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Calculating field adapted irrigation requirements of Highbush Blueberry (*Vaccinium corymbosum* L.) considering fruit developmental stage

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The site- and cultivar adapted analyses of the daily water demand are crucial for resource efficient irrigation management of blueberries, even in semi-humid regions such as Brandenburg. Especially in the drought stress-sensitive developmental stage of the crop, water deficit increases the risk of diminished, non-marketable fruit size. In the present study, the crop evapotranspiration was calculated by means of adjusted FAO approach that considers the soil and plant characteristics in the field. Furthermore, the timing of crop coefficients (K_C) was adapted to specific requirements of blueberry. The adaptation of the model was carried out by considering the entry of fruit in the stage of cell expansion and by taking into account the end of harvest window with regard to selective harvest. The fruit size analysis was suitable for characterising the beginning of enhanced cell expansion and the adjusted timing of K_C. The timing of K_C adjusted to the requirements of blueberry crop supports the water use efficiency.

Keywords
Precision horticulture, field management, water supply, drought stress, fruit quality

Highbush blueberry (*Vaccinium corymbosum* L.) is the most important bush fruit in Germany (Statistisches Bundesamt 2018). The yield increased from 2008 to 2017 by 70 % and cropland expanded to 2,844 ha (Statistisches Bundesamt 2018). The blueberry is a true berry and shows three stages of growth (Coombe 1976). An increase of size can be measured in stage I determined by the cell division, followed by a size-steady period that is majored by the embryonal development. The stage III is characterised by distinct increase of fruit size due to cell expansion (Coombe 1976). The fruit size of blueberry is an important quality criterion of consumers and distributers (Ehret et al. 2012).

The growth is mainly determined by water supply and the actual water needs vary during the developmental stages (Jorquera-Fontena et al. 2017). In previous studies, it was concluded, that cell number is a factor for the final size of blueberry (Johnson und Malladi 2011). Thus, limiting drought stress of the fruit during both, cell division and cell expansion, is crucial to reach varietal sensory properties. However, an increase of water supply by irrigation early in the year, during cell division, may cause splitting of woody parts of the bush. In stage II shows a limited water need as well. Resulting the transition from stage II to stage III may be used to set the enhanced K_C, but this hasn't been approached so far. Furthermore, the fruit clusters show high variability considering fruit maturity at harvest and selective harvesting is economically necessary. Particularly in this late stage of fruit development, lack of water may cause yield loss.

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The threshold of the beginning of drought stress is commonly indicated by the readily available soil water content (RAW) (Jensen et al. 1990, Allen et al. 1998). A frequently used method to estimate the irrigation needs of the fruit is the calculation of crop evapotranspiration (ET_C). Taking into account the ET_C allows reduction of irrigation during growth periods characterised by less pronounced water requirements. Estimating ET_C, using guidelines from Food and Agriculture Organisation (Allen et al. 1998) by multiplying reference evapotranspiration (ET_O) with a FAO-listed crop coefficient (K_C), improved water use efficiency in blueberry 'Star' and achieved water savings (Keen and Slavich 2012). Consequently, the improvement of estimating K_C adapted to fruit growth characteristics, is assumed advantageously (Pereira et al. 2015). However, some fine-tuning of the K_C-setting may be conducive to meet specific requirements in blueberry production, while irrigating resource-efficiently.

This study was aimed at comparing the timing of (i) adjusted K_C based on FAO table and field parameters, (ii) adjusted K_C based on FAO table, field parameters and fruit developmental stages. Both cases were used for (iii) calculating the daily water balance over two years.

Material and methods

Experimental site

In 2017, the highbush blueberry cultivar 'O‘Neal' was sampled at ATB research site, field lab for digital agriculture, located in semi-humid climate in Potsdam-Marquardt. In addition, the cultivar 'Bluecrop', grown in a commercial orchard, was analysed. In 2018, the sampling of the commercially important cultivars 'Duke' and 'Bluecrop' took place in a commercial orchard of the same production region in Germany. All plants used in the study were drip irrigated. The soil was characterized as sandy loam with field capacity (Θ_{FC}) 0.18 m^3 m^{-3} and wilting point (Θ_{WP}) at 0.06 m^3 m^{-3}.

