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2 **Simulating yield potential by irrigation and yield gap of rainfed soybean using**

3 **APEX model in a humid region**

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Abstract

Soybean is generally grown under rainfed conditions in a humid region, Mississippi, USA. In order to determine how much maximum yield could be increased by irrigation, it is crucial to investigate the yield potential (Y_p) without any drought stress and yield gap (Y_g , between Y_p and rainfed yield (Y_w)). Further, it is also important to determine the amount of irrigation water needed to alleviate any drought stress during the entire growing season, and conduct cost-return analysis for irrigated soybean. Therefore, the objectives of this study were to: (1) simulate Y_p , analyze Y_g and determine the timing and amount needed to achieve Y_p for soybean using the Agricultural Policy/Environmental eXtender (APEX) model; and (2) compute water use efficiency (WUE), irrigation water use efficiency (I_{WUE}) and conduct the cost-return analysis on irrigation events. Simulated Y_p of soybean without water stress for nine soil types from 2002 to 2014 ranged from 4.47 to 6.51 Mg ha⁻¹, and was strongly correlated with accumulative solar radiation during the growing season ($R^2=0.71$, $P\leq 0.01$). The Y_g in dry years was much higher than that in normal and wet years, with average Y_g of 1.58, 0.60 and 0.71 Mg ha⁻¹ for dry, normal and wet years, respectively. Griffith, Sumter and Demopolis soils had the highest average Y_g over 13 years, ranging from 1.37 to 1.60 Mg ha⁻¹. The average irrigation amount was 308, 192 and 157 mm in dry, normal and wet years, respectively. The average irrigation amount was 75 mm from R1 to R8 stages. The WUE of nine soil types from 2002 to 2014, under non-limiting water conditions, ranged from 9.5 to 13.8 kg ha⁻¹ mm⁻¹. The magnitude of Y_g was the principle factor affecting I_{WUE} among nine soil types. The average I_{WUE} over 13 years ranged from 1.8 to 7.8 Kg ha⁻¹ mm⁻¹ for nine soil types. Compared with a rainfed condition, average net return of irrigated soybean increased by 93 \$ ha⁻¹ (dollar per hectare) among nine soil types from 2002 to 2014. The average net return increased by 195, 58 and 70 \$ ha⁻¹ for dry, normal and wet years, respectively.

Keywords: Soybean, Yield potential, Yield gap, Irrigation timing and amount, Irrigation cost-return analysis, APEX model

1. Introduction

Soybean is mostly grown under rainfed conditions in India, USA, south America, and Africa, and drought stress is one of the most important factors limiting crop growth and yield worldwide (Boyer, 1982). However, there is a growing realization that the rainfed soybean productivity must be improved to meet the increasing demand of food for the growing population (Bhatia et al., 2008).

Soybean is an important crop in the USA, approaching the economic values of 40.29 billion dollars, or 29.61% of the total value of production of principal field crops in 2014 (NASS, 2015). The irrigated soybean area in 2012 was only 9.38% of the total harvested cropland area (NASS, 2014). Similarly, soybean is the cash crop in Mississippi, with value of production approximately 2.81 billion dollars, accounting for 50.6% of the total value of production of principal field crops in 2014 (NASS, 2015). Yet, only about 25 to 30 % of Mississippi's soybean crop is irrigated (Thomas and Blaine, 2014). Although low in total area, there has been a rapid increase in area of irrigated soybean in the Mid-South states, especially in Mississippi with the largest percentage increase of 92% occurred from 1998 to 2008 (NASS, 1999, 2010). Furthermore, soybean yield is also increased by supplemental irrigation (Heatherly and Elmore, 1986; Sincik et al., 2008), which is often needed during water stress period to achieve a stable and higher yield even in a humid region (Nijbroek et al., 2003; Karam et al., 2005; Mullen et al., 2009; Garcia y Garcia et al., 2010), because of high variability in rainfall during a growing season (Paz et al., 2007). Thus, it is important to investigate soybean yield potential (Y_p) and how much increase in yield could

be obtained by supplemental irrigation. Furthermore, analysis on the amount, timing and numbers of irrigations determined by crop models using historical weather data could provide guideline for irrigation scheduling to achieve high water use efficiency (WUE) and irrigation water use efficiency (I_{WUE}).

The yield gap (Y_g) is an important agronomic concept (Lobell et al., 2009), and a powerful method to reveal and understand the biophysical potential of a crop to meet the projected increase in demand for food by 2050, and to provide the decision support on research, policies, development and investment (Van Ittersum and Cassman, 2013). Y_g is defined as the difference between yield under optimum management and the average yield achieved by farmers (Van Ittersum and Rabbinge, 1997; Evans, 1998). For example, Bhatia et al. (2008) estimated Y_g of soybean by using the data on potential yields (water non-limiting and water limiting) at 21 locations representing major soybean regions of India. Grassini et al. (2015) measured the Y_g as the difference between Y_p and on-farm yields. Licker et al. (2010) reported that Y_g is the difference between climatic potential yield and the actual yield (Y_a). The difference in yield is determined by growth defining, limiting and reducing factors. In addition, there are four production levels in order of descending productivity. In the production level one, Y_p of irrigated crops without any drought and other stress at all the time is determined by weather conditions such as solar radiation, and temperature regime (Van Ittersum et al., 2013). In the level two, for crops grown under rainfed conditions, the water-limited yield (Y_w) represents the ceiling yield (Van Ittersum and Rabbinge, 1997). In the level three, crop production is limited by both water regime and plant nutrition (Y_n). In the level four, the actual yield (Y_a) is the one that is harvested on a farm. Hence, crop productivity and Y_g can be quantified in terms of the differences of Y_p , Y_w , Y_n and Y_a .

