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ESTIMATION OF WATER STRESS BY COMPARING THE THORNTHWAITE WATER BALANCE MODEL WITH A TREE RING WIDTH ANALYSIS

by

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ABSTRACT

The high frequency of extreme climate events and the increasing severity of summer droughts have caused water stress and triggered mass mortality in Hungarian forests. Several examples show the deteriorating health status of sensitive tree species, such as the Scots pine (*Pinus sylvestris*) in a protected research area, i.e., the Fenyőfő site. A complex site survey in the study area has shown that both the unfavourable soil conditions and warming climate trends to have caused the huge amount of mortality. In the last few decades extreme warm periods have occurred that were unprecedented. Therefore, in our investigation we used the Thornthwaite-type monthly water-balance model (THORNTHWAITE & MATHER, 1955), which is based on the monthly temperature and precipitation data, soil texture, rooting depths, and maximum amount of available water in the soil to calculate the relative water capacity in the soil.

Based on the paper of GRANIER et al. (1999) we assumed water stress, when the relative soil water capacity decreased below 40%. These results were compared with tree ring widths (*TRW*) of the Scots pine wooden discs from the area. We collected 23 pieces of wooden discs from 11 cut trees. After the drying of the discs, we created high-resolution pictures and measured the tree ring widths with AutoCad software. Since the 1980s, the *TRW* values show a strong decreasing trend, which seems to correlate with the warming trend.

Keywords: water balance model, mortality, tree ring width, extreme climate events

1 INTRODUCTION

Meteorological measurements and observations prove the increasing average annual temperature and decreasing precipitation sums. Extremely hot summers, droughts, heavy precipitation events and flood incidences are also growing, and these trends will continue into the 21st century (SREX, 2011; EASAC POLICY REPORT, 2013).

The increasing number of climatic extremes rather will test the adaptability of the vegetation, such as slowly changing climatic averages (MÁTYÁS et al., 2010; RASZTOVITS et al., 2013). The reason is that the forests are experiencing these sudden climatic extremes as a stress. The tolerance level of the tree species are significantly decreased (MÁTYÁS & GÁLOS, 2010). In Hungary one of the biggest problem is the abiotic damages caused vitality declension followed by tree mortality (BERKI et al., 2007). Areas, where the water is limiting factor, the water stress, and the effects of water deficit cause large amount of health decline. Hungary has already several places where natural ecosystems are changing, because of these processes. Numerous examples show the deteriorating health status of sensitive tree species, such as the Scots pine (*Pinus sylvestris*) in a protected research area, i.e., the Fenyőfő site, where huge mortality occurred at the last few years. Earlier complex investigations show that the unfavorable soil conditions, the changes of climate parameters, the low ground water level and the biotic factors caused together the mass mortality in the research area (GULYÁS et al., 2014a,b).

In this study, we present the Thornthwaite-type monthly water-balance model and the applications of this method to estimating water stress index (*Is*). The changes of temperature and precipitation thresholds (and as a result the water deficit) may effect critical to forest tree growth (D'APRILLE et al., 2015). Therefore twenty-three pieces of wooden discs from eleven cutted trees were measured for dendrochronological analysis.

2 MATERIALS AND METHODS

2.1 Study area

The research site is a protected old-growth Scots pine forest (~150 years old) in Hungary. Scots pine with diverse health condition was felled and two discs were taken at breast height (1.3 m) and from root welling (0.1 m). Dry samples were sanded with progressively finer sandpaper until a highly polished surface was acquired (STOKES AND SMILEY, 1968). After this preparation of discs, we created high-resolution pictures and measured the tree ring widths (*TRW*) with AutoCAD software. *Figure 1* shows the location of the research site, and the sampling points, where the trees were cutted to *TRW* analysis.

