precipitation in Zala County for the time period 1981–2010

| | Temperature mean [°C] | Precipitation sum [mm] |
|---|---|---|
| Annual | 10.4 | 717 |
| Spring | 10.6 | 162 |
| Summer | 19.6 | 241 |
| Autumn | 10.5 | 193 |
| Winter | 0.5 | 121 |
| Vegetation period | 15.9 | 494 |

Measured data of Zalaegerszeg (in Zala County) indicate that in the last decade, almost all summers were warmer than the average of 1981–2010 (*Fig. 1*). Extremely dry periods (at the beginning of the 1990s, 2000s, and 2010s) can be clearly detected that could induce the reported drought damages in forestry (Section 1.1). Summers with precipitation sum below the 30-year mean often have extreme high temperatures as well (*Fig. 1*). Observed tendencies of general climate indices (*Table 1*) show that frequency of hot days ($Tmax \geq 30$ °C) and extremely hot days ($Tmax \geq 35$ °C) increased during the investigated time period (*Fig. 2*). Whereas there was only 1 year in the last 8 years when the total number of frost days ($Tmin < 0$ °C) exceeded the long term mean (*Fig. 2*), which indicates the recent warming of the region.

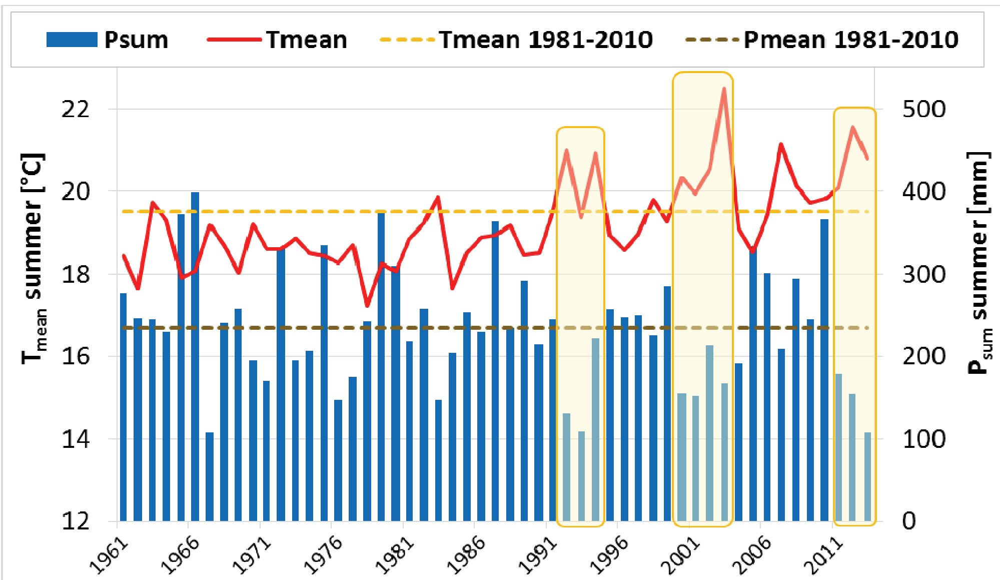


*Fig. 1.* Summer (June-July-August) temperature means and precipitation sums observed in Zalaegerszeg in the time period 1961–2013.