Four methods of estimating the Y_p , Y_w , Y_a and Y_g at a local level (Lobell et al., 2009) include: field experiments, yield contests, maximum farm yields based on surveys, and crop model simulations. Conducting field experiment is time-consuming and expensive to measure Y_g . Further, field experiment must be replicated over several years to obtain confident data on Y_p , Y_w , Y_a , Y_g and their inter-annual variation (Cassman et al., 2003). Yield contest may be affected by any restriction in practice as it is difficult to obtain consistent results in a site-specific research over a long period. If obstacles prevent all surveyed farmers from realizing Y_p or Y_w , then Y_g will be underestimated by using a survey method (Van Ittersum et al., 2013). Since crop productivity is highly affected by the interactions of genetics, weather, soil, and management factors; yield experiments, field contests and survey approaches are not sufficient to estimate a confident Y_p , Y_w , Y_a and Y_g in a site-specific field or an agro-ecological zone because it is hard to consider all the biotic and abiotic stresses.

There have been a rapid development and application of crop growth models since 1990s, which have proven useful in simulating Y_p , Y_w and Y_g (Hoogenboom et al., 1992; Ma et al., 2007; Bhatia et al., 2008; Powers et al., 2011; Lv et al., 2015). Such process-based models have been designed to study the interactions of genetics, environment and management ($G \times E \times M$), which has become a hot research topic to close Y_g and meet projected global food demand (Van Ittersum et al., 2013; Hatfield and Walthall, 2015). Crop growth models can overcome limitations of the above methods (Van Ittersum and Donatelli, 2003; Ma et al., 2007; Bhatia et al., 2008; Grassini et al., 2011; Lv et al., 2015). Van Ittersum et al. (2013) opinioned that crop growth modeling is the most reliable approach to estimate Y_p , Y_w or Y_g of a specific crop because interactions among weather, soils and management are duly considered. Meanwhile, crop simulation models can identify and alleviate limiting factors that affect productivity. Furthermore,

simulated results are not only single values, but comprise a series of data which can be easily used to determine probability distributions with mean, median, range and standard deviation (Van Ittersum et al., 2013; Van Ittersum and Donatelli, 2003). Assessing variation in Y_p , Y_w and Y_g is an effective way to reveal not only differences in field management practices, but also the variability in weather and soil across years and fields.

The Agricultural Policy/Environmental eXtender (APEX) (Williams et al., 2008) is one of such models which can simulate daily crop growth, yield, biomass, leaf area index (LAI), evapotranspiration, components of soil water balance (runoff, percolation, soil water content) under different climatic and soil conditions, and management practices (i.e., irrigation, fertilizer, and pest control). The APEX model was developed to extend the Environmental Policy Integrated Climate (EPIC) model capabilities to entire farms and small watersheds (Williams et al., 2012). The APEX and EPIC models have been widely and successfully used in diverse regions to simulate crop productivity, runoff and sediment losses as affected by soil and water management, and irrigation strategies (Wang et al., 2008; Powers et al., 2011; Cavero et al., 2012).

Soybean irrigation regimes, timing, amount and numbers, have been researched globally (Sionet and Kramer, 1977; Eck et al., 1987; Sweeney et al., 2003; Ucan et al., 2007; Garcia y Garcia et al., 2010). However, in a humid region of Mid-South USA, though irrigated area has increased greatly over several years in response to economic imperatives (risk avoidance) and recurring short and long-term drought conditions, research conducted in the region is scanty compared to that in the western states (Vories and Evett, 2014). Soil properties have a strong impact on outcomes for irrigated agriculture. Variability of soil types and topography within a field in Mid-South raises questions about a suitable irrigation regime, including irrigation timing

and amount (Vories and Evett, 2014). Most importantly, what crop producers concerned is not only the increase in yield, but also the increase in net return by irrigation. Though farmers are confronting the difficult choice whether or not to purchase and install irrigation equipment, few studies exist on cost-benefit analyses of irrigation. Therefore, it is an emerging issue to study irrigation regime (timing and amount) and analyze cost-return by irrigation for soybean production in a humid region of Mississippi, USA.

Therefore, the objectives of this study were to: (1) simulate Y_p without drought stress at any time by irrigation and investigate Y_g between Y_p and Y_w (rainfed yield) for soybean among nine soil types from 2002 to 2014 using the APEX model; (2) determine irrigation timing (growth stages), amount and number of irrigations required to achieve Y_p , and assess WUE , I_{WUE} and components of water balance for soybean grown on nine soil types in different years; and (3) conduct cost-return analysis for irrigated soybean on nine soil types from 2002 to 2014.

