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Modeling relations of tomato yield and fruit quality with water deficit at different growth stages under greenhouse condition

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ABSTRACT

Nowadays more and more attentions are paid to fruit quality in the production of tomato. In order to better understand the effects of deficit irrigation on tomato yield and fruit quality, four years of deficit irrigation experiments were investigated to simulate water-yield and water-fruit quality relationships of tomato in greenhouses. The yield and fruit quality parameters like total soluble solids (*TSS*), reducing sugars (*RS*), organic acids (*OA*), sugar/acid content ratio (*SAR*), vitamin C (*VC*), firmness (*Fn*), color index (*CI*) were correlated with seasonal evapotranspiration (*ET*) and *ET* deficit at flowering and fruit development stage (*Stage II*) and fruit ripening stage (*Stage III*) using linear regression. Three water-yield models (Jensen, Stewart, Minhas) and three water-fruit quality models (multiplicative, additive, exponential) were applied to simulate the relationships of tomato yield and fruit quality parameters with water deficit at various growth stages. The water deficit sensitivity indexes ($\lambda/Ky/\delta$ or $\gamma/Kq/\psi$) of the models were calculated with the method of multiply linear regression. The performance and sensitivity analysis of the models were evaluated. Results showed that the relative yield decreased linearly with the drop of relative seasonal *ET*, mainly due to the yield depression by *ET* deficit at *Stage II* and *Stage III*; the relative values of fruit quality parameters increased with the drop of relative seasonal *ET*, mostly because of the enhancement by *ET* deficit at *Stage III*. The calculated water deficit sensitivity indexes indicated that both the yield and fruit quality were hardly sensitive to water deficit at *Stage I*, but sensitive to water deficit at *Stage II* and that at *Stage III*; *TSS*, *RS*, *SAR* and *VC* were much more sensitive to water deficit at *Stage III* than that at *Stage II*; *RS*, *SAR* and *VC* were more sensitive to water deficit than *TSS*, *OA*, *Fn* and *CI*. The Minhas model with its water deficit sensitivity indexes was recommended to simulate water-yield relations of greenhouse tomato in the study area; multiplicative model and additive model were, respectively, recommended to simulate the relationships of fruit quality parameters like *TSS*, *RS*, *SAR*, *Fn* and fruit quality parameters like *OA*, *VC*, *CI* with water deficit at various growth stages. The water-yield and water-fruit quality models would be helpful to optimally allocate irrigation water during the growth season, thus achieving efficient production of tomato in greenhouses in consideration of the compromise between tomato yield and fruit quality.

1. Introduction

In recent years, fruit quality has become a major concern for fruit production in response to the increasing consumers' demand (Guichard et al., 2001), for its importance to human health and pleasure (Dumas et al., 2006). Tomato is favored by people as an important source of lycopene, phenolic, and vitamin C in human diets (Toor et al., 2006). The consumption of tomato is also associated with a lower risk of developing some cancers (Giovannucci et al., 1995; Franceschi et al., 1994). Since the fruit with high quality is more popular among consumers, the price of tomato fruit would increase with the improvement of fruit quality. It has been predicted that the tomato consumption and profitability for producers would increase due to consumers' satisfaction with the quality of tomato fruit (Kader, 2008). Hence, improving tomato fruit quality is beneficial for consumers as well as growers.

A ripe tomato is principally composed of water and 5–8% dry matter, half of which is mainly glucose and fructose (Davies and Hobson, 1981). The quantity of water present in the fruit is responsible for its quality since it determines the concentration of different elements such as sugars and acids. Therefore the factors which influence the water uptake of the fruit play a significant role in

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determining the fruit size and the dry matter concentration, that is, its final quality (Guichard et al., 2001). Irrigation is considered as one of the most influential factors which affect the fruit water status. Many studies have shown that tomato fruit quality is enhanced by deficit irrigation (Mitchell et al., 1991; Pulupol et al., 1996; Zushi and Matsuzoe, 1998; Veit-Köhler et al., 1999; Johnstone et al., 2005; Favati et al., 2009; Patanè and Cosentino, 2010; Wang et al., 2011; Patanè et al., 2011). However the improvement of tomato fruit quality by deficit irrigation is often paralleled with an undesirable reduction in yield, mainly due to a smaller fruit size (Nuruddin et al., 2003; Kirda et al., 2004; Machado and Oliveira, 2005; Zegbe et al., 2006; Topcu et al., 2007; Marouelli and Silva, 2007; Zheng et al., 2013; Kuscu et al., 2014).

The effects of deficit irrigation on tomato fruit yield and quality are poorly defined because of its complexity, despite much research (Renquist and Reid, 2001; Marouelli and Silva, 2007; Favati et al., 2009; Patanè and Cosentino, 2010). The incompatible relationship between tomato yield and fruit quality should be taken into consideration when regulating tomato fruit quality through irrigation management. A good tradeoff between tomato yield and fruit quality could be achieved when irrigation amount was reduced to 70–85% of crop evapotranspiration (*ET*) during fruit enlargement and ripening either by irrigation cutting-off 2 weeks earlier than conventional cut-off dates or by applying deficit irrigation (Cahn et al., 2001). In a typical Mediterranean environment, an optimal irrigation strategy which balanced the relationship between yield and fruit quality of processing tomato was that irrigation was carried out to supplement crop evapotranspiration once the cumulative crop evapotranspiration minus effective rain reached 40 or 60 mm and with a reduction of 50% irrigation volume during fruit ripening (Favati et al., 2009).