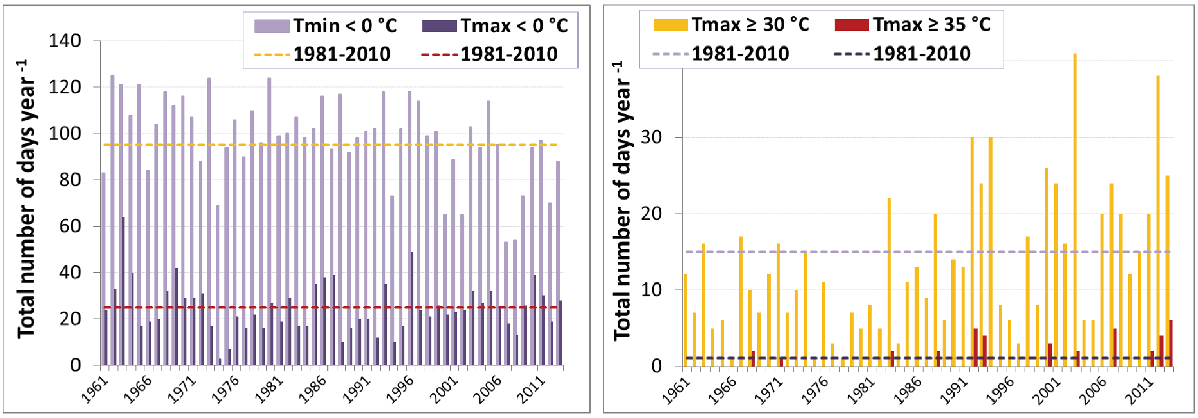


*Fig. 2.* Left part: total number of frost days (*Tmin* < 0 °C) and ice days (*Tmax* < 0 °C), right part: total number of hot days (*Tmax* ≥ 30 °C) and extremely hot days (*Tmax* ≥ 35 °C) observed in Zalaegerszeg.

### *3.2. Projected changes of temperature means and precipitation sums*

Regional climate model simulations agree on a significant increase of temperature for all investigated time periods. Annual temperature means are "likely" to be 0.5–1.5 °C higher in 2011–2040, 1.5–2.8 °C higher in 2041–2070, and 2.4–4.2 °C higher in 2071–2100 relative to the time period 1981–2010 (*Fig. 3, Table 2*). The magnitude of warming is expected to increase in all seasons towards the end of the century. Summer temperature means shows the largest changes (for the mean projection of change by up to +3.9 °C in 2071–2100 compared to the reference period), whereas the smallest warming is projected for spring.

Change of annual precipitation sum is not significant, simulation results show a relatively large spread in magnitude and uncertainty in sign (*Fig. 3*). However, the inter-annual distribution of precipitation may change. The winter precipitation amount can be 12% larger for the period 2071–2100. Together with the higher temperatures, more rain is expected instead of snow.

Summers are projected to be significantly drier towards the end of the century. Considering the mean of the simulated changes, decrease of the precipitation sum can exceed the 7%, 12%, and 25%, respectively, in the analyzed 30-year future time periods compared to 1981–2010 (*Fig. 3*). In this case, Zala County might be characterized by similar summer precipitation conditions for the end of the century, like one of the driest regions in Hungary now. From forestry point of view it is important, that less precipitation is projected for the vegetation period, as well. For spring and autumn, expected changes are smaller and less clear in sign. The bandwidth of climate projections is the largest in summer and in the far future time period for both temperature and precipitation.

