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RESEARCH ARTICLE

Estimation of irrigation requirements for drip-irrigated maize in a sub-humid climate

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Abstract

Drip-irrigation is increasingly applied in maize (*Zea mays* L.) production in sub-humid region. It is critical to quantify irrigation requirements during different growth stages under diverse climatic conditions. In this study, the Hybrid-Maize model was calibrated and applied in a sub-humid Heilongjiang Province in Northeast China to estimate irrigation requirements for drip-irrigated maize during different crop physiological development stages and under diverse agro-climatic conditions. Using dimensionless scales, the whole growing season of maize was divided into diverse development stages from planting to maturity. Drip-irrigation dates and irrigation amounts in each irrigation event were simulated and summarized in 30-year simulation from 1981 to 2010. The maize harvest area of Heilongjiang Province was divided into 10 agro-climatic zones based on growing degree days, arid index, and temperature seasonality. The simulated results indicated that seasonal irrigation requirements and water stress during different growth stages were highly related to initial soil water content and distribution of seasonal precipitation. In the experimental site, the average irrigation amounts and times ranged from 48 to 150 mm with initial soil water content decreasing from 100 to 20% of the maximum soil available water. Additionally, the earliest drip-irrigation event might occur during 3- to 8-leaf stage. The water stress could occur at any growth stages of maize, even in wet years with abundant total seasonal rainfall but poor distribution. And over 50% of grain yield loss could be caused by extended water stress during the kernel setting window and grain filling period. It is estimated that more than 94% of the maize harvested area in Heilongjiang Province needs to be irrigated although the yield increase varied (0 to 109%) in diverse agro-climatic zones. Consequently, at least 14% of more maize production could be achieved through drip-irrigation systems in Heilongjiang Province compared to rainfed conditions.

Keywords: drip irrigation, irrigation requirements, maize, agro-climatic regionlization, crop simulation, sub-humid climate

1. Introduction

Heilongjiang Province has the largest maize area and production in China, accounting for 15 and 16% of national maize area and production, respectively (NBSC 2015), playing an important role in national food security. In Heilongjiang Province, the dominant climate is temperate

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sub-humid continental monsoon, where winter is long, cold, and dry with a short but warm and wet summer growing season. The total seasonal precipitation in Heilongjiang Province usually meets the water demand for maize in most years but poor rainfall distribution in relation to crop water demand often leads to crop water stress at critical stages (e.g., kernel setting, grain filling, etc.), resulting in reduced yields. Less than 10% of the maize sown area is irrigated and on-farm maize yields were, on average, only 51% of the potential yields in this region (Liu Z J *et al*. 2012, 2016). Moreover, the rain-fed maize yield is low and unstable in areas with lower precipitation (Liu *et al*. 2016). Consequently, effective irrigation could improve maize production and narrow yield gaps between rainfed and irrigated conditions in Northeast China (Liu Z J *et al*. 2012; Liu C *et al*. 2017).

Drip irrigation is one of the most efficient methods of irrigation/fertigation in terms of application efficiency and reducing soil evaporative losses (Irmak *et al*. 2016). In recent years, drip irrigation has widely been applied to maize production in sub-humid regions like North China Plain (Wang *et al*. 2014), Northeast China (Liu *et al*. 2015), and Central U.S. (Lamm and Trooien 2003; Irmak *et al*. 2016) due to its advantages of precise application in amount and at location throughout the field and effectiveness in improving water and nitrogen use efficiency compared to other irrigation methods (Bar-Yosef 1999; Guan *et al*. 2013). After ten years of research in Kansas in the U.S., Lamm and Trooien (2003) concluded that irrigation water used for corn can be reduced by 35 to 55% when using subsurface drip irrigation compared with traditional irrigation. For drip-irrigation management in the field (e.g., irrigation frequency, amounts), several methods are commonly used including readings from soil moisture sensors (Leib *et al*. 2003), monitoring of crop water stress index (Jackson *et al*. 1981), and estimating crop evapotranspiration (Allen *et al*. 1989). Although those methods can be used at field level, they do not allow easy estimation of regional irrigation requirements at larger spatial scales, e.g., for a province like Heilongjiang Province due to variations in climate, crop systems, management practices and soil types.

Crop growth modeling can potentially be a good method to estimate the water and nutrient managements under varying weather and soil conditions (Boote *et al*. 1996). Some simulation models (e.g., CERES-Maize, AquaCrop, APSIM, RZWQM, Hybrid-Maize) have been tested to simulate crop yield, evapotranspiration and water management strategies for maize in arid or semi-arid regions (Abedinpour *et al*. 2012; Jiang *et al*. 2016). Abedinpour *et al*. (2012) evaluated the performace of the FAO AquaCrop model for maize crop in a semi-arid region and the results showed that the model predicted maize yield with acceptable accuracy under variable irrigation and nitrogen levels. The Hybrid-Maize model (Yang *et al*. 2014, 2016) has also been widely tested under rainfed and irrigated conditions and applied to the U.S. corn-belt (Grassini *et al*. 2009, 2011; Morell *et al*. 2016), South Asia (Timsina *et al*. 2010), and North China (Hou *et al*. 2014a; Bu *et al*. 2015). Liu Y *et al*. (2012) evaluated the Hybrid-Maize model to simulate maize growth and yield in a semi-arid Loess Plateau and applied the model to assess effects of meterological variations on the performance of maize under rainfed and irrigated conditions. According to the simulations, the average rainfed yield was 1 830 kg ha^{-1} less than the average potential yield with irrigation. In contrast, there were few studies that have used models to simulate water and nitrogen strategies for maize in sub-humid regions (Liu *et al*. 2013; Zhang *et al*. 2015). Jiang *et al*. (2016) used long-term weather data to simulate the effects of different irrigation treatments on maize yield and water use efficiency and recommended the total irrigation amounts regardless of the rainfall each season. Using the calibrated CERES-Maize model, He *et al*. (2012) identified the best irrigation management practices for sweet corn production on sandy soils, which indicated that irrigation frequency had a strong influence on sweet corn yield. However, crop water requirements varied from different physiological stages and the effects of water stress on growth and yield during different growth stages might also differ (Jones and Kiniry 1986; Kozak *et al*. 2005). Liu Y *et al*. (2017) simulated the sensitivity of maize to water at varied stages and the simulation results indicated that the descending order was pollen shedding and silking, tasselling, jointing, initial grain filling, germination, middle grain filling, late grain filling, and end of grain filling. In Florida, He *et al*. (2012) found corn growth suffered water stress and the simulated yield was reduced if irrigation events were triggered when the maximum allowable depletion of soil water content was greater than 60%. In practice, a substantial number of fields (55% of total) had water supply in excess of that required to achieve yield potential (Grassini *et al*. 2011). Analysis results in the Western U.S. Corn Belt also indicated that up to 32% of the annual water volume allocated to irrigated maize in the region could be saved with little yield penalty (Grassini *et al*. 2011). Such research on estimating irrigation requirements during mazie water-sensitive stages was helpful to reduce water supply and improve irrigation schedules to be more synchronous with crop water requirements.

For regional upscaling, irrigation requirements (e.g., irrigation timing and amounts) could be estimated with consideration of soil water content at sowing stage, crop water requirements at different stages, crop management practices, cultivar maturity, plant population, soil type, and climate characteristics at diverse agro-climatic zones for