2. Materials and Methods

2.1 Study area and field experiments for APEX model

2.1.1 Study area in Noxubee county

The study area is located in Noxubee county, Mississippi, with the soybean crop area of 7100 ha, at about 31% of total cropland area in Noxubee county (NRCS, 2015; Fig. 1). It is a humid region, with 30-year (1981-2010) mean annual rainfall of around 1400 mm. However, the rainfall during the growing season varies from 218 to 627 mm (Table 2). The mean daily temperature is about 18 °C (about 27°C in July and about 9 °C in January) and the mean daily solar radiation is 17 MJ m⁻². This research was conducted on nine dominant agricultural soil types (namely, Vaiden, Catalpa, Leeper, Brooksville, Okolona, Kipling, Griffith, Sumter and Demopolis), covering about 97% of total cropland area in Noxubee county (NRCS, 2003). Soil

texture in 0.50 m surface is clay for Vaiden, clay loam for Demopolis and silty clay for the remaining seven soils (Table 1). The saturated hydraulic conductivity (K_{sat}), field capacity (FC), permanent wilting point (PWP) and soil available water content (AWC) are shown in Table 1.

2.1.2 Field experiment for APEX model

The study utilized data from two irrigated fields in 2014 and 2015 located in Noxubee County, Mississippi. The experiments were conducted on Vaiden (VA), Okolona (OK), Demopolis (DE) and Brooksville (BR) soil types. And, there were three treatments for each soil type which consisted of three irrigation levels during the entire soybean growing season.

Parameters of weather, soil, crop and management required by the APEX model were measured. The weather data including precipitation, air temperature, solar radiation, wind speed and relative humidity were obtained at Macon weather station located in Noxubee county, USA (<http://ext.msstate.edu/anr/drec/stations.cgi>). Undisturbed soil core samples (rings, 1 cm and 6 cm height with 6 cm in diameter) were collected at soil surface, and depths of 0-15, 15-30, 30-60 and 60-100 cm from both bed and furrow for measuring FC, PWP, K_{sat} and bulk density (BD). Soybean crop data on leaf area, the above and below ground biomass, grain yield, root depth and weight in the entire growing stage of soybean were also measured for APEX modeling. The detailed field experiments and irrigation treatments were described by Zhang et al. (2016). The field experiment data of weather, soil, crop and management were used for calibrating and validating APEX model, which have been completed by Zhang et al. (2016). Thus, the calibrated APEX model and crop parameters measured in fields (Zhang et al., 2016) were used in this study for simulating the soybean growth and grain yield under rianfed and irrigation conditions.

2.2 Definition of yield potential and yield gap

The yield potential (Y_p), also called potential yield, is the yield of a crop cultivar when grown under non-limiting water and nutrients and when any biotic stress is effectively controlled (Evans, 1993; Van Ittersum and Rabbinge, 1997; Evans, 1998). Rainfed productivity or water-limited yield (Y_w), equivalent to water-limited potential yield, is the most relevant benchmark. Y_w is defined as the yield when crop growth is limited by plant available water which is affected by soil type and field topography (Van Ittersuma et al., 2013). Y_g is often defined as the difference between Y_p (irrigated crops), or Y_w (rainfed crops) and Y_a (actual field yield) (Ittersuma et al., 2013). However, many current studies have neglected the yield difference between Y_p and Y_w . This article defines Y_g as:

$$Y_g = Y_p - Y_w \quad (1)$$

Where, Y_p is the optimum productivity under water non-limiting irrigation condition; and Y_w is soybean productivity under rainfed condition.

2.3 APEX model and irrigation schedule design

The APEX model (Williams et al., 2008) is a flexible and dynamic tool, and developed to conduct evaluation on all kinds of land management scenarios and identify best management practice (Borah et al., 2006) at whole farm scale or small watershed scale. This study used WinAPEX 0806 version, which is a user-friendly Windows interface designed to assist users in executing APEX. It is a processed and continuous daily time-step model.

The major inputs of APEX include weather data, crop data, soil properties and management. The weather data comprise of daily solar radiation, the maximum and the minimum air temperature, precipitation and wind speed. The crop data to run APEX model is biomass energy ratio or radiation use efficiency, maximum LAI, root depth and crop height, fraction of growing

season when LAI start to decline, and harvest index. Soil properties by layer are depth, BD, FC, PWP, K_{sat} , percentage clay, sand and silt, and soil organic carbon content. The management parameters include all operations, such as date, rate and machine type of plow, planting, fertilization, irrigation, pesticide, harvest, hauling and kill. Besides the biomass and grain yield, the outputs include components of water balance (daily precipitation, irrigation, runoff, percolation, ET_c and soil water content), which are useful to conduct irrigation analysis, planning and management.

For this study, irrigation schedule (timing and amount) was designed to simulate Y_p without water stress. The APEX model has the capability to automatically schedule irrigation for the above goal. The automatic irrigation is triggered based on soil water deficit. The irrigation trigger point (soil water deficit) is calculated as Eq. (2):

$$ITP = \left[(FC - PWP) / 2 + PWP \right] \times D \quad (2)$$

Where, ITP is the automatic irrigation trigger point defined as the largest permitted soil water deficit; FC is water content at field capacity, and PWP is water content at plant permanent wilting point; D is rooting depth, which is set at 0.50 m in this study.

