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Modeling the water balance of sloped vineyards under various climate change scenarios

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Abstract. Grapes for wine production are a highly climate sensitive crop and vineyard water budget is a decisive factor in quality formation. In order to conduct risk assessments for climate change effects in viticulture, models are needed which can be applied to complete growing regions. We first modified an existing simplified geometric vineyard model of radiation interception and resulting water use to incorporate numerical Monte Carlo simulations and the physical aspects of radiation interactions between canopy and vineyard slope and azimuth. We then used four regional climate models to assess for possible effects on the water budget of selected vineyard sites up to 2100. The model was developed to describe the partitioning of short-wave radiation between grapevine canopy and soil surface, respectively green cover, necessary to calculate vineyard evapotranspiration. Soil water storage was allocated to two sub reservoirs. The model was adopted for steep slope vineyards based on coordinate transformation and validated against measurements of grapevine sap flow and soil water content determined down to 1.6 m depth at three different sites over two years. The results showed good agreement of modelled and observed soil water dynamics of vineyards with large variations in site specific soil water holding capacity and viticultural management. Simulated sap flow was in overall good agreement with measured sap flow but site-specific responses of sap flow to potential evapotranspiration were observed. The analyses of climate change impacts on vineyard water budget demonstrated the importance of site-specific assessment due to natural variations in soil water holding capacity. The model was capable of describing seasonal and site-specific dynamics in soil water content and could be used in an amended version to estimate changes in the water budget of entire grape growing areas due to evolving climatic changes.

1. Introduction

Grapevines are cultivated on 6 out of 7 continents, between latitudes 4° and 51° in the Northern Hemisphere (NH) and between 6° and 45° in the Southern Hemisphere (SH) across a large diversity of climates [1]. Wine grapes are traditionally grown in geographical regions where the growing season (April-October for the Northern Hemisphere) mean temperature is within the range of 12–22 °C [2]. Warming during the growing season has been observed in all studied wine regions over the past 50–60 years [3–7]. Within the existing production areas, water shortage is probably the most dominant environmental constraint [8] and even in moderate temperate climates, grapevines often face some degree of drought stress during the growing season [9–12].

Most European grape growing areas are non-irrigated and there is a rising concern if this is sustainable in the future. Additionally, many of the most valuable areas in terms of quality and reputation are located on steep slopes which may exacerbate the impact of climate change due to a reduced potential for adaptation (high labour costs, technical challenges, access to water a.s.o).

Yet, for the determination of vineyard water balance in research, vineyards are considered to be flat (with very few exceptions). Since evapotranspiration is largely affected by slope because of the received amount of solar radiation [13], it is necessary to incorporate these aspects into available models [14–16] in order to estimate the water balance of sloped vineyards.

Such a model needs to account for the feedback of drought stress on transpiration [16–18] and has to establish frameworks to account for common cultivation practices. We therefore amended a simple model approach [15] by the implementation of a grapevine specific transpiration coefficient which allowed a decoupling of plant responses to drought either induced by high evaporative demand or by water deficit and used the model in conjunction with 4 time series of regional climate models to project possible changes of drought stress risk for three vineyards of the Rheingau grape growing region.

2. Material and methods

2.1. Model description

We used the soil water balance model of Hofmann et al. [18]. This model is based on the model of Lebon et al. [16] with some extensions introduced by Celette et al. [19] and uses weather data on daily time steps.

The soil water is represented by a reservoir characterized by its total transpirable soil water (*TTSW*), representing the difference between maximum and minimum (extractable) water content, the transpirable soil water (*TSW*) and the fraction of transpirable soil water ($FTSW = TSW/TTSW$) remaining at any time during the season. The reservoir incorporates two sub reservoirs, one for cover crops and one for bare soil. The sub reservoirs are used to calculate individual water balance routines for cover crops and bare soil in order to separate the actual evapotranspiration fluxes between cover crops, bare soil, and grapevines [19]. The sub model to calculate the evaporation of the bare soil based on the approach of Allen et al. [20] and Allen [21]. The evapotranspiration of cover crops based on the assessment of the soil volume from which the cover crops can extract water and by calculating a water stress coefficient accounting for the feedback of water stress on evapotranspiration, which itself relied on a daily water balance routine, taking into account the precipitation, the actual evaporation of cover crops and the amount of water extracted by the grapevines from the cover crop reservoir. Growth stages of the cover crops throughout the annual cycle were modelled following the system of Allen et al. [20]. The transpiration of grapevines was calculated according to the formulation of an expression for the potential grapevine transpiration [15,16,22], based on the approach that the ratio of potential grapevine transpiration, $T_{0,v}$, to potential evapotranspiration, ET_0, equals the ratio of solar radiation absorbed by the vines, R_v, to solar radiation absorbed by the vineyard, R_{vy}:

$$T_{\alpha,v} = \frac{R_v}{R_{vy}} ET_0. \quad (1)$$

Actual grapevine transpiration was computed by:

$$T_{\alpha,v} = k_{c,v} k_s T_{D,v}, \quad (2)$$

where $k_{c,v}$ is a grapevine transpiration coefficient and k_s is a water stress coefficient [0-1]. Both coefficients allow a decoupling of soil induced (drought stress, k_s) or atmosphere induced (evaporative demand, $k_{c,v}$) responses of relative transpiration rates to changing environmental conditions. The grapevine transpiration coefficient $k_{c,v}$ was set to a fixed value of 0.56 and the water stress coefficient k_s was computed as a function of *FTSW* and was equal to 1 for FTSW $>= 0.4$ and equal to $0.4/FTSW$ for $FTSW < 0.4$ [18].

2.2. Radiation partitioning

R_v and R_{vy} were calculated with radiation interception fractions for direct and diffuse solar radiation (R_{dir}, R_{dif}). The interception fractions were calculated with a numerical simulation based on the Monte Carlo method. The model and the transformation of radiation components to slopes is described in [18].

2.3. Evapotranspiration

Evapotranspiration was calculated according to Allen et al. [23] taking into account that received net radiation at the slope surface is altered. The technique to adapt and calculate potential evapotranspiration to sloped surfaces is described in [18]. In case of slopes it is necessary to distinguish between the evapotranspiration fluxes with respect to the normal of the slope surface (ET_{0s}) and its horizontal equivalent (ET_0). This can be calculated by:

$$ET_0 = ET_{0s}/cos\beta \quad (3)$$

where β is the slope angle [24].

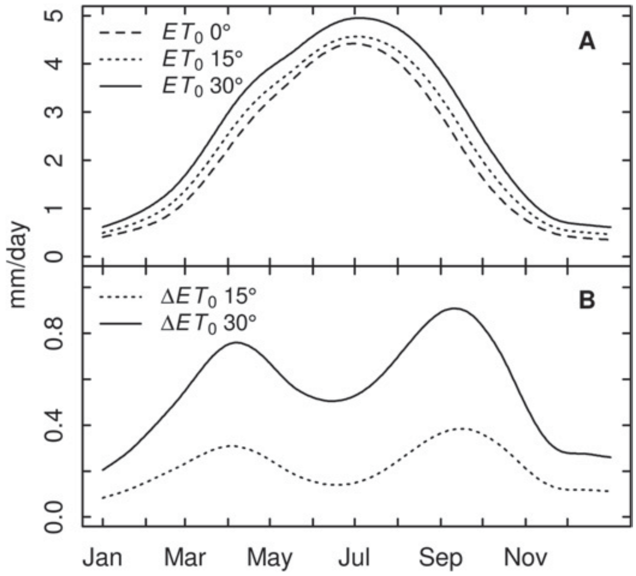

Figure 1. (A) Mean daily potential evapotranspiration (horizontal equivalent, based on data from Geisenheim from 2000–2013) for a horizontal surface and two slopes facing south (15° and 30° slope angle, resp.). (B) Difference between the potential evapotranspiration of two sloped surfaces and a horizontal surface (shown in A).

2.4. Climate models, weather data and risk analyses

We used observation data of the weather station of Geisenheim (from 1955–2013) and four time series of regional climate models, two of the statistical model Wettreg-UBA [25,26] and two of the statistical model StarII [27,28]. The Wettreg-UBA model provides data from 1961–2100 and StarII from 1981–2060. Each time series represented a dry or a wet realisation of future climate projections of both models for the weather station of Geisenheim. The water balance was calculated for three vineyards of the Rheingau growing region, different in water holding capacity, slope, aspect and the type of soil management. The sites were named Ehrenfels (EF, 35° slope angle, 85 mm *TTSW*), Burgweg (BU, 27° slope angle, 115 mm *TTSW*) and Wilgert (WI, 15° slope angle, 160 mm *TTSW*, see [18] for more details). Because of the well-known relationship between the soil water status parameter *FTSW* and the plant water status parameter predawn leaf water potential, ψ_{pd}, [12,29,30], we used a threshold value of $FTSW < 0.15$ (corresponding to the common threshold value for severe water stress of $\psi_{pd} = -0.6$ MPa) and classified each day during the

