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Impact of irrigation on plant growth and development of white cabbage

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ABSTRACT

It is widely known that an optimal irrigation water supply is a key to high horticultural productivity, efficient water use, and the reduction of off-site effects due to percolation of excess water. To promote better agronomic practices in irrigated horticulture, three different irrigation scheduling approaches based on soil water balance calculations, soil water potential measurements (sensor-based), and crop growth model simulations, were evaluated in a two-year field experiment. The experiments were conducted with white cabbage on a loamy sand soil near Dresden, Germany. The results show that sensor-based irrigation, at a soil water potential of −250 hPa measured at a soil depth of 30 cm, achieved high yields with moderate to low irrigation water inputs. Irrigation scheduling based on soil water balance calculations led to unproductive over-irrigation due to overestimated crop coefficients, which highlight the need for more accurate estimates of these coefficients. Simulation-based irrigation scheduling resulted in acceptable water productivities but can only be recommended to farmers to some extent because it requires a robust crop model calibration. Analysis of the plant development indicates that maintenance of field capacity until the end of head formation is favorable. Drought stress lead to reduced plant heights, leaf area indices and head yields. Furthermore, the results show that early drought stress effects can be compensated by an appropriate water supply in later growing stages.

1. Introduction

Improving water productivity in crop production is gaining further importance, with increasing irrigation costs and world wide progressing water scarcity. High-precision irrigation systems like drip irrigation combined with an adequate irrigation management can reduce irrigation water requirements, while maintaining high yields and fruit quality (Kumar and Sahu, 2013). Correct timing of the right amount of water is the basic ingredient to achieve these goals. Crop irrigation scheduling is in the simplest case based on farmers experience, while more objective approaches are provided by soil water balance calculations, soil moisture or plant sensing methods or the application of crop growth simulation models. However, especially in horticultural production where yield and fruit quality can be influenced beneficially by irrigation, relevant recent literature about irrigation scheduling and application techniques of some individual vegetables is scarce. In the following, irrigation scheduling of white cabbage (*Brassica oleracea* L. var. capitata (L.) *alef*) as an important member of the collard crops, is analyzed.

Irrigation scheduling based on soil water balance (SWB) calculations is very common. The soil moisture status is estimated by calculations using a water balance approach. The crop coefficient approach of the FAO (Food and Agriculture Organization of the United Nations) Irrigation and Drainage Paper 56 (FAO-56) (Allen et al., 1998), estimates the potential crop evapotranspiration ET_c by multiplying the reference evapotranspiration ET_o with a crop-specific, empirically determined crop coefficient (K_c factor). ET_c is defined as the amount of water required by a crop for optimal growth. ET_o is determined using measured climatic data and the required K_c factors are provided by the FAO for a multitude of plants (Allen et al., 1998).

The SWB calculation approach has generally been found to be sufficiently robust under a wide range of conditions (Jones, 2004). Although, it ignores the influence of thermal time and stress effects on crop development by assuming that plant growth and

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development depends on calendar time alone (Annandale et al., 2000). According to the authors, this limits the ability to apply a particular K_c factor curve to different regions and even to different planting dates within the same region. Furthermore, the K_c factors depend on the climatic conditions and are therefore not universally valid (Annandale et al., 2000), resulting in a limited transferability of these factors. Moreover, water balance errors accumulate over time which makes a data assimilation necessary (Jones, 2004).

In sensor-based irrigation scheduling, the irrigation water requirement is estimated directly from the soil moisture status, either in terms of soil water content or soil water potential (Jones, 2004; Kloss et al., 2014). Hereby, the soil water potential is more important for irrigation scheduling as it is closely related to the stress experienced by plant tissues (Jensen et al., 1998; Shock and Wang, 2011). A major advantage is the relatively easy application and automatization of this approach (Jones, 2004). Shock and Wang (2011) summarized studies which investigated the effect of different soil water potential thresholds on the productivity of cole crops and found a higher productivity when irrigated at −200 to −400 hPa compared to −500 to −750 hPa. Smittle et al. (1994) grew cabbage in drainage lysimeters and investigated the impact of the tension threshold in 10 cm depth. The authors showed that total and marketable cabbage yields were highest when the soil water potential was above −250 hPa. Inaccuracies of soil water based approaches are caused by the fact that many features of the plants physiology respond directly to changes in water status in the plant tissues rather than to changes in the bulk soil moisture (Jones, 2004). Moreover, difficulties arise from the question where exactly to probe (in vertical as well as in horizontal direction) and extensive measurement programs might be required under the influence of high soil heterogeneity.