2.4 ET estimating method in APEX

For estimating potential evaporation, five options of Hargreaves and Samani (1985), Penman (1948), Priestley-Taylor (1972), Penman-Monteith (Monteith, 1965), and Baier-Robertson (1965) are provided in the APEX model. The Penman and Penman-Monteith methods require inputs of solar radiation, air temperature, wind speed, and relative humidity (Williams et al., 2012).

If wind speed, relative humidity, and solar radiation data are not available, the Hargreaves or Priestley-Taylor methods can provide realistic results in most cases (Williams et al., 2012). Meanwhile, Penman-Monteith methods is typically applied under windy conditions (Williams et al.,

2012). The simulation study was conducted in a humid region, and weather data used in the simulation are solar radiation, air temperature, wind speed, and relative humidity. Hence, for the above reasons, the Penman (1948) method for estimating potential evaporation is chosen in this paper, which is calculated based on Eq. (3):

$$EO = f(RA, TX, ELEV, U10, RH, AB, RAMX) \quad (3)$$

Where, EO is the potential evaporation (mm d^{-1}), RA is solar radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$), TX is the mean daily air temperature ($^{\circ}\text{C}$), U10 is the mean wind speed at 10 m height (m s^{-1}), RH is the relative humidity, AB is the solar albedo, RAMX is the clear day radiation at the surface ($\text{MJ m}^{-2} \text{ d}^{-1}$).

The APEX model computes evaporation from soils and plants separately (Ritchie, 1972). Potential plant water evaporation is computed by Eq. (4):

$$EP = \begin{cases} LAI \times EO / 3 & 0 < LAI < 3 \\ EO & LAI > 3 \end{cases} \quad (4)$$

Where, EP is the potential plant water evaporation (mm d^{-1}).

The soil water evaporation is calculated based on Eq. (5).

$$SE = \begin{cases} PSE \times e^{-2.5 \times \frac{FC-ST}{FC-PWP}} & PWP < ST < FC \\ PSE & FC \leq ST \end{cases} \quad (5)$$

Where, SE is the soil water evaporation (mm), PSE is the potential soil evaporation (mm), ST is soil water content in the root zone ($\text{cm}^3 \text{ cm}^{-3}$).

Actual evapotranspiration (ET_c) during the growing season is computed by Eq. (6):

$$ET_c = EP + SE \quad (6)$$

2.5 Water use efficiency and irrigation water use efficiency

2.5.1 Water use efficiency

WUE is defined as Eq. (7):

$$WUE = Y_p / ET_c \quad (7)$$

Where, WUE is soybean water use efficiency ($\text{kg ha}^{-1} \text{ mm}^{-1}$), Y_p and ET_c is defined as Eq. (1) and Eq. (6), respectively.

2.5.2 Irrigation water use efficiency

Irrigation water use efficiency (I_{WUE}) is defined as yield per unit irrigation amount (Payero et al., 2008). However, this method does not consider the increment of yield through irrigation as compared with that under rainfed condition. Hence, in this paper, the I_{WUE} was estimated using the method shown in Eq. 8 proposed by Bos (1980, 1985):

$$I_{WUE} = Y_g / I_a \quad (8)$$

Where, Y_g is defined as in Eq. (1) (kg ha^{-1}); and I_a corresponds to the irrigation amount to achieve Y_p under designed irrigation schedule (mm). This method developed by Bos (1980, 1985) provides more consistent data for discriminating the role of irrigation in WUE (Howell, 2001). It also takes into account the yield under rainfed conditions (Garcia y Garcia et al., 2010).

2.6 Cost-return analysis method

The cost-return analysis was conducted using the micro-economic method based on pivot-sprinkler-irrigation equipment (MSU, 2015). The irrigation costs include direct and fixed expenses. Direct expenses include estimated costs of repairs and maintenance for sprinkler equipment and include fuel costs for powered machinery of irrigation. Annual fixed cost estimates for machinery are based on a budgeting technique which computes the annual capital recovery charge. Cost of irrigation and increased returns by irrigation for achieving Y_p are calculated as follows Eq. (9):

$$R_{ij} = Y_{gij} \times P_1 - (I_{ij} \times P_2 + F) \quad (9)$$

Where, R_{ij} is the net return of irrigated soybean as compared to rainfed conditions, $\$ \text{ ha}^{-1}$; i is the order of simulated years, from 2002 to 2014; j is the order of nine soil types as listed above;

Y_{gij} is the yield gap of i_{th} year and j_{th} soil; P_1 is the soybean price in 2014 of Mississippi (USDA-NASS, 2015; 11.1 \$ Mg⁻¹), I_{ij} is the irrigation amount of i_{th} year and j_{th} soil; P_2 is the direct expense per irrigated amount in Noxubee county, Mississippi (0.16 \$ ha⁻¹ mm⁻¹); F is the annual fixed expense for a sprinkler irrigation equipment, (16 \$ ha⁻¹ year⁻¹). P_2 and F are revised and calculated by Department of Agricultural Economics of Mississippi State University (MSU, 2015).