In order to achieve more precise management of regulated deficit irrigation in tomato production, a better understanding of quantitative relationships between tomato yield, fruit quality and water use would be expected. Relative tomato yield reduction $(1 - Y_a/Y_m)$ was described as a function of relative crop seasonal *ET* deficit $(1 - ET_a/ET_m)$ with the equation: $1 - Y_a/Y_m = Ky(1 - ET_a/ET_m)$, developed by Stewart et al., 1977 (Kirda et al., 2004; Patanè et al., 2011; Kuscu et al., 2014). The positive relationships between tomato yield and seasonal *ET* were fitted by linear models (Zheng et al., 2013; Kuscu et al., 2014) as well as by curvilinear models (Renquist and Reid, 2001; Patanè et al., 2011). It was also reported that tomato yield was linearly or nonlinearly correlated with soil water deficit (Patanè and Cosentino, 2010), soil water tension thresholds (Marouelli and Silva, 2007), and seasonal irrigation volume (Cahn et al., 2002; Machado and Oliveira, 2005; Favati et al., 2009; Zheng et al., 2013; Kuscu et al., 2014). Accompanying with the positive relations between tomato yield and seasonal irrigation volume, negative linear or curvilinear relationships were found between total soluble solids content (*TSS*) of tomato fruit and seasonal irrigation amount (Cahn et al., 2002; Machado and Oliveira, 2005; Favati et al., 2009; Ozbahce and Tari, 2010; Kuscu et al., 2014). Some positive relationships of *TSS*, reducing sugars content (*RS*), organic acids content (*OA*), firmness (*Fn*), color of tomato fruit with soil water deficit during fruit enlargement and ripening were also evaluated by Patanè and Cosentino (2010). Moreover, some negative linear relationships were established between fruit quality parameters (such as *TSS*, *RS*, *OA*, vitamin C (*VC*), *Fn*, color index (*CI*), sugar/acid content ratio (*SAR*)) and seasonal *ET* as well as *ET* at tomato fruit development and ripening stages (Chen et al., 2013).

Many studies showed that the response of tomato yield and fruit quality to deficit irrigation at various growth stages was different, depending on the period and the degree of water deficit (Nuruddin et al., 2003; Zegbe et al., 2006; Marouelli and Silva, 2007; Chen et al., 2013; Kuscu et al., 2014). It was reported that there were no adverse effects on tomato yield and fruit quality by imposing a certain degree of water stress during vegetative stage (Zegbe et al., 2006; Marouelli and Silva, 2007; Chen et al., 2013; Kuscu et al., 2014). Moreover, the study of Ngouajio et al. (2007) showed that withholding irrigation between transplanting and flowering may save the amount of irrigation water by 20% while increase tomato yield by 8–15%. Chen et al. (2013) stated that tomato yield was sensitive to water deficit during fruit development and ripening, while fruit quality was mainly affected by water deficit during fruit ripening. Lots of studies also reported that tomato fruit quality was enhanced by water deficit at fruit growth and ripening stages, but with a yield depression (Renquist and Reid, 2001; Nuruddin et al., 2003; Favati et al., 2009; Patanè and Cosentino, 2010; Kuscu et al., 2014). Consequently, before using deficit irrigation strategies to regulate tomato yield and fruit quality, it is important to obtain adequate information about the relationships between tomato yield, fruit quality and water deficit with its timings and magnitudes.

The dated crop water production functions (*DCWPF*) describe the functional relationships of crop yield with *ET* or *ET* deficit at some specific growth stages, which include the effects of both timings and magnitudes of water deficit (Rao et al., 1988). The *DCWPF* are formulated in additive or multiplicative forms by postulating that water deficit in each growth stage has independent effects on crop yield, and the combined effects of water deficit at different growth stages are additive or multiplicative (Rao et al., 1988). Typical examples of multiplicative-type *DCWPF* are the models by Jensen (1968), Minhas et al. (1974) and Hanks (1974); and the additive-type *DCWPF* include those by Blank (1975), Stewart et al. (1976) and Sudar et al. (1981). The *DCWPF* are useful in predicting the crop yield and optimizing irrigation water allocation during the whole growing season when the available water is not sufficient to cover the crop water requirement. The *DCWPF* like Jensen, Stewart and Minhas models are widely used to simulate the relationship between some cereal crops' production and water deficit at various growth stages, e.g. rice, wheat, and maize (Mao et al., 1994; Zhang and Oweis, 1999; Zhang et al., 1999; Igbadun et al., 2007; Li et al., 2011; Paredes et al., 2014). However, few studies (Xu et al., 2001) were reported about the application of *DCWPF* in water-yield relations of tomato. And unfortunately, so far as the literatures reported, no modeling equations have been established to evaluate the effects of different degrees of water deficit at various growth stages on tomato fruit quality.

In order to improve tomato fruit quality and simultaneously compromise its incompatible relationships with tomato yield by precise deficit irrigation, modeling equations should be established to simulate the relationships of tomato yield and fruit quality with deficit irrigation. In the present study, four years of deficit irrigation experiments on greenhouse tomato in Northwest China were investigated. The aims of this study were to model water-yield and water-fruit quality relationships of greenhouse tomato considering the combined effects of timings and magnitudes of water deficit. The specific objectives, using the data acquired from the field experiments, include: (1) investigating the relationships of tomato yield and fruit quality parameters with crop seasonal *ET* as well as *ET* deficit at flowering and fruit development and fruit ripening stages; (2) Using Jensen, Stewart and Minhas models to simulate the response of tomato yield to water deficit at various growth stages; (3) Developing an additive model, a multiplicative model and an exponential model to simulate the relationships between fruit quality parameters and water deficit at various growth stages; (4) Evaluating the performance of the models in predicting tomato yield and fruit quality parameters under deficit irrigation. The output of this study is expected to improve our knowledge of deficit irrigation and predict its influence on tomato yield and fruit quality, and will have potential applications in precise irrigation management for high quality tomato production.