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Response of the leaf phenology and tree-ring width of European beech to climate variability

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Supplementary file 1 – AWR calculation procedure:

The principal method used to determine the relative soil water content (i.e., percentage to which water fills the soil pores between the so called wilting point and field capacity). The procedure is explained by Hlavinka et al., 2011 in detail and further tested by Trnka et al. (2015a, b). It relies on the SoilClim model based on the Allen et al. (1998) model which was programmed using Borland Delphi^{TM} 7 (Borland Software Corporation) as a modular system. The model works with a daily time step and requires six meteorological parameters: global solar radiation ($MJ \cdot m^{-2} \cdot day^{-1}$), maximum and minimum air temperature (°C), precipitation (mm), vapor pressure (kPa) and average wind speed ($m \cdot s^{-1}$). The outputs from the basic modules (e.g., reference evapotranspiration calculation, snow presence and melting estimates) are then used as inputs for the soil water balance model. The defined wilting point and field capacity within the profile, described by an arbitrary number of layers, are necessary for the soil moisture and *ETa* estimates. In our study we simulated soil moisture content at two layers: AWR1 for a depth of 0–0.4 m and AWR2 for layer 0.4–1.3 m. For the daily *ETo*, the Penman-Monteith method was adopted as published in the Food and Agricultural Organization of the United Nations (FAO) paper No. 56 by Allen et al. (1998). Actively growing and adequately watered grass of 0.12 m height with a surface resistance of 70 $s \cdot m^{-1}$ and albedo of 0.23 was used as the reference cover. Because information about net radiation as a crucial variable is often unavailable at meteorological or agrometeorological stations, SoilClim calculated it as the difference between the estimated incoming net shortwave (Rns) and the outgoing net long-wave (Rnl) radiation. The daily soil heat flux beneath the reference grass surface was relatively small and was ignored (Allen et al. 1998). The Rns was derived from global solar radiation, measured by pyranometer, and albedo, and the Rnl was estimated using the Stefan-Boltzmann constant, daily minimum and maximum temperature, vapor pressure, global and clear sky solar radiation as a function of elevation and extraterrestrial radiation, as described by Allen et al. (1998). This approach was successfully tested for various vegetation covers and climatic conditions within central Europe by Hlavinka et al. (2010).

SoilClim accounts for the snow cover accumulation and melting, allowing more precise water balance estimates in the areas where snow cover represents a significant portion of the annual precipitation total. The presence of snow cover, its accumulation (in mm of equivalent water) and melting were estimated based on the SnowMAUS model (Trnka et al. 2010), which operates with a daily time step with maximum (T_{max}) and minimum (T_{min}) temperatures at a height of 2 m, and daily sums of precipitation (*Precip*) as inputs.

The module for *ETa* and soil water content, which are used to determine AWR1 and AWR2 estimates in the two defined soil layers in the crop-soil-atmosphere system (hereafter, the soil water balance model), relied on the concept and model formulation within the FAO Irrigation and Drainage paper No. 56 (Allen et al. 1998; Allen et al. 2005). The module for the dynamically simulated vegetation cover, based on the sum of effective air temperature, was newly developed in this study and modified compared to the original formulation in Allen et al. (1998). The soil layers named as moisture control Sections I and II (abbreviated as MCS I and MCS II) are specified by the field capacity, wilting point and depth. The calculation of the daily *ETa* is described by the set of Equations (1) and (2):

$$ETa = ETa_{\mathrm{MCSI}} + ETa_{\mathrm{MCSII}} \qquad (1),$$

$$ETa_{MCS\,i} = ETo\ .\ Kc\ .\ Ks_i\ .\ (Ratio_{MCS\,i} / 100) \qquad (2),$$

where ETa is the total daily actual evapotranspiration (mm·day^{-1}), $ETa_{MCS\ I}$ and $ETa_{MCS\ II}$ are ETa values from MCS I and MCS II (mm·day^{-1}), respectively, $ETa_{MCS\ i}$ is the ETa from the moisture control section i (mm·day^{-1}), Kc is the coefficient of crop (dimensionless), Ks_i is the water stress coefficient within MCS i (dimensionless), $Ratio_{MCS\ i}$ is the possible participation of MCS i within evapotranspiration (%). The sum of $Ratio_{MCS\ I}$ and $Ratio_{MCS\ II}$ is always 100%.