Plant and fruit developmental stage

Phenological stage of full bloom was visually rated at 50 % of open flowers. Fruit sampling took place twice a week (n = 45) for measuring the fruit diameter by calliper. The transition from phase II to phase III was determined by a statistical t-test. Differences between the measurement interval of the calculated growth rate were considered significant for $\alpha \leq 0.05$.

Water balancing

The air temperature (T in °C), relative humidity (RH in %), wind speed (u in m s^{-1}), solar radiation (R_n in W m^{-2}), and precipitation (P in mm) were monitored by weather stations (IMT, Pessl, Austria) located next to the plant rows and recorded every 15 minutes. To calculate adjusted ET_C (mm d^{-1}), the estimation of crop coefficient (K_C) by means of basal crop coefficient (K_{cb}) and soil surface evaporation coefficient (K_e), soil water stress coefficient (K_s), and the reference evapotranspiration (ET_O) was needed (Eq. 1). The ET_O was calculated daily using the standard FAO Penman–Monteith equation (Allen et al. 1998). Methods to estimate the coefficients were shown in previous studies (Jensen et al. 1990, Allen et al. 1998).

$$ET_C = (K_s\, K_{cb} + K_e)\, ET_O \qquad \text{(Eq. 1)}$$

Basal crop coefficients were calculated by daily measured weather data considering mean plant height of h = 1.8 m for 'O'Neal', h = 1.5 m for 'Duke', and h = 1.2 m for 'Bluecrop'. The FAO-K_C used from bud break till full bloom ($K_{cb,ini}$) has been set at 0.30, from full bloom till harvest ($K_{cb,mid}$) has been set at 1.05 and at 0.50 from harvest till leaf drop ($K_{cb,end}$) (Allen et al. 1998, Table 12). The coefficients were adjusted according to field parameters (Eq. 2, 3, 4).

$$K_{cb,ini} = K_{cb,ini(tab)} + [0.04\ (u-2) - 0.004(RH-45)]\ (\tfrac{h}{3})^{0.3} \quad \text{(Eq. 2)}$$

$$K_{cb,mid} = K_{cb,mid(tab)} + [0.04\ (u-2) - 0.004(RH-45)]\ (\tfrac{h}{3})^{0.3} \quad \text{(Eq. 3)}$$

$$K_{cb,end} = K_{cb,end(tab)} + [0.04\ (u-2) - 0.004(RH-45)]\ (\tfrac{h}{3})^{0.3} \quad \text{(Eq. 4)}$$

The soil parameters were calculated based on the total available soil water in the root zone (TAW) considering the measured mean root depth (z) of 0.25 m (Eq. 5). The total evaporable water (TEW) is the maximum evaporable water, which is equally defined according to the soil texture and resulting volumetric water content at field capacity and wilting point (Eq. 5, 6). The Z_e is the depth of soil that can be dried from evaporation. The readily available water (RAW) was calculated and used as threshold (Eq. 7, 8). The readily evaporable water (REW) was at 6 mm (Allen et al. 1998, Table 19). Only in case the water depletion, D_r (mm), in the root zone exceeded the RAW at the end of day, the K_s was estimated.