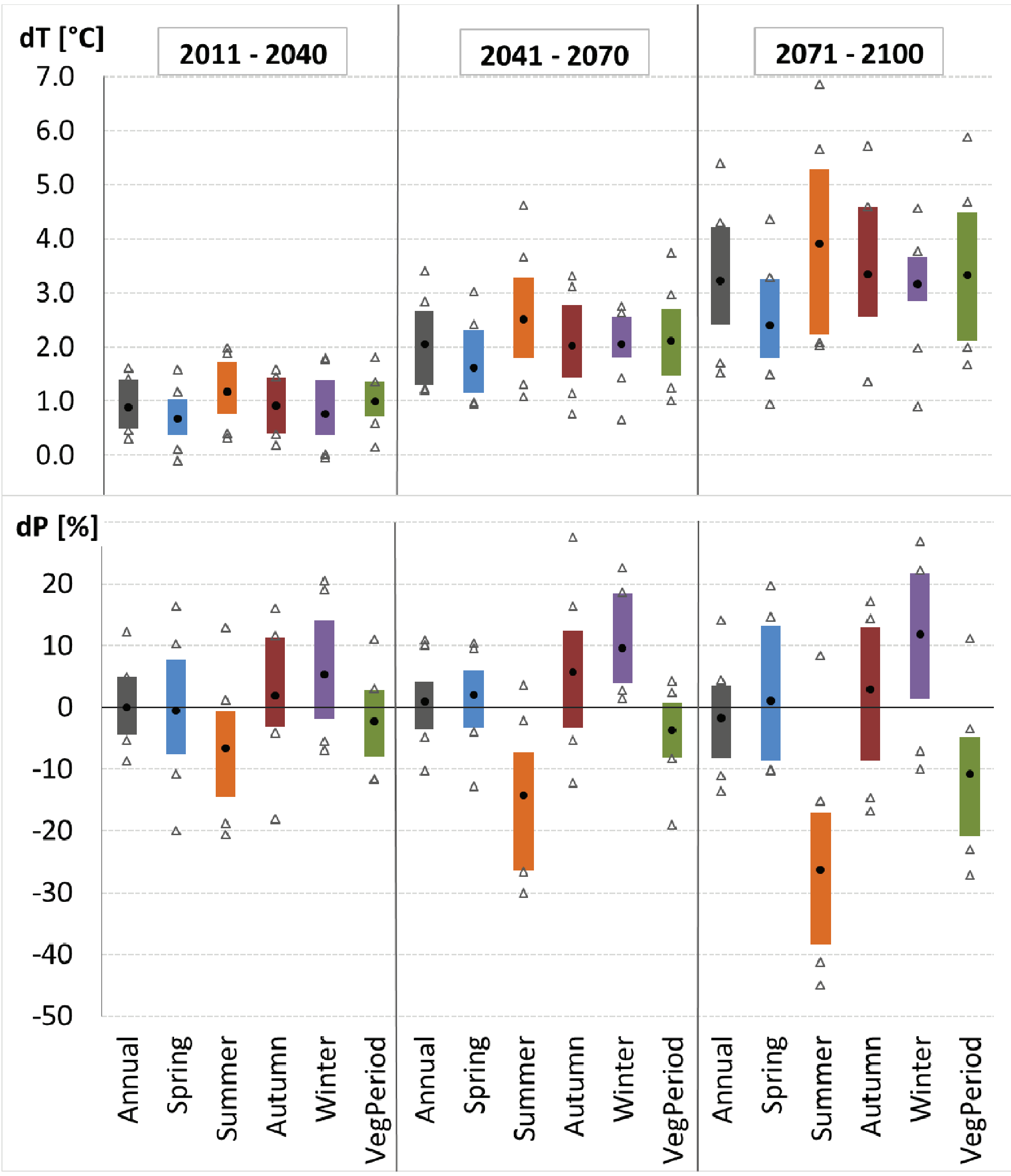


*Fig. 3.* Projected change of the temperature means (*dT*; top) and precipitation sums (*dP*; bottom) for the 30-year periods in Zala County. Columns: 66% of all projected changes fall within this range. Filled dots: mean projection of 12 regional climate models. Empty dots: bandwidth of all projected changes.

## 3.3. *Projected changes of the probability of temperature and precipitation extremes*

Additionally to the increase of the 30-year mean temperature, the distribution of its daily values is projected to shift into the warmer direction. That can lead to higher probability of extremely warm days and to less extremely cold days (*Fig. 4*). The "likely" range of the simulation results shows a clear signal in sign. Considering the mean of the projected changes, the total number of hot days

($Tmax \geq 30$ °C) can increase by 17 days/year for the middle of the 21st century compared to 1981–2010. It would mean that the period when daily temperature maximums are greater than 30 °C may last 1 month/year. In the time period 1981–2010, only 1 extremely hot day/year ($Tmax \geq 35$ °C) in average was observed (*Fig. 2*). This amount might be 20 days/year higher by the end of the century. The total number of frost days may decrease by up to 1 month/year for 2071–2100 relative to the reference time period (*Fig. 4*).