Crop growth simulation models can be powerful tools to support crop management as they can be applied for real-time irrigation scheduling under variable rainfall conditions (Seidel et al., 2015), for the estimation of calender-based irrigation schedules in arid regions (Schütze et al., 2012), or for the estimation of optimal soil water potential thresholds for sensor-based irrigation (Kloss et al., 2014). Currently, more than two dozen crop models exist, but in most cases standard parameterizations do not include horticultural crops. Due to the lack of input data and modeling approaches, horticultural crops have been barely (if) explored (Sthapit et al., 2012). The crop growth simulation models Daisy (Abrahamsen and Hansen, 2000), DSSAT (Hoogenboom et al., 2003) and AquaCrop (Steduto et al., 2009) are among the few models, which provide standard parameterizations for several horticultural crops including white cabbage. The only simulation studies which deal with the prediction of growth dynamics and the associated water demand of white cabbage found by the authors of this manuscript applied the model AquaCrop (Kiptum et al., 2013; Wellens et al., 2013a,b) and the model Daisy (Seidel et al., 2016b).

White cabbage is a crop with a high leaf area index (LAI), leading to relatively high transpiration rates which in turn contributes to fast soil drying. The plant possesses a deep (more than 240 cm) and fast growing root system, which exhibits the highest root density in deeper soil layers at about 50–80 cm depth (Kristensen and Thorup-Kristensen, 2004, 2007). Regarding the development stage dependent drought susceptibility, white cabbage was classified by Smittle et al. (1994) as intermediately susceptible to water stress. In contrast, Shock and Wang (2011) reported that collard crops are among the species most sensitive to soil water potential. Nelson and Hwang (1976) determined the water demand of cabbage cultivated in a growth chamber at weekly intervals. The authors stated that high cabbage yield depends on a plentiful supply of water throughout plant growth and that drought stress during head formation had the biggest influence on observed yield. Radovich et al. (2005) studied the effects of irrigation timing from planting to maturity, as well as only during frame development and only during head development. Irrigation during head development resulted in larger, heavier heads, with relatively low dry matter content. The authors furthermore suggest that drought stress during frame development and the early stages of head development may influence yield by reducing frame size and restriction of head leaf expansion. Seciu et al. (2016) state that 75% ET_c irrigation significantly reduced total and marketable yield in their field experiments in Romania. Xu and Leskovar (2014) report that irrigation at 75% ET_c had little influence on plant growth and physiology, but reduced both marketable and total yield (South Texas, 2012). However, irrigation at 50% ET_c significantly reduced head fresh weight, height and width, but it increased dry matter biomass. McKeown et al. (2010) recommended consistent irrigation over the growing season to maintain field capacity for maximal cabbage yield. The authors stated that white cabbage has a high water demand and mainly the head volume is influenced by water application. Fereres et al. (2003) recommend full irrigation for high value horticultural crops. However, Cripps et al. (1982) found that over-watering and too frequent watering both resulted in reduced yields, although not as much as insufficient irrigation.

Next to high yields, the yield quality plays an important role. Radovich et al. (2004) demonstrated that irrigation and its timing relative to plant developmental stage can influence cabbage sensory quality and physical traits of cabbage heads (e.g. weight, mean diameter, shape). Heads from plants receiving irrigation throughout plant development were larger, heavier and more round than heads from other treatments. The authors conclude that irrigating only during head development may help reduce irrigation costs and conserve water resources while maintaining sensory quality. Maršić et al. (2012) analyzed the quality of white cabbage yield as affected by nitrogen fertilization and irrigation practices. Broadcast NPK fertilization with sprinkler irrigation caused a significant increase in the cabbage N-content, whereas in drip irrigation treatments no significant differences were detected between fertilization treatments. The authors emphasized the importance of adequate irrigation in vegetable production and the linkage of irrigation and the risk for nitrate leaching.

The effect of different irrigation techniques and scheduling approaches on white cabbage growth and development has been investigated by several researchers (Cripps et al., 1982; Drew, 1966; Ells et al., 1993; Nelson and Hwang, 1976; Smittle et al., 1994; Kumar and Sahu, 2013; Seciu et al., 2016) for different regions of the world. Some studies present experimental results from different regions (Australia, USA, Botswana, India, Slovenia, Canada, and Romania) where irrigation water was applied on cabbage based on SWB calculations covering 50-150% of the crop's water requirement (Cripps et al., 1982; Ells et al., 1993; Imtiyaz et al., 2000; Tiwari et al., 2003; Šturmet al., 2010; McKeown et al., 2010; Kumar and Sahu, 2013; Seciu et al., 2016). However, none of the available studies was conducted on white cabbage for the growing conditions and soils encountered in Central Europe, which prevents a transfer of their results.

The presented study aims to shed some light on the irrigation water demand of white cabbage under Central European growing conditions in temperate climate. Therefore, the impact of three different irrigation scheduling approaches on white cabbage growth were investigated in a two year field trial: irrigation scheduling based on (i) soil water balance calculations applying the Geisenheim K_c factors (Paschold et al., 2010), (ii) sensor-based irrigation using tensiometers and (iii) simulation-based irrigation. The individual approaches are compared regarding their overall performance by evaluating achieved yields, the water requirements and the resulting water productivities. Furthermore, the assessment of irrigation effects on plant development are supported by detailed