3. Results and Discussion

3.1. Soybean potential productivity without water stress

Simulated soybean potential productivity (Y_p) without any water stress by irrigation didn't differ among nine soil types in each year, with standard deviation (S_d) of nine soil types ranging from 0.00 to 0.02 Mg ha⁻¹ from 2002 to 2014 (Fig. 2). These results are in agreement with those by Van Ittersum et al. (2013) and Egli and Hatfield (2014). Under optimal growing conditions, crop yield is a location specific and determined by climatic factors and genetic traits. Under an optimal condition of nutrition and water, yield is also not significantly affected by soil properties (Van Ittersum et al., 2013). Actually, based on the automatic irrigation schedule in APEX model, there is adequate amount of water to meet the water requirement of soybean. Meanwhile, all simulation scenarios were set without any nutrients stress by management inputs of APEX. The typical field operations on local farms such as planting, seeding rate, tillage and pest control were held constant when simulating the potential productivity of soybean on all nine soils. Thus, the difference in Y_p without any stress among years is attributed to the differences in climatic factors such as solar radiation, temperature and wind speed rather than rainfall.

Simulated Y_p without any water stress on nine soil types from 2002 to 2014 varied broadly from 4.47 to 6.51 Mg ha⁻¹ (Fig. 2). From 2002 to 2014, Y_p was 4.61, 4.89, 4.64, 6.08, 5.58, 5.77,

6.26, 6.51, 4.47, 4.87, 5.14, 5.18 and 5.02 Mg ha⁻¹, respectively (Fig. 2). This wide range of variation in simulated Y_p is not unexpected given varying weather conditions across 13 years and among nine soil types. Grassini et al. (2015) also reported that simulated Y_p of irrigated soybean ranged from 4.4 to 7.1 Mg ha⁻¹ in the U.S. Corn Belt. Meanwhile, the simulated soybean maximum potential yields of 6 to 7 Mg ha⁻¹ have been reported by other researchers (Specht et al., 1999; De Bruin and Pedersen, 2008; Sinclair and Rufty, 2012).

Rainfall during the growing season varied widely over years even in the humid region of Mid-South such as Mississippi (Paz et al., 2007), which in turn contributes to the differences in solar radiation. From 2002 to 2014, large variations were observed in accumulative solar radiation during the growing season, ranging from 2309 to 3634 MJ m⁻² (Fig. 3). The simulated Y_p without any drought stress by irrigation over 13 years showed a significant positive correlation with accumulative solar radiation during the soybean growing season ($R^2 = 0.71$, $P \leq 0.01$, Fig. 3). Spaeth et al. (1987) and Bhatia et al. (2008) also reported similar results in Japan and India, respectively, and observed that higher solar radiation contributed to greater Y_p of soybean.

3.2 Yield gap of rainfed soybean on nine soil types in different category year

The Y_g broadly ranged from 0.19 to 3.35 Mg ha⁻¹ and with an average of 0.86 Mg ha⁻¹ over 13 years across nine soils (Table 2), which is similar to that reported by previous studies on irrigated soybean in India and southeastern USA, with Y_g of 0.85 and 0.92 Mg ha⁻¹, respectively (Bhatia et al., 2008; Garcia y Garcia et al., 2010). Meanwhile, the overall average Y_g of 0.86 Mg ha⁻¹ accounted for 16.2% of the average simulated Y_p , which coincide with the range of 10 % to 30% reported in the western U.S. Corn Belt (Grassini et al., 2014; Grassini et al., 2015). Hence, the yield increase (Y_g) by irrigation in the USA is one of the most important approaches to meet

the projected soybean demands in 2050, as soybean production of 85 Mt annually in the USA accounts for 38% of global soybean production (USDA-NASS, 2014; Hatfield and Walthall, 2015).

3.2.1 Statistic analysis of yield gap in different category year

The category years (wet, normal and dry years) were determined by the empirical frequency analysis method using rainfall during the soybean growing season, and accordingly 2002, 2006 and 2007 were classified as dry years; 2004, 2009, 2010, 2011, 2013 and 2014 as normal years; and 2003, 2005, 2008 and 2012 as wet years (Liu et al., 2013; Zhang et al., 2016).

The data in Table 2 shows that, the Y_g in dry years was much higher than that in normal and wet years, with average Y_g of 1.58, 0.60 and 0.71 Mg ha⁻¹ for dry, normal and wet years, respectively. The median Y_g of dry, normal and wet years was 1.27, 0.21 and 0.35 Mg ha⁻¹, which was lower than average Y_g , indicating uneven distribution of Y_g . Meanwhile, a larger range of Y_g was simulated in dry years as compared to that in normal and wet years, ranging from 0.19 to 3.35, 0.17 to 2.85 and 0.19 to 2.96 Mg ha⁻¹, respectively. As the wet years had a relatively higher rainfed yield (Y_w) of 4.88 Mg ha⁻¹ than that in normal years of 4.51 Mg ha⁻¹ (Zhang et al, 2016), the higher average Y_p in wet years of 5.59 Mg ha⁻¹ as compared to that of 5.11 Mg ha⁻¹ in normal years, was the major reason resulting in average Y_g (or the median Y_g) in wet years being higher than that in normal years. Furthermore, the higher accumulative solar radiation during the growing season of 2909 MJ m⁻² led to higher Y_p in wet years, in comparison with the value of 2671 MJ m⁻² in normal years. The minimum Y_g in dry, normal and wet years was similar and close to 0, while the maximum values of Y_g were different. The maximum Y_g in dry years was higher than that in normal and wet years. Y_g varied greatly in dry years, while variation of Y_g in

normal and wet years was relatively lower, with $\bar{Sd}$ of 1.09, 0.73 and 0.76 Mg ha⁻¹ for dry, normal and wet years, respectively.