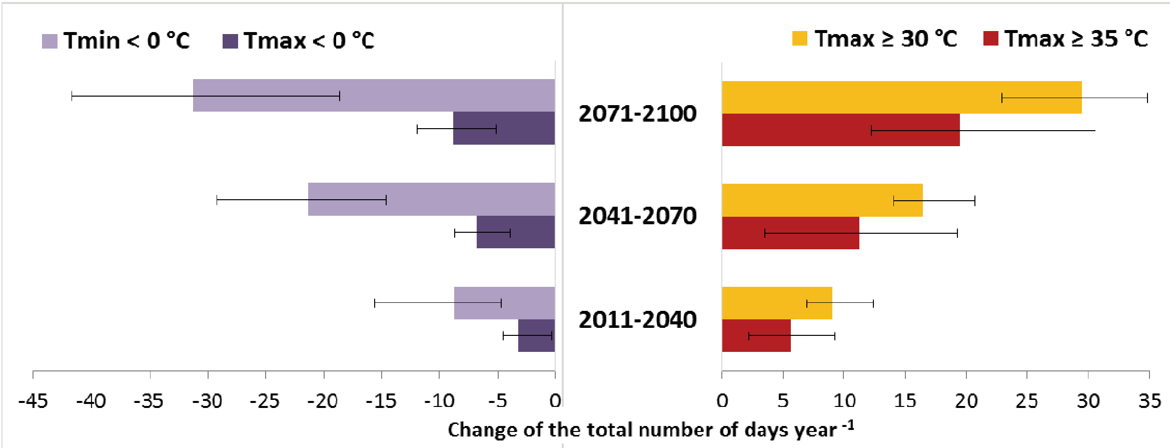


*Fig. 4.* Left part: mean annual change of the total number of frost days ($Tmin < 0$ °C) and ice days ($Tmax < 0$ °C); right part change of the total number of hot days ($Tmax \geq 30$ °C) and extremely hot days ($Tmax \geq 35$ °C) for the 30-year periods in Zala County based on the mean projection of 6 regional climate models. Error bars: 66% of all projected changes fall within this range.

Simulation results show that the change of the temporal distribution of precipitation can result in more intense precipitation events, especially in autumn and winter (*Fig. 5*). The bandwidth of the projections is relatively large on annual timescale, but for 2041–2100, more than 66% of the climate models agree in the direction of the change.

The total number of summer droughts is expected to increase. Not only the probability but also the severity of these events can be higher for the end of the 21st century (*Fig. 6*). For 2071–2100, more than half of the 30-year period can be extremely dry. Consequently, the consecutive dry periods may last longer compared to the end of the 20th century (*Gálos et al.,* 2014). More frequent warm extremes (*Fig. 4*) strengthen the effects of dry conditions due to the higher atmospheric evaporative demand.

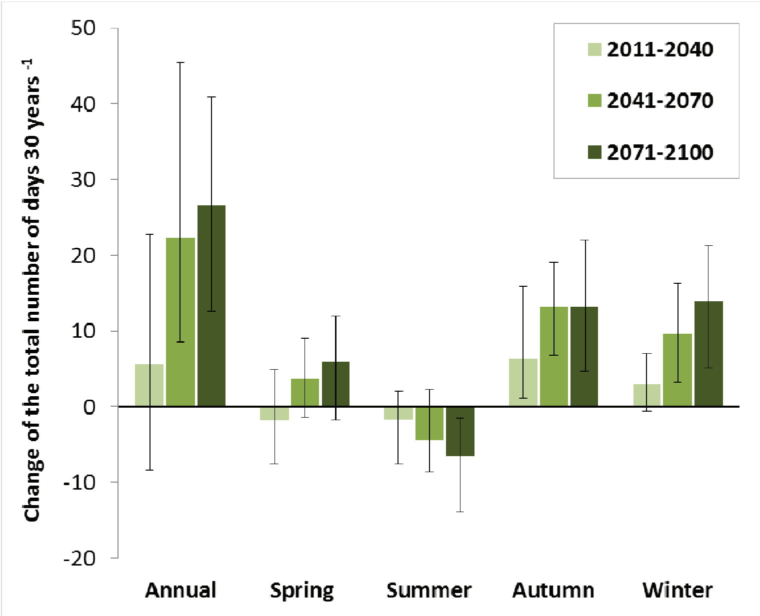


*Fig. 5.* Change of the total number of wet days ($P > 20$ mm day$^{-1}$) for the 30-year periods in Zala County based on the mean projection of 12 regional climate models. Error bars: 66% of all projected changes fall within this range.