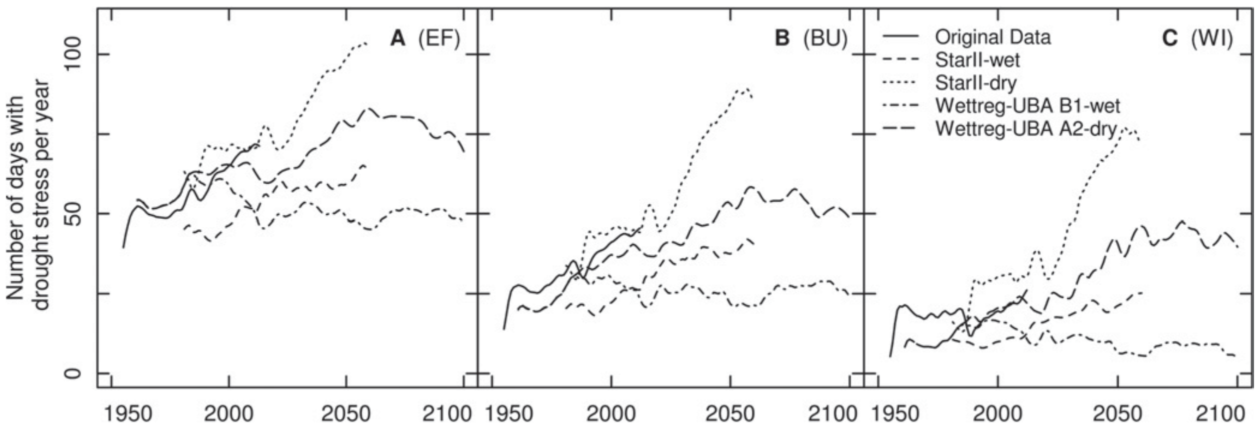

Figure 2. Smoothed 30-year running means of the yearly sum of days with drought stress for three different vineyards (EF, BU, WI; A C), calculated using a soil water balance model, original weather data (from Geisenheim) and projections of regional climate.

vegetation period (May-September, 152 days) as a drought stress day when *FTSW* dropped below this threshold value.

3. Results and discussion

Sloped vineyards are commonly south oriented, which increases the received solar radiation and the evaporating surface per horizontal equivalent, with both leading to higher potential evapotranspiration rates. The annual ET_0 of Geisenheim (50° north latitude, based on data from 2000–2013) for a horizontal surface is 791 mm, for a slope inclined by 15° 872 mm (+10%) and for a slope of 30° 998 mm (+26%). Sloped vineyards face therefore a higher risk for developing water deficit independent of soil type and depth. The highest daily mean values of ET_0 occur at the beginning of July (around 4-5 mm/day, Fig. 1A). The daily difference of inclined surfaces compared to the horizontal has two maxima during the course of the year, one around the beginning of April and one in mid-September (Fig. 1B), exceeding the daily ET_0 rates by approx. 0.3 mm/day (15° slope) and by 0.8 mm/day (30° slope), respectively.

Model runs with original (1955–2013) and climate projection data incorporating specific site characteristics were performed for EF, BU, and WI (Fig. 2A-C). The analyses revealed that the number of days with drought stress has already increased in the past for the sites EF and BU but not for WI, the site with high water holding capacity. Beside the wet realisation of the Wettreg-UBA model all other models projected an increase in the occurrence of drought stress days in the future. The Wettreg-UBA wet time series is driven by a global climate model based on the assumptions of the moderate B1 greenhouse gas emission scenario [31]. Because of different biases of the model projections for the past compared to the original data, change signals of the individual models are more reliable than the projected absolute values of drought stress days. Comparing the periods from 1981–2000 and 2011–2030 for each model reveals that the StarII model projects an increase of drought stress risk for the near future (for StarII-wet respectively StarII-dry realisations in days, EF: +11/+13, BU: +11/+19, WI: +10/+20), whereas the Wettreg-dry model projects a distinct increase for the period from about 2030–2060 and less changes for the second half of the century. For the well watered site WI this might lead to an increase of drought stress up to a level comparable to the situation of the dry site EF during the last century (Fig. 2C).

4. Conclusion

The results suggest that climate change might have a huge impact on the water budget of vineyards of the Rheingau grape growing region. Therefore a more in depth analyses on a regional scale is needed to assess for future changes of the drought stress risk and to develop adaptation strategies.

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