The data in Table 2 also demonstrates that average Y_g of nine soil types varied largely from 2002 to 2014, ranging from 0.19 to 2.22 Mg ha⁻¹. The average Y_g was higher in the years 2006, 2007, 2009 and 2008, with values of 1.97, 2.22, 1.58 and 1.59 Mg ha⁻¹, respectively. The high Y_g in 2008 was determined by high Y_p of 6.26 Mg ha⁻¹ (Fig. 2) and relatively low Y_w of 4.67 Mg ha⁻¹ (Zhang et al., 2016). Despite a wet year of 2008 with seasonal rainfall of 508 mm, serious water stress resulted from uneven rainfall distribution evidenced by the rainfall reaching 50 mm two times and reaching 70 mm two times during the growing season (Zhang et al., 2016) was the primarily reason for a relatively low Y_w in 2008. Meanwhile, supplemental irrigation is an effective way to obtain a higher Y_p even in a wet year like 2008. The average Y_g in 2002, 2010, 2011, 2014, 2005 and 2012 was relatively lower, at Y_g of 0.54, 0.80, 0.48, 0.32, 0.66 and 0.38 Mg ha⁻¹, respectively. While the average and median Y_g in 2004, 2013, 2003 were close to 0, indicating that there was no yield difference between Y_p and Y_w in these years among all nine soil types. The median Y_g of nine soil types was smaller than the average Y_g in each year from 2002 to 2014, indicating that the overall value of Y_g was lower than the average value and there also existed some extremely higher values. Meanwhile, the variation of Y_g in 2006, 2007, 2009, 2010 and 2008 was much higher, with $\bar{Sd}$ of 1.01, 0.88, 0.99, 0.83 and 0.98 Mg ha⁻¹, respectively. While, Y_g varied slightly in 2002, 2011, 2014, 2005 and 2012, with $\bar{Sd}$ of 0.28 to 0.49 Mg ha⁻¹. Y_g did not vary in 2004, 2013 and 2003, with $\bar{Sd}$ close to 0.

3.2.2 Characteristics of yield gap on nine soil types

The data in Fig. 4 indicates that Griffith, Sumter and Demopolis soils had the highest average Y_g over 13 years, ranging from 1.37 to 1.60 Mg ha⁻¹. While, averaged Y_g across 13 years for

Vaiden, Catalpa and Leeper was the lowest among nine soil types, ranging from 0.34 to 0.54 Mg ha⁻¹, and for Brooksville, Okolona and Kipling was in the middle, ranging from 0.62 to 0.74 Mg ha⁻¹. The minimum Y_g of 13 years in each of nine soils was similar and close to 0, ranging from 0.17 to 0.20 Mg ha⁻¹. The maximum Y_g was observed for Griffith, Sumter, Demopolis and Leeper with the highest value ranging from 2.84 to 3.35 Mg ha⁻¹; followed by that of Brooksville, Okolona, Kipling and Catalpa ranging from 1.64 to 2.38 Mg ha⁻¹; and that of Vaiden with lowest value of 1.11 Mg ha⁻¹. As the Y_p was the same across nine soils, the Y_w was the direct reason of the difference in Y_g among nine soils. Under rainfed conditions, the soil properties such as AWC, K_{sat} and soil texture probably resulted in variance in Y_w among nine soils. For example, the highest Y_g value for Demopolis was the reason of the lowest Y_w mainly caused by the highest K_{sat} value of 6.85 mm/h (Table 1). Accordingly, the relatively low Y_g values in Vaiden, Catalpa, Leeper, Brooksville and Okolona were probably caused by relatively low K_{sat} values from 1.75 to 2.87 mm/h (Table 1). Therefore, K_{sat} was a major reason to cause Y_g differences among soils. The Y_g of Griffith, Sumter and Demopolis had the largest variation, with S_d of 1.08, 1.17 and 1.17 Mg ha⁻¹, respectively. While the Y_g of Catalpa, Leeper, Brooksville, Okolona and Kipling varied slightly, with S_d from 0.52 to 0.80 Mg ha⁻¹. The lowest variation in Y_g with S_d only of 0.28 Mg ha⁻¹ was observed for the Vaiden soil (Fig. 4).