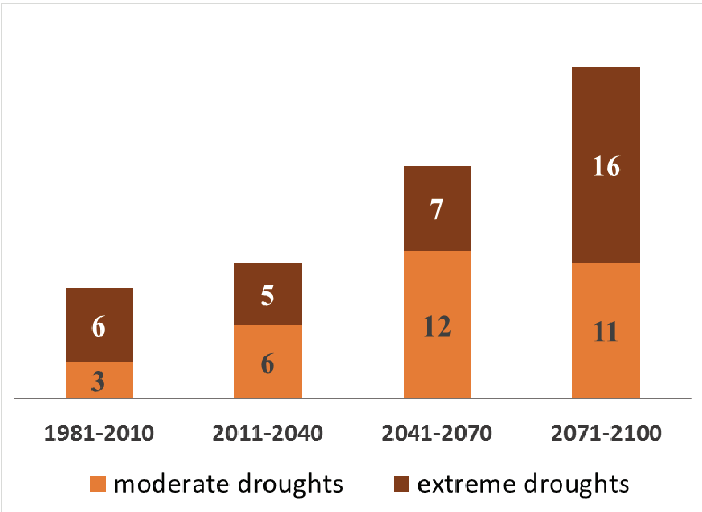


*Fig. 6.* Total number of summer droughts for the investigated time periods in Zala County (for 1981-2010: observed data, for the future time periods: observed data + simulated changes based on the mean projection of 12 regional climate models. Drought definition is based on *Gálos et al.,* 2007).

## *4. Application of the results for decision support in the forestry sector*

Long term climate projections introduced in Section 3 provide information for two main user-groups: for climate impact researchers and for end users in the affected sectors.

*4.1. Climate information for impact research in forestry*

In terms of forest management, projection of forest yield conditions is highly important. Their estimation on a geoinformatic basis requires correlations between growth and vitality of species and the determining climatic factors. Different approaches are simultaneously applied in the *D*ecision *S*upport *S*ystem.

- *Forest yield potential.* The Ellenberg's climate quotient (*EQ*; *Ellenberg,* 1988; *Table 1*) has been used for instance to estimate the yield potential of beech. *Fig. 7* shows that beech sites with warmer and dryer conditions (indicated by higher *EQ* values) can be characterized by lower yield potential. Yield potentials with the same *EQ* values show large standard deviation that can be explained by the effect of other site conditions, in particular by soil texture and topsoil layer thickness (*Bidló,* 2014). Connection of yield potential and locally determined drought index may be interpreted also as a series of data predicting yield change over time. Projected increase of *EQ* values by 7.7 units for the end of the 21st century (*Table 3*) would mean a yield potential loss of beech (*Fig. 7*).

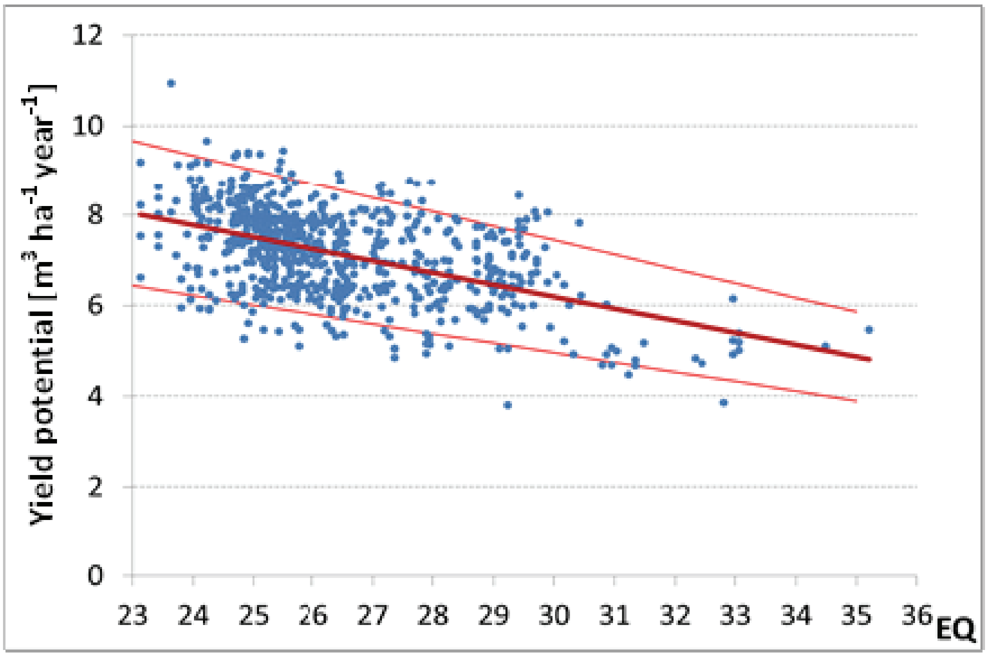


*Fig. 7.* Yield potential of beech forests in Southwest Hungary calculated as mean annual increment at age 80, in function of long-term values of the Ellenberg's climate quotient (*EQ*). Limiting lines stand for ±20% error (*Veperdi*, 2014).