The Kc parameter varies through the year using parameters approximating a mature deciduous forest stand. It defines the present crop evapotranspiration properties against the reference grass cover. Unlike the approach put forward in Allen et al. (2005), SoilClim relies on daily estimates of Kc through dynamically simulated vegetation cover driven by the sum of growing degree days. The approach described in McMaster and Wilhelm (1997) was adopted, and if the daily mean temperature was less than base temperature (TBase), it was set equal to the TBase. The Kc is derived from Kc_{tab} (defined in Allen et al., 1998), which evolves within specific parts of the growing season. The start and duration of relevant phases were directed on a degree-day basis and defined by the user interface. Used breakpoints were described as: sowing (A), beginning of emergence (B), beginning of the middle phase with maximum leaf area index (C), start of senescence (D), and leaf fall (E).

The deduction of the water consumption rate from MCS I and II (defined as $Ratio_{MCSI}$ and $Ratio_{MCSII}$) was crucial within evapotranspiration estimates. For instance, when MCS I participation as a water source within evapotranspiration is 85%, then 15% of the water is taken from MCS II. These values depend on the maximum soil water holding capacity and the depth of each MCS, and they evolve during the year due to root growth. $Ratio_{MCSI}$ and $_{MCSII}$ are simulated by the SoilClim vegetation cover module that accounts for the type of the crop (perennial or annual) and is driven by the degree days. The values of $Ratio_{MCSI}$ and $_{MCSII}$ were user-defined for the Ini, Mid, End and Interim phases, acting as a constant, and during B-C and D-E, they developed as a function of degree-days from Ini to Mid and from Mid to End levels, respectively.

The effect of soil water stress on crop *ETa* reduced the value of the crop coefficient *Kc*, multiplying it by the water stress coefficient *Ks* as defined in Allen et al. (1998). The user could define the fraction of total available soil water above the wilting point in the appropriate MCS that a crop can extract without suffering water stress according to soil properties.

Consequently, the cumulative water depletion was derived from the appropriate MCS from a selected day (in mm). The precipitation after snow accumulation and melting was taken into account and reduced by interception and runoff. The simple algorithm for runoff was incorporated within SoilClim and followed the scheme used in the WOFOST model (van Diepen et al. 1988). Runoff is the portion of daily precipitation lost from water balance and could be considered only for daily precipitation sums above certain thresholds (defined in mm of the water column). The runoff threshold (in mm) and proportion (%) were considered as constant through the selected period and site and could be defined by the user within program interface. If the threshold is set to 0 mm, then the runoff is considered for all precipitation. The threshold was set to 5 mm, and the reduction was 5–15% based on the local conditions in this study as the precipitation was not corrected for the influence of the wind. The amount of precipitation captured within the aboveground biomass interception was determined through interception capacity (in mm per day) for the Interim, Ini, Mid and End phases as adjusted within the user interface. The intercepted water was directly evaporated during the next day or days based on proper condition and was included in the *ETa*. In such a case, the available energy for the evapotranspiration from MCS I and II was reduced by the energy spent for the evaporation of the intercepted water. The soil water percolation (*Dpi*) from MCSi to the deeper soil layer occurs when the MCSi is saturated to field capacity and additional water from precipitation or percolation from higher layers occurs. In this case, all additional water above the field capacity percolates to lower positions. This original assumption introduced in Allen et al. (2005) was expanded to allow for a partial percolation that could take place when the available soil water content during the previous day (abbreviated as AV_{i-1}; $AV = 0$ % is wilting point, $AV = 100$ % is field capacity) was from 50% to 100% in a given MCSi. For these cases, the partial percolated water ($Dpart_i$; in mm) could be determined for both MCS as a function of volumetric soil moisture within the previous day (abbreviated as vol$\%_{i-1}$; in %), volumetric soil moisture within wilting point (*WP*; in %), the depth of soil layer (abbreviated as *Z*; in mm) and the infiltration coefficient (*Ic*, in %). The *Ic* is assumed as a constant for the selected soil layer and could be adjusted within the user interface.

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