Agricultural Water Management 204 (2018) 180–191

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Soybean crop-water production functions in a humid region across years and soils determined with APEX model

Bangbang Zhang[a], Gary Feng[b], Lajpat R. Ahuja[c], Xiangbin Kong[d,e,*], Ying Ouyang[f], Ardeshir Adeli[b], Johnie N. Jenkins[b]

[a] College of Economics and Management, Northwest A&F University, Yangling 712100, China
[b] Genetics and Sustainable Agriculture Research Unit, US Department of Agriculture, Agricultural Research Service, Starkville, MS 39762, USA
[c] Agricultural Systems Research Unit, US Department of Agriculture, Agricultural Research Service, Fort Collins, CO 80526, USA
[d] College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China
[e] Key Laboratory for Farmland Quality, Monitoring and Control, National Ministry of Land and Resources, Beijing 100193, China
[f] Center for Bottomland Hardwoods Research, US Department of Agriculture, Forest Service, Starkville, MS 39762, USA

ARTICLE INFO

Keywords:
APEX model
Soybean
Crop water production function
Yield response factor
Irrigation management
A humid region

ABSTRACT

Crop production as a function of water use or water applied, called the crop water production function (CWPF), is a useful tool for irrigation planning, design and management. However, these functions are not only crop and variety specific they also vary with soil types and climatic conditions (locations). Derivation of multi-year average CWPFs through field experiments for different locations and soils is time-consuming and expensive, as it requires careful long-term and multi-location field experiments to obtain them. Process based crop system models provide a useful tool for determining CWPFs using short-term field experimental data for calibration and validation. The aim of this study was to determine soybean CWPFs using the Agricultural Policy/Environmental eXtender (APEX) model across three soil types (Vaiden-silty clay, Cahaba-sandy loam, and Demopolis-clay loam) and three weather conditions (14-year average from 2002 to 2015, dry, and wet) of a humid irrigated region in Mississippi, USA. The results showed that the relationship between simulated soybean grain yield (GY) and the seasonal crop evapotranspiration (ET) for each soil under 14-year average weather condition was linear. Compared with the Vaiden soil, the Cahaba and Demopolis soils had slightly higher water use efficiency (WUE) over 14-year average weather conditions. The CWPFs for GY vs supplemental irrigation were cubic polynomials for all soil types and weather conditions, with varying coefficients. The maximum values of irrigation water use efficiency ($IWUE_{max}$) derived from these cubic CWPFs varied from 2.58 to 9.89 kg ha^{-1} mm^{-1} across soils and weather conditions. The irrigation amount during the growing season required (I_{max}) to achieve the maximum GY for soybean also had a wide range of values, from 110 to 405 mm. The IWUE and I_{max} were related to available water holding capacity of soils. The relationship between GY and total plant available water supply (TWS) was also a cubic function, with coefficients varying with soil types and climatic conditions. The yield response factor (K_y) was 1.24 (greater than 1.00) when averaged over 14 years' weather data, indicating that soybean was very sensitive to water stress even in a humid region like Mississippi. Thus, supplemental irrigation is necessary to increase GY and ensure stability in yields.

1. Introduction

Worldwide, there has been a rapid increase of urban and industrial water demand in recent decades, which in turn makes water become a limiting factor for crop production. Most soybean in the world is grown under rainfed conditions, such as in USA, India, Africa, Brazil and China (Bhatia et al., 2008; Heinemann et al., 2016). There is a common view that achieving the maximum possible economic yield through optimizing irrigation management is crucial to meet the increasing food and nutritional demands of the growing global population (Bhatia et al., 2008; Van Ittersum and Cassman, 2013). Even in a humid region, like Mississippi, USA, due to the uneven distribution of precipitation during the growing season (Paz et al., 2007), supplemental irrigation issues of timing and amount in the dry periods have increasingly attracted the concern of governments, experts and farmers (Karam et al., 2005; Garcia y Garcia et al., 2010; Vories and Evett, 2014). Hence, agricultural water resource management that uses the available water to obtain the most economic crop production is important all over the world.