*Table 3.* Ellenberg's climate quotient (*EQ*) and its projected change (*dEQ*) for the 30-year time periods in the entire Zala County based on the results of 12 regional climate models. Likely range: 66% of all projections fall within this range

| | ***EQ*** | ***dEQ*** (reference period: 1981–2010) | | |
|---|---|---|---|---|
| **Time period** | **1981-2010** | **2011–2040** | **2041–2070** | **2071–2100** |
| Mean over the time period | 28.5 | +2.1 | +3.9 | +7.7 |
| Likely range of changes | | –1 – +4.9 | +0.6 – +5.7 | +2.4 – +11.6 |

- *Climate extremes and their effect on mortality.* Effects of extremes are determining the vitality of forest stands rather than average climate conditions. Projected increase of probability and severity of droughts (*Fig. 6*) overwrites the projections of yield potential functions. Consecutive periods characterized by *EQ* values above a threshold are the basis for modeling present and future tree species distribution as well as tree mortality induced by drought stress (*Móricz et al.,* 2013; *Rasztovits et al.,* 2014).
- *Genetically directed adaptation.* Survival of forest populations is also influenced by genetic factors. Increase of *EQ* indicate the increment decline beech due to suboptimal adaptation (*Horváth* and *Mátyás*, 2014). According to the climate tolerance limit, genetic diversity of oak stands may drastically decline (*Borovics* and *Mátyás,* 2013).

In addition to projections of yield, a number of other important aspects of the climate impact research in forestry will be imported into the decision support system such as:

- *Forest climate zones and production capacity*. Among the site conditions, climate is changing the most dynamically. Therefore for decision support, appropriate determination of climate tendencies and forestry climate categories are essential. Contrary to the climate classification derived from the forest inventory database, a meteorology-based forestry aridity index (*FAI*) has been developed (*Führer*, 2010; *Table 1*) and applied to assess the ecological and economic impacts climate change (*Führer et al.,* 2011, 2013). *FAI* considers not only the distribution and vitality of tree species but also their complex relationships with growth and production.
- *Changes of the forestry climate classes* in Zala County also refer to the more frequent and severe drought periods in the last 30 years (*Fig. 2*). For 1981–2010, most of the climatically suitable areas of beech changed to hornbeam-oak compared to 1961–1990 (*Fig. 8*). In case of the projected

temperature increase and precipitation decrease for May-August (*Fig. 3*), climate conditions are assumed to be favorable for sessile oak – turkey oak rather than for beech in the case study region (*Fig. 8*).

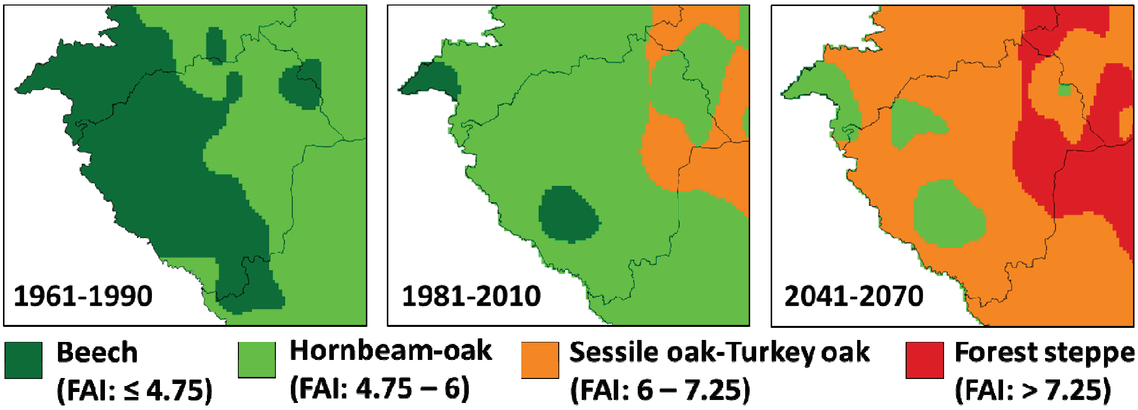


*Fig. 8.* Climatically suitable areas of different forests derived from the *FAI*-based forestry climate classification (*Führer,* 2010). For 1961–1990 and 1981–2010: observed data, for 2041–2070: observed data + simulated changes based on the mean projection of 12 regional climate models.