$$TAW = 1000\ (\Theta_{FC} - \Theta_{WP})\ _Z \quad \text{(Eq. 5)}$$

$$TEW = 1000\ (\Theta_{FC} - \Theta_{WP})\ Z_e \quad \text{(Eq. 6)}$$

$$RAW = p\ TAW \quad \text{(Eq. 7)}$$

$$p = ptab + 0.04\ (5-ET_C) \quad \text{(Eq. 8)}$$

For further considering soil evaporation in the water balance model, the K_e for the mid and the last growth stage was calculated according to previous experiments (Allen et al. 2005) (Eq. 9), where $K_{C,max}$ is the maximum value of K_C during the cultivation period. The estimation of K_e takes place when the soil starts to dry. In other words, when the daily cumulative depth of water depleted from the surface ($D_{e,i}$) exceeds readily evaporable water (REW). This has been defined by the soil evaporation reduction coefficient (K_r) (Eq. 10).

$$K_e = K_r\ (K_{c,max} - K_{cb,mid,end}) \quad \text{(Eq. 9)}$$

$$K_r = \frac{TEW - D_{e,i}}{TEW - REW} \quad \text{(Eq. 10)}$$

We compared two cases, where the timing of K_C, ($K_C = K_{cb} + K_e$), was set according to the time intervals tabulated in FAO-56 or adjusted to the growth stage relevant in blueberry. Using these two cases of timing, the resulting two ET_C cases, adjusted to reference FAO data ($ET_{C,RF}$) and K_C timing according to the fruit developmental stage and end of harvest found in the orchard ($ET_{C,FD}$) for calculating the daily water balance (WB in mm). In both cases (Eq. 11, 12) daily precipitation (P) was used in the balance.

$$WB_{RF} = ET_{C,RF} - P \quad \text{(Eq. 11)}$$

$$WB_{FD} = ET_{C,FD} - P \quad \text{(Eq. 12)}$$

Data analysis

The analyses were carried out in Matlab (Version R2017a, Mathworks). Analysing fruit developmental stages and figures were performed in R (R core Team 2018).

Results and discussion

Determining the timing of K_C

Measurements of fruit diameter revealed the characteristically double-sigmoid growth curve of blueberry with fast increase of fruit diameter throughout cell division, followed by a size-steady period at embryonal development, and a change of growth with distinct increase of fruit diameter due to cell expansion. These findings appear similar to previous characterisation of blueberry development (Retamales and Hancock 2012). Particularly the growth rate revealed that the first peak of growth rate was already declining, when the measurements started. Subsequently, change of growth pattern from stage II to stage III was used to adjust the timing of K_C. In 2017, growth rate decreased till 28 days after full bloom (dafb) for 'O'Neal' (Figure 1) and 43 dafb for 'Bluecrop', followed by increase of fruit diameter. In 2018, change of growth pattern from stage II to stage III occurred 30 dafb for both, 'Bluecrop' and 'Duke'. The relatively early transition from stage II to stage III appeared due to the high temperatures in 2018 (Figure 2).

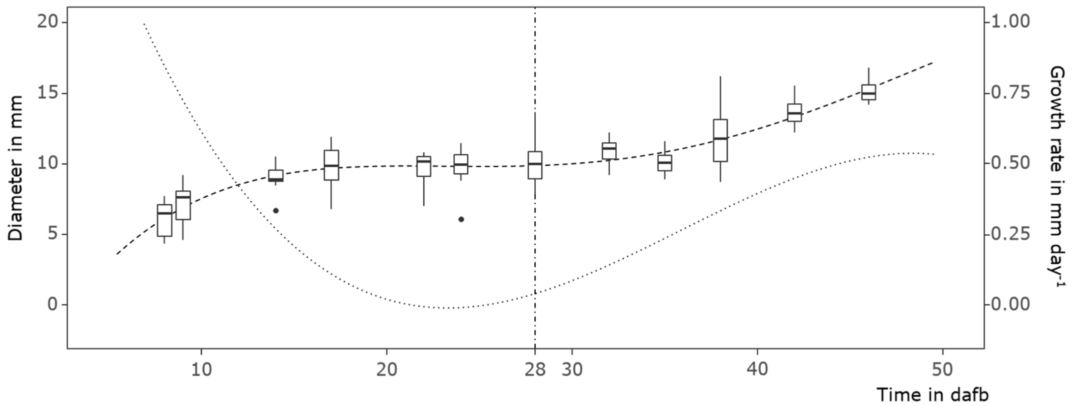

Figure 1: Diameter (in mm; dashed line) and growth rate (in mm day^{-1}; dotted line) of blueberry 'O'Neal' in 2017 throughout fruit development in days after full bloom (dafb). Dashed-dotted vertical line indicates the transition from developmental stage II (embryonal development) to stage III (cell expansion).