* Corresponding author at: College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China.
E-mail address: kxb@cau.edu.cn (X. Kong).

https://doi.org/10.1016/j.agwat.2018.03.024
Received 14 October 2016; Received in revised form 27 February 2018; Accepted 14 March 2018
Available online 30 April 2018
0378-3774/

Soybean is the dominant crop in Mississippi, with harvest area of 8.17×10^5 ha, accounting for 44% of the total crop area in 2014 (NRCS, 2015). Only 25–30% of the soybean area is irrigated (Thomas and Blaine, 2014). Although smaller in soybean irrigated area, Mississippi experienced the largest percentage increase of 92% in irrigated area from 1998 to 2008 among the Mid-South states of USA (NASS, 1999, 2010), and the increasing trend will continue. Current research on defining irrigation for optimum yield can't keep pace with the increase of soybean irrigated area in these states (Vories and Evett, 2014). The soybean producers still confront the dilemma on how much and when water should be applied to obtain optimal yield with available water. Crop water production functions (CWPFs), which express the relation between crop yield and consumptive water use, plant available water, or irrigation water applied, along with the knowledge of temporal crop water demands and deficits, are an effective way to answer these questions. However, CWPFs are crop, site and time specific, and vary considerably among soils and climatic zones (Stewart and Hagan, 1973; Kipkorir et al., 2002; Igbadun et al., 2007). Moreover, the current studies on CWPFs are mainly concentrated in arid or semi-arid regions, much less in humid regions. Hence, it is meaningful to determine soybean CWPFs in a humid region like Mississippi for optimizing irrigation management.

CWPFs have been shown to be a very useful tool to optimize irrigation planning and management strategies, as well as to calculate and compare water use efficiency (Al-Jamal et al., 2000; Kipkorir et al., 2002). With the help of CWPFs, decision makers can calculate the amount of irrigation to meet the evapotranspiration demand during dry spells for targeted crop yield, accounting for rainfall and soil water, or conversely, assess likely grain yield for fixed volumes of water including effective rainfall, irrigation and soil water (Brumbelow and Georgakakos, 2007). Thus, the economic return of different irrigation levels can be estimated by CWPFs when the yield price and crop production costs are known, which supports the decision making on how much irrigation is a profitable investment in a humid region (e.g., Mississippi). The dependent variables in CWPFs are usually biomass or grain yield, while the independent variables are crop actual evapotranspiration (ET_c), irrigation amount (I), or available plant water supply, which is the sum of effective rainfall, plant available soil water and applied irrigation (Hanks, 1974; Al-Jamal et al., 2000; Kipkorir et al., 2002; Brumbelow and Georgakakos, 2007; Tolk and Howell, 2008; Saseendran et al., 2015). The current reports on CWPFs concentrated mainly on crop ET and water issues including precipitation and irrigation. The soil properties which are crucial factors to generate grain yield are much less addressed. There is a need to determine CWPFs under different soil types.

Approaches to determine CWPFs include field experiments and crop modeling. Although the experimental method is ideal, determining multiyear average CWPFs from field experiments is quite expensive and time consuming as it generally requires extensive, long-term experimental data to get reliable results (Russo and Bakker, 1987; Zhang and Oweis, 1999; Brumbelow and Georgakakos, 2007). Even when the CWPFs are derived from long-term field experiments, they are still not geographically portable (Rhenals and Bras, 1981; Clumpner and Solomon, 1987). Process-oriented crop models are an effective approach to overcome these limitations of the field experiments. However, some experimental data are still needed to ground-truth the models in simulating the daily crop growth, grain and biomass yield, and components of water balance (soil water content, runoff, percolation, ET, irrigation and precipitation) for generating the CWPFs (Brumbelow and Georgakakos, 2007; Saseendran et al., 2015). Furthermore, CWPFs developed by a crop model are not single functions, but multiple functions reflecting the variability in weather, soils and locations or multiple-year averaged functions for each soil and location (Van Ittersum et al., 2013). The Agricultural Policy/Environmental eXtender (APEX) is a process-based agricultural system model (Williams et al., 2008; Cavero et al., 2012), which was developed to simulate various agricultural management practices and land use strategies (Borah et al., 2006). Crop growth, production, irrigation, runoff, soil and N management, and water quality have been successfully simulated by APEX model (Wang et al., 2008; Powers et al., 2011; Cavero et al., 2012). APEX is very suitable for developing CWPFs, as it provides three automatic irrigation methods triggered based on soil water deficit, plant water stress and soil water tension (Williams et al., 2012), which support a fast and effective way to determine CWPFs.