Y_g in dry years (e.g., 2006 and 2007) had the highest value for each soil type, indicating that water was the major limiting factor, as rainfall in 2006 and 2007 was the lowest for the entire period from 2002 to 2014, with 272 and 218 mm, respectively. Relatively large solar radiation and high temperatures in dry years may contribute to higher Y_p if supplemental irrigation is supplied during the drought stressed period. Y_g of Vaiden, Catalpa and Leeper was large in 2006, 2007, 2008 and 2009, ranging from 0.37 to 2.84 Mg ha⁻¹, respectively. For the remaining nine

years, Y_g of Vaiden, Catalpa and Leeper was similar and ranged from 0.17 to 0.26 Mg ha⁻¹ (Fig. 5).

Y_g of Brooksville and Kipling was also high in 2006, 2007, 2008 and 2009, and ranged from 1.21 to 1.89 Mg ha⁻¹; and 1.58 to 2.38 Mg ha⁻¹, respectively. In 2005 and 2010, Y_g of Brooksville and Kipling was smaller and ranged from 0.27 to 0.43 Mg ha⁻¹. In the remaining seven years, Y_g of Brooksville and Kipling was close to 0.20 Mg ha⁻¹. Y_g of Okolona was large in 2002, 2006, 2007, 2008 and 2009, ranging from 0.98 to 1.64 Mg ha⁻¹. In 2005 and 2010, the Y_g of Okolona was relatively small, with 0.43 and 0.28 Mg ha⁻¹ respectively. In the remaining six years, Y_g of Okolona was close to 0.20 Mg ha⁻¹ (Fig. 5).

In contrast, Y_g of Griffith, Sumter and Demopolis was large in most years from 2002 to 2014. However, Y_g of Griffith, Sumter and Demopolis in 2006, 2007, 2008, 2009 and 2010 was much higher than that in any other years, ranging from 1.75 to 3.35 Mg ha⁻¹; in 2002, 2005, 2011 and 2012, was in the middle, ranging from 0.61 to 1.40 Mg ha⁻¹; and in 2003, 2004 and 2013, was small, ranging from 0.19 to 0.36 Mg ha⁻¹ (Fig. 5).

3.3 Irrigation amount required to achieve soybean potential productivity

3.3.1 Statistical analysis of irrigation demand in different category years

Soybean grown on nine soil types required different amount of irrigation (I_a) each year. The average I_a in dry years was 308 mm, which was significantly greater than 192 and 157 mm in wet and normal years, respectively (Table 3). The average I_a (or the median I_a) in wet years was higher than that in normal years, which attributed to high I_a of 286 mm in the wet year 2008 and only 16 mm I_a in the normal year 2013 caused by specific rainfall pattern during the growing season (Fig. 6). The variation in I_a was the highest in wet years, the smallest in normal years and medium in dry years, with S_d of I_a 96, 87 and 94 mm, respectively (Table 3). The median I_a in

wet years was close to the average I_a , while the median I_a for dry years was higher than the average I_a , indicating that more values were higher than the average I_a . The maximum I_a of 437 mm in dry years was much higher than 333 mm in normal years. The minimum I_a was 86, 0 and 163 mm for wet, normal and dry years, respectively (Table 3). According to Farm and Ranch Irrigation Surveys of USDA, the average irrigation amount for soybean during 1998 to 2003 in Mississippi was 221 mm (Mullen et al., 2009). Hook (1994) reported that the seasonal irrigation requirements for soybean ranged from 180 to 310 mm in a humid region of Georgia, USA in 15 drought years between 1938 and 1996. Sincik et al. (2008) applied 617 mm for a full season irrigated treatment in a sub-humid region in Turkey. Garcia y Garcia et al. (2010) applied 78 to 137 mm of water for soybean to obtain Y_p in Georgia, USA. Hence, even in a humid region, the supplemental irrigation amount to achieve Y_p varies greatly from 78 to 617 mm as a result of variable annual precipitation during a long period and the uneven distribution of rainfall during the soybean growing season. Therefore, the results on irrigation requirements from 0 to 437 mm (Table 3) agree with previous results, considering the long duration of 13 years and nine soils in the present simulations.

The average I_a required by soybean on the nine soil types was the highest, 378 and 364 mm in 2006 and 2007, respectively (Fig. 6). The minimum and maximum value of I_a were 356 and 401 mm in 2006, and 318 and 437 mm in 2007, respectively. These trends also indicate that I_a in 2006 and 2007 had the highest values over the 13 years period from 2002 to 2014 because of the least rainfall received in these periods (Table 2). The average I_a in 2005, 2008 and 2009 was similar and relatively higher, ranging from 271 to 286 mm. The higher amount of irrigation in 2005, 2008, 2009, 2006 and 2007 was related to the water requirement (ET_c) in these periods, which ranged from 498 to 609 mm (Fig. 7). The other reason of the higher amount of irrigation

in 2005, 2008 and 2009 was the higher water losses caused by higher runoff and percolation in these years. Low rainfall in 2006 and 2007 caused the high irrigation demand in these two years (Fig. 7). The average I_a in 2002 and 2010 was similar, with values of 183 and 211 mm, respectively. Though ET_c in 2010 was lower at 381 to 432 mm among nine soils, rainfall losses due to runoff and percolation resulted in a higher I_a in 2010 (Fig. 7). The average I_a in 2004 and 2011 was similar at 161 and 160 mm, respectively. Meanwhile, the average I_a in 2003, 2012 and 2014 was smaller and similar to each other, and ranged from 104 to 121 mm (Fig. 6). The year 2013 may be a special situation as I_a of seven soils was 0, except for Okolona and Griffith with I_a of 25 and 123 mm, respectively (Fig. 6). The average I_a in 2013 was the lowest at only 16 mm, which was probably due to high effective rainfall and low ET_c ranging from 385 to 439 mm (Fig. 7). In addition, the lower AWC may be the reason that Okolona and Griffith soils needed supplemental irrigation in 2013 (Table 1).