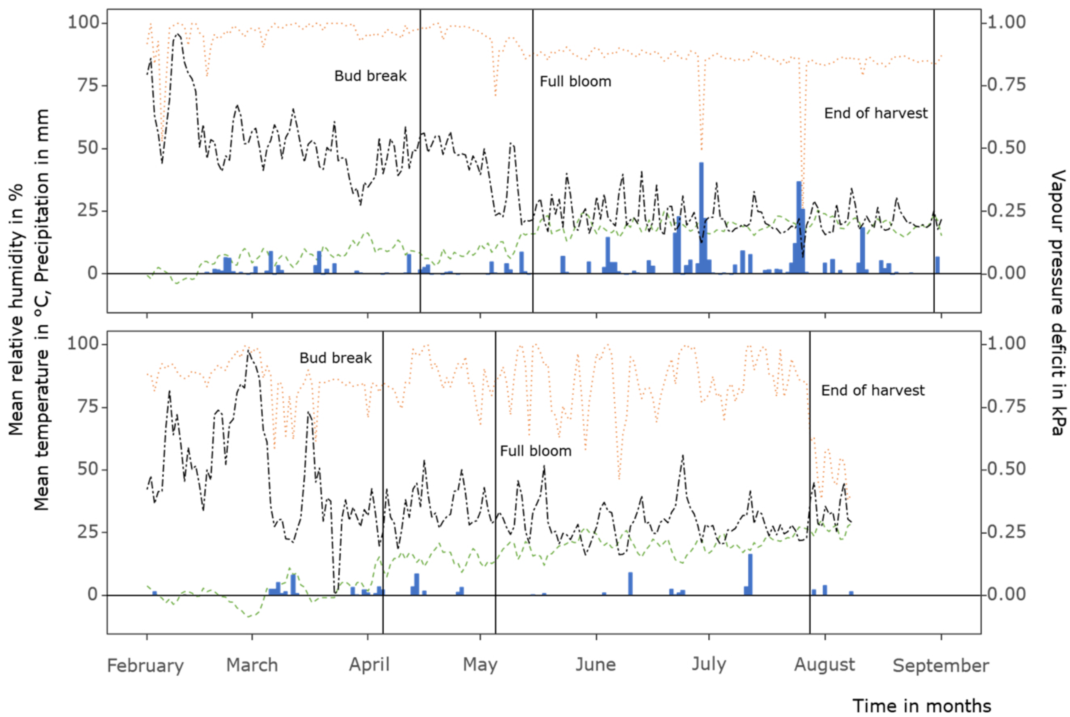

Figure 2: Daily weather data throughout the vegetation period 2017 (top) and 2018 (bottom) showing mean temperature (in °C; green dashed line), mean relative humidity (in %; orange dotted line), precipitation (in mm; blue vertical bars), and vapour pressure deficit (in kPa; black two-dashed line). Solid vertical lines indicate specific phenological stages of blueberry bush, here considering 'Bluecrop'.

Crop development and weather data

The year 2017 was characterised by outstanding high precipitation compared to mean precipitation rate of last 30 years (Deutscher Wetterdienst 2018) throughout fruit development (Figure 2). Between bud break in April and the end of harvest in August precipitation of 357 mm was monitored. Frost occurred till end of April. The length of the period between full bloom and harvest appeared similar to the experiences in commercial production. In contrast, in 2018, the vegetation period was characterised by high temperature and low precipitation. Only 87 mm precipitation was recorded throughout fruit development. Frost was not monitored later than 3rd April. The fruit development was accelerated, and harvest was extremely early.