Main objectives of this study were to: (1) determine the average CWPFs across 14 years for three soils in a humid region using a modeling approach; (2) examine CWPFs for a wet and a dry year for each soil, (3) develop yield response factors and determine ET, yield and irrigation amount from CWPFs of soybean grown in a humid region.

2. Materials and methods

2.1. The study site

2.1.1. Study area

This study was conducted to simulate conditions in Noxubee County, Mississippi, USA. Soybean is the dominant crop of Noxubee county, grown on 7×10^3 ha, corresponding to 31% of its total cropland (NRCS, 2015). Noxubee county is located in the Blackland Prairie region of Mississippi, which is the major agricultural region in the East Gulf Coastal Plain Section of the Atlantic Plain and it's slightly elevated and hilly. Most of this area is underlain by Createaceous-age clay, marl, soft limestone, or chalk of the Selma Group. The region is characterized as a humid region, with the mean annual rainfall of about 1400 mm over 30 years (1981–2010). The mean daily temperature is about 18 °C and the mean daily solar radiation is 17 MJ m^{-2}. This research was conducted on three dominant agricultural soil types, namely the Vaiden silty clay, Cahaba sandy loam, and Demopolis clay loam, which cover about 79% of the total soybean area in Blackland Prairie, Mississippi (Fig. 1; USDA, 2003).

2.1.2. Field experiments

The field experiments were conducted on a 7.04 ha irrigated field in 2014, and on a 1.2 ha irrigated field in 2015, located in Noxubee County, Mississippi. These experimental fields were conducted on Vaiden (VA), Okolona (OK), Demopolis (DE) and Brooksville (BR) soil types. The experiments consisted of three irrigation treatments both in 2014 and 2015, which utilized a completely randomized block design with four replicates. The size of field experimental plots is 6 rows × 5 m, namely 4.23 m × 5 m. The soil hydraulic properties of saturated hydraulic conductivity (K_{sat}), field capacity (FC) and permanent wilting point (PWP) of the three soil types were used for model inputs in the simulations (Table 1). A soybean group IV cultivar, Asgrow 4632 was planted at 296,525 seeds per hectare for the experimental trials. Soils of VA, OK and DE were provided three irrigation levels of 25.4, 12.7 and 0 mm during the soybean growing season in 2014, while irrigation levels of 114, 57 and 0 mm were supplemented for BR soil for experimental trials in 2015. The irrigation was applied when measured root zone soil moisture is 50% of total plant available water (TAW) in experimental trials. The treatments are defined as (i) 'SM', the amount of irrigation is the water needed to recharge to field capacity; (ii), 'halfSM', only half amount of 'SM' is applied; (iii), 'RF', rainfed or not irrigated. Accordingly, the evaluated treatments were named with acronyms of VARF, OKSM, BRSM, DERF, OKhalfSM and BRhalfSM.

During the growing season, crop height, canopy cover, rooting depth, leaf area, and dry biomass of leaf, stem and root were determined weekly. For measurements of soil hydraulic properties (porosity, soil water retention curve, FC, PWP, and K_{sat}), undisturbed core samples of 5 cm diameter with 1 cm and 6 cm heights, were collected from the soil surface, and at 0–15, 15–30, 30–60 and 60–100 cm depths in both the bed and furrow. Four samples were collected for each soil