The I_a in 2002, 2003, 2004, 2006 and 2012 varied slightly, and $S\bar{d}$ ranged from 14 to 28 mm. In comparison, I_a in 2008 varied widely, with $S\bar{d}$ of 58 mm. Meanwhile, I_a had a relatively low variation in 2005, 2007, 2009, 2010, 2011, 2013 and 2014, with $S\bar{d}$ of only 37 to 45 mm (Fig. 6).

3.3.2 Difference of irrigation amount among soils

The difference between the maximum and minimum I_a (ΔI_a) among nine soil types in each year could explain the discrepancy of irrigation amount required for achieving Y_p without any drought stress. The I_a varied greatly among nine soils in 2008, with ΔI_a of 161 mm; while gently in 2002 with ΔI_a of 39 mm (Fig. 6). The discrepancy of I_a among soils in the same year is the interaction effect of runoff and percolation determined by soil properties (i.e. FC, PWP, AWC and K_{sat}). For example, Demopolis soil had the highest percolation of 156 mm as the highest K_{sat} of 6.85 mm/h among nine soils in 2008, while the runoff was the second lowest of 78 mm (Table

1; Fig. 7). Accordingly, the irrigation amount of Demopolis-clay loam in 2008 was in the middle at 279 mm, compared with the lowest value of 209 mm for Kipling and the highest value of 370 mm for Leeper. Similarly, Okolona and Griffith in 2008 had higher percolation of 91 and 130 mm, respectively, as the lowest AWC of 0.10 and 0.12 m/m; and the runoff is 137 and 155 mm (Table 1; Fig. 7). However, the I_a of Okolona and Griffith in 2008 differed widely, with the third lowest value of 254 mm and the second highest value of 326 mm, respectively (Fig. 7).

Even for the same seven soils of silty clay, the I_a in 2008 varied widely from 209 mm for Kipling-silty clay to 370 mm for Leeper-silty clay because of difference in soil properties (i.e. FC, PWP, AWC and Ksat) (Fig. 7). While, I_a varied gently among soils in 2002, ranging from 163 mm for Leeper-silty clay to 202 mm for Vaiden-clay (Fig. 7). All in all, I_a varied year by year because of the uneven rainfall and differed among soils as the effect of soil properties; and such difference may be the reason for diversity of Y_g (Fig. 5).

3.3.3 Irrigation timing trend at each growth stage

In general, soybean needed irrigation at R2, R3, R4, R5, R6 and R7 growth stages, which accounted for 97% of total numbers of irrigation among nine soil types from 2002 to 2014 (Fig. 8). The number of irrigation events occurred at R2, R3, R4, R5, R6 and R7 stage was 48, 34, 34, 98, 70 and 19 over 13 years, respectively. These results agreed the previous studies and indicated that drought stress during reproductive stages led to decrease in soybean yield (Sionet and Kramer, 1977; Kadhmet al., 1985; Eck et al., 1987), while avoiding irrigation during the vegetative stages could produce yields as high as those fully irrigated during the entire growing season (Ashley and Ethridge, 1978; Heatherly, 1983; Elmore et al., 1988; Spetch et al., 1989). Thus, drought stress during the less critical growing stages (vegetative stages) can be acceptable,

however, irrigation is essential to alleviate drought stress during the critical reproductive stages for ensuring a high soybean grain yield.

The number of irrigation required on nine soil types during growing stages of R5 and R6 from 2002 to 2014 was 98 and 70, respectively. The highest probability of irrigation was 31% for R5 and 22% for R6. These data indicated that drought stress during R4 to R6 stages was the most detrimental to soybean yield (Korte et al., 1983; Stegman et al., 1990) and a single irrigation at R5 or R6 stages can increase yield by 20% compared with rainfed conditions (Sweeney et al., 2003). Therefore, supplemental irrigations during R4 to R6 stages produce the highest yield. Accordingly, the amount of irrigation used was approximately 75 mm when averaged over reproductive stages R1-R8 in the 13 years. While the average amount of irrigation for the V3 stage was only 45 mm across nine soil types from 2002 to 2014 (Fig. 8).

3.4 Water use efficiency and irrigation use efficiency

3.4.1 Water use efficiency

The *WUE* of nine soil types from 2002 to 2014 under non-limiting water condition is shown in Fig. 9, and ranged from 9.5 to 13.8 kg ha⁻¹ mm⁻¹, which are relatively higher than the *WUE* of 9.1 kg ha⁻¹ mm⁻¹ in Nebraska, USA (Grassini et al., 2015