Water balancing

The adjusted ET_C considered the plant height and volumetric water content at field capacity and wilting point. The timing of K_C recommended by FAO started at bud break, changed at full bloom, and at first day of harvest (Figure 3). However, blueberry specific needs throughout fruit growth are not considered. Therefore, it was tested to similarly start at bud break. Subsequently, during stage III of fruit development, the cell expansion, water supply of the fruit is important for achieving quality according to requirements at the market, while before excessive water supply can affect the quality of the wood. Therefore, the transition of $K_{C,ini}$ to $K_{C,mid}$ was shifted from full bloom to the transition from stage II to stage III in the present study (Figure 3).

Due to variable ripening of blueberry in the cluster, the crop is subject to selective harvesting. The period of cell expansion lasts during the entire harvest window. Thus, change from $K_{C,mid}$ to $K_{C,end}$ was determined at the end of harvest in blueberry instead of the beginning as generally proposed in the FAO paper. Such approach in combination with measured length of growth stages, allows the consideration of the actual water needs by the fruit. For 'O'Neal' the stages $K_{C,ini}$ lasted 59 days, $K_{C,mid}$ 72 days followed by $K_{C,end}$. For 'Bluecrop' in 2017 $K_{C,ini}$ was scheduled for 73 days and $K_{C,mid}$ 64 days. In 2018 for 'Bluecrop' $K_{C,ini}$ 62 days and $K_{C,mid}$ 61 days and 'Duke' $K_{C,ini}$ 62 days and $K_{C,mid}$ 54 days, respectively.