- *Water cycle of forested catchments*. Monthly temperature means and precipitation sums are the input of water balance models. The tendency towards a warmer and drier climate (*Fig. 3*) may result in a larger amount of annual evapotranspiration in Zala County, whereas the runoff may decrease to the one third by end of the century (*Csáki et al.,* 2014). Distribution of daily precipitation and its projected changes are used for deriving rainfall interception functions (*Zagyvainé Kiss et al.,* 2014).
- *Soil conditions*. More frequent heavy precipitation days or extreme winds may lead to the decrease of the topsoil layer thickness through higher erosion and deflation risks (*Bidló et al*., 2014).
- *Potential biotic damages, pests and diseases*. For projecting the frequency of biotic damages as well as the appearance of new insects and diseases, more complex analyses are essential (*Csóka* and *Hirka,* 2011), these cannot be directly derived from the climate input.
- *Wildlife management in forests*. From the projected change of the probability distribution of temperature and from the related reduction of snowfall and snow cover, consequences are drawn for the game damage risks.

### 4.2. *Decision support for end users*

Forest management planning needs concrete and quantified information about the possible change of the yield potential, including the economic consequences of premature harvesting due to stability loss on the level of forest sub-compartments, in order to make decisions on species preference. It is a challenge for the decision support system to translate and interpret projected climate change (including the range and likelihood of the simulation results) as well as the standard deviation of the possible impacts as a quantified risk factor, so far.

## 5. *Summary*

Long term climate projections have been analyzed that serves as basis of climate impact research and adaptation support in forestry, focusing on the expected probability and magnitude of threatening climate conditions. In the case study region (Zala County in Southwest Hungary), simulation results of an ensemble of regional climate models indicate a significant warming in all seasons towards the end of the 21st century (by up to 3.9 °C for summer in 2071–2100). Both increasing frequency of warm temperature extremes and less cold extremes confirm the warming tendency. Although the mean annual values of precipitation remain almost constant, in winter an increase, whereas in summer a decrease of precipitation can be expected. The latter can exceed 25% until the end of the century in Zala County compared to the climate baseline period 1981–2010. Warmer and drier conditions in summer can result in an increase of the probability and severity of droughts. Heavy precipitation days can be more frequent, especially in autumn and winter. Magnitude of all simulated changes is expected to increase towards the end of the century.

These climate projections have been included as one of the basic datasets in the GIS-based "Agroclimate" decision support system. From the climate input, general climate indices (e.g., hot days, extremely hot days, wet days) and forestry climate indicators (e.g., Ellenberg's climate quotinent; *Ellenberg,* 1988 and forestry aridity index; *Führer,* 2010) are derived. They are used to develop correlation functions for forest growth, yield potential, and production as well as to model many other variables such as species distribution, water and carbon cycle of forests, etc. (see Section 4). Results of climate impact assessments indicate that in case of projected warming and drying of summers, the already observed damages in forestry are very likely to occur with higher probability and severity.

The geoinformatic system allows the integrated data processing and the complex investigation of the climate influenced processes in forest ecosystems. In this way, the GIS-supported climate services can provide a basis of new scientific results in impact research.

However, there is still a gap between provided climate information and required data for impact assessments regarding to the spatial and temporal resolution and the appropriate bias correction methods. Forest responses are also influenced by other factors (e.g., site conditions beyond climate, biotic damages and adaptive capacity) that have been shown to contribute to the relatively large standard deviation of the estimated impacts. The main challenge is to interpret the different bandwidths and uncertainties and to provide a quantified risk factor regarding to possible climate change impacts for end-users in forest management planning.

Climate impact research is being continued in the frame of the "Agroclimate-2" project, where results are planned to be extended to country scale and to the climate-dependent sectors of agriculture by continuous update with recent data and climate projections.

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