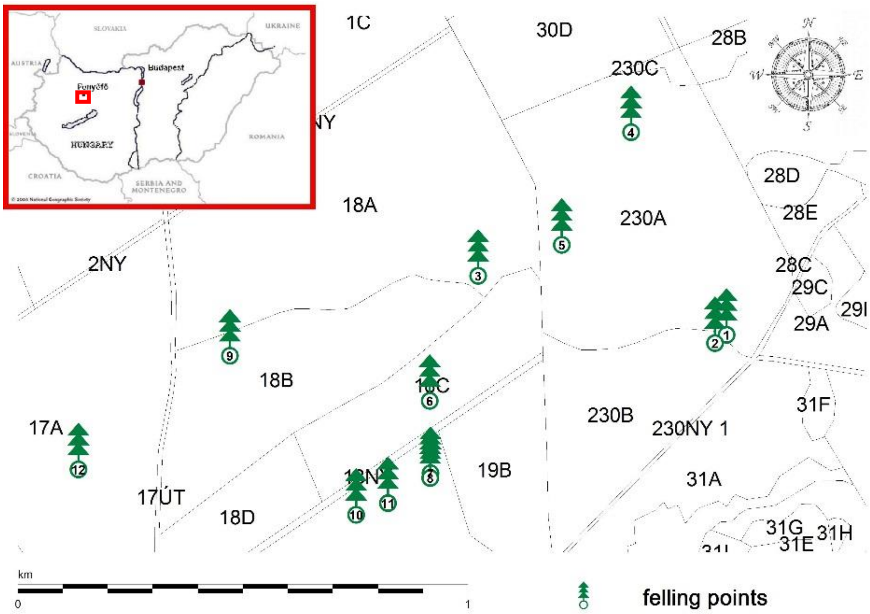


Figure 1 – The location of the research area, and the sampling points

2.2 The Thornthwaite-type monthly water-balance model

In our investigation we used monthly temperature and precipitation values, from the Hungarian Meteorological Service for the Thornthwaite-type monthly water-balance model (THORNTHWAITE & MATHER, 1955) shown in *equlation 1*.

Equlation 1.

$$\Delta W = P - In - T - Eu - D$$

Where, ΔW is the change in soil water content, P is precipitation, In is interception, T is tree transpiration, Eu is evaporation from understorey plus soil and D is drainage at the bottom of soil layer (GRANIER et al., 1999). We used for calculating the interception in Scots pine forest the following equlation (*equlation 2.*):

Equlation 2.

$$In_{Scots\ pine} = 0.15 \cdot LAI \left[1 - e^{\left(\frac{-P}{0.15 \cdot LAI}\right)}\right] + 0.1 \cdot P$$

Where, $In_{Scots\ pine}$ is the interception in the investigated pinus forest, *LAI* is the leaf area index, and P is precipitation (*Brook 90 model*). After that, we can calculate the relative soil water capacity (*REW*), and the annual water stress index (*Is*) using the soil texture and rooting depths (*equlation 3* and *4).*

Equlation 3.

$$REW = \frac{EW}{EW_m}$$

Where, EW is the extractable water, and the EW_m is the maximum extractable water in he soil.
Equlation 4.

$$SWD = EW_m \cdot 0.4 - EW$$

$$I_s = \frac{\sum SWD}{EW_m}$$

Where, SWD is the soil water deficit, and we use the 0.4 constans value, because we assumed water stress, when the relative soil water capacity decreased below 40% (GRANIER et al., 1999).

In our study we used the Simple Pearson's correlation test in R program to find connections between same selected climate parameters and *TRW* thresholds. The selected parameters were the followings:

- Temperature mean (*T*)
- Potential evapotranspiration (*PET*)
- Aridity index (*P/PET*)

3 RESULTS

Based on Thornthwaite-model the monthly relative water capacity the in the soil (*REW*), and the water stress limit shown in *figure 2*.

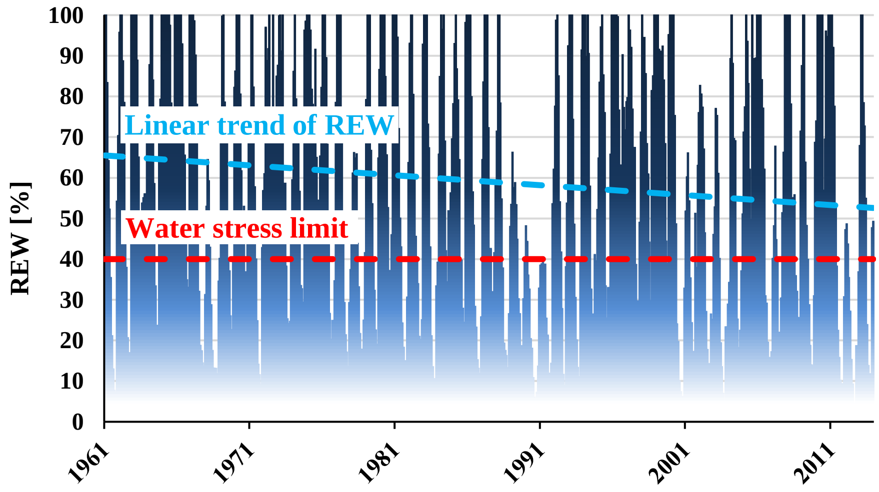
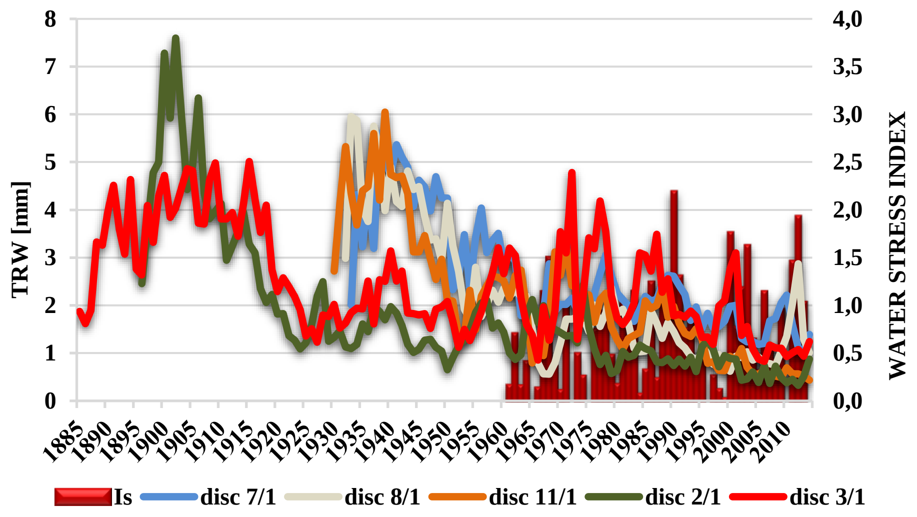


Figure 2 – The relative water capacity based on Thornthwaite water balance modell between 1961-2013. Red dashed line signed the limit of water stress, blue dashed line is the linear trend.

As we see, the amount of available water (*REW*) strongly decreased in 1961-2013 time period. During the years 1990-1991, in 2001-2004 and in 2011-2012 there were a huge water deficit in the soil, which mean high water stress, and dry soil conditions. The most drastically water decreasing was in the beginning of the 90's. The extreme summer drought caused the low water content, and have on negative effect of the investigated forest.

During the analysis of *TRW*, we observed a decreasing tendency from the 1990s, which is conciding the low *REW*, and it was characteristic of the young and old individual trees also. We analyzed two groups of wooden discs, where the first group were taken on the root welling (signed with /1), and the second on the breast high (1.3 m) (signed with /2) (*figure 3*).



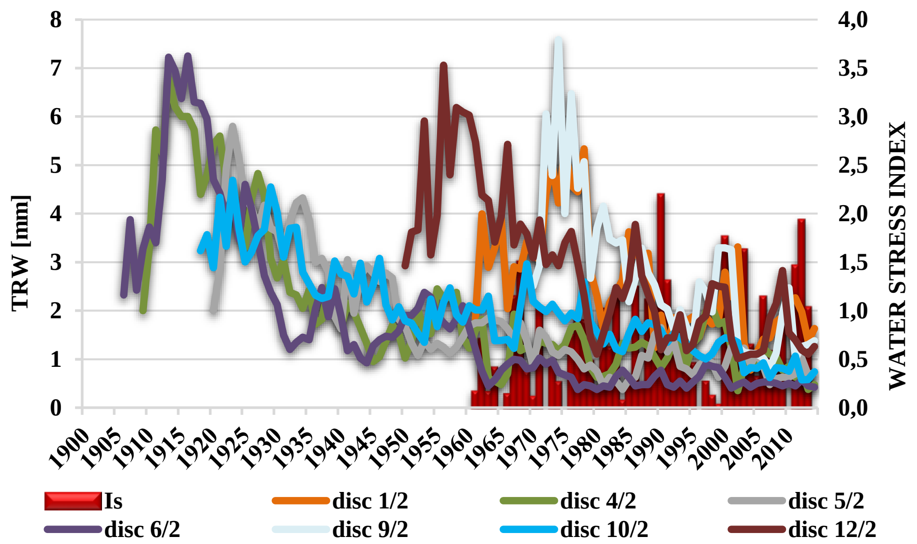


Figure 3 – TRW values of the two groups of wooden discs, upper side represent TRWs from the root welling (/1), at the bottom from the breast high (/2).

When the *Is* index is high, it means drier climate conditions and huge water deficit in the soil. As a result of water stress, the widths of the rings became smaller, but after a low value of *Is* the *TRW*s increasing both of the two groups of wooden discs. The water deficit have a negative influence on ring widths, and also the health of the stand. The effect of lower available water in the soil, that the shallow rooted Scots pine forest cannot uptake the water. The trees become sensitive to pest and other diseases, and after the abiotic and biotic damages the stand will decease (which happened in the research area).

We compare the climate datasets and the growth of tree ring widths some selected climate parameters. *Figure 4* shows the Simple Pearson's correlation test for the two groups of ring width and the temperature, the potential evapotranspiration (*PET*), and aridity index (*P/PET*).

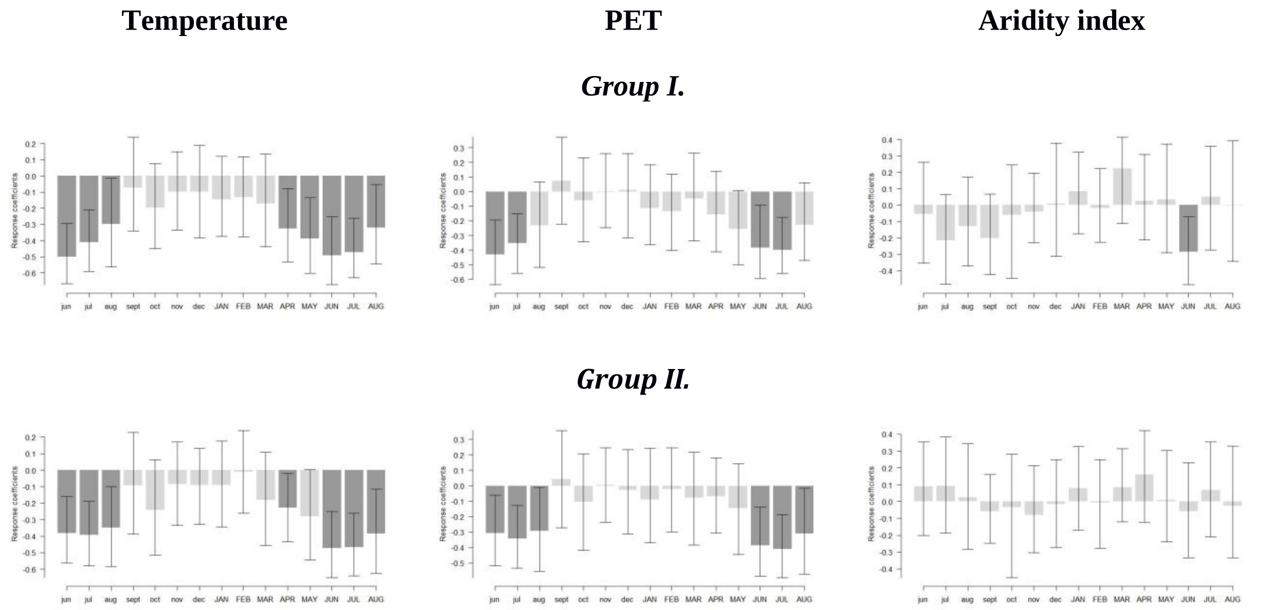


Figure 4 – Simple Pearson's correlation between TRW values and temperature, PET, and aridity index (left to right) for the two groups of tree rings (with small letters representing the previous year and capital letters the year of growth). Light grey is the correlation values, where dark colour represents bootstrapped correlations significant at $p<0.05$, lower and upper lines represent 95 % confidence limit for the calculated parameters.

The temperature of June-August has the most important negative effect on the ring growth. The high temperature in summer and the intensive potential evapotranspiration shows significant negative correlation with *TRW*. The connections between the aridity index and *TRW* are not significant, which we can explain that we could not find high correlation with precipitation and *TRW*. In Group I. the influences of the three selected parameter are stronger than in Group II.

4 CONCLUSIONS

In our research we used the Thornthwaite-type monthly water-balance model, to detect the water stress in a protected old *Pinus sylvestris* forest in Hungary. The earlier investigations in the field show that the frequency of drought periods are increased and the severe and longer dry summers have a negative effect on health status of forest, so the Scots pine stand become more sensitive. The unfavourable soil and climatic conditions have led that the relative water capacity in the soil are decreased, which mean that the water stress increased in the last few decades.

Scots pine with diverse health condition was felled and two discs were taken at breast height (1.3 m) and from root welling (0.1 m), to dendrochronological analysis. Based on our results, we found decreasing in the rate of radial growth in every case. It mines, that we found decrease in the growth of *TRW* of young trees also. This decrease caused by the extremes, the growth of temperature, the decreasing precipitation and the unfavourable sand soils together. We found significant negative correlation between *TRWs* and temperature of June-August but the precipitation sums showed no significant results. The connections between the aridity index and *TRW* are not significant also, because of the low correlation between the precipitation and *TRW*.

Summarized, the unfavourable conditions of soil (low water capacity, sandy soils with calcium carbonate content in the topsoil) occurred together with high temperature values in the last years caused continuously decreasing relative water capacity, and increasing water stress index, and after all mortality in the research area.

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