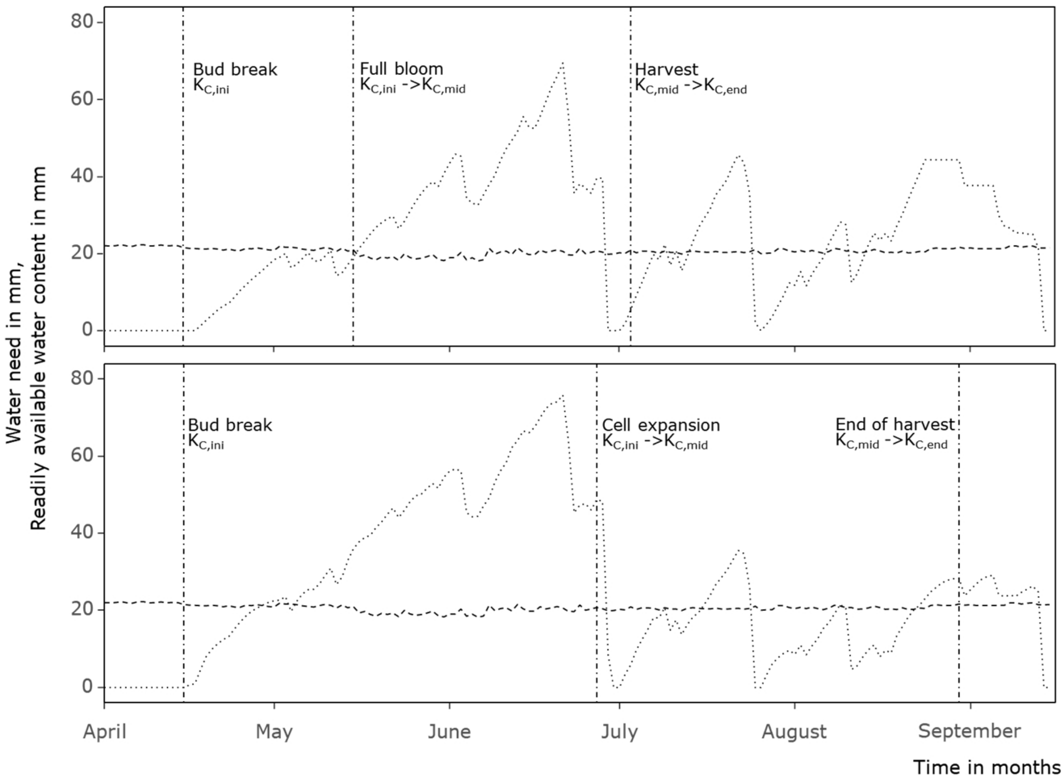

Figure 3: FAO-adjusted (WB_{RF}; top) and adjusted, fruit growth stage adapted timing (WB_{FD}; bottom) water balance (in mm; dotted line) as well as readily available water content (in mm; dashed line) in 2017. Vertical dashed-dotted lines indicate the change of the crop coefficient (K_C).

In 2017, irrigation needs calculated by WB_{RF}, increased up to 69.6 ± 14.5 mm in June (Figure 3, top). Subsequently, after the drop of water needs, occurring simultaneously to increased precipitation, water needs increased again following transition of $K_{C,mid}$ to $K_{C,end}$ at the beginning of July, the commercial harvest window. Guided by the developmental stage of blueberry (Figure 1), the change from $K_{C,ini}$ to $K_{C,mid}$ was set at beginning of cell expansion at the end of June (Figure 3, bottom), but lasted longer due to shift from beginning of harvest to end of harvest. Shifting of the timing in WB_{FD} caused an increase of water needs between April and July, but a decrease during the harvest window.

Measurements in the relatively dry year 2018 considered two commercially important cultivars 'Duke' and 'Bluecrop' grown in commercial production site. Here, similar water balance patterns were found (Table 1). Consequently, water balancing for blueberry considering the fruit development more precisely, shows potential for optimized water use efficiency.

Table 1: Monthly water needs of 'Bluecrop' and 'Duke' in 2018 (mean ± standard deviation) based on FAO field-adjusted daily water balance (WB_{RF}) and additionally adapted to measured fruit development of blueberry (WB_{FD}).

Case	Water needs in mm				
	April	May	June	July	August
WB_{RF}	0.0 ± 0.0	0.0 ± 0.0	0.8 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
WB_{FD}	0.0 ± 0.0	29.8 ± 1.3	84.2 ± 2.7	73.2 ± 1.3	0.0 ± 0.0

Not only the daily water needs should be taken into account, but also the threshold determined by the readily available volumetric water content, shown as RAW. The water deficit exceeded the RAW in both years. Shifting the timing of K_C affects the ET_C, which is a factor in calculating the RAW (Eq. 8). Despite the model is based on similar field conditions of blueberry in both cases, irrigation needs differ between cases. However, in the present study the RAW threshold change by 1/100 only. The fine-tuned adjustment of the water balancing to the fruit water requirements (Figure 3, bottom) revealed a water need of 186 mm in 2018 compared to field adapted water balancing over the relevant period between bud break and harvest. Consequently, in addition to field-adjusted FAO-based K_C-values, the adjustment of K_C-timing by fruit growth stage and consideration of harvest window, allows to reveal the actual drought stress of the fruit, not only the drought stress at the plant level. This may result in enhanced water needs, but considering the realistic demands occurring in the field. The influence of the fruit adjusted water balancing on the yield was not carried out in this study but should be investigated in future research. Furthermore, alternative methods for characterisation of fruit developmental stages could be applied, e. g. temperature sums, which can easily be integrated in field management systems.

Conclusions

The daily irrigation threshold was determined for 'O'Neal', 'Duke', and 'Bluecrop'. Implementing the timing of adjusted K_C-value in the water balancing allows the avoidance of drought stress in stress sensitive growth stages, important for gaining high fruit size. It may be assumed that a field management system, based on adjusted FAO values and fruit developmental stages, can optimise water use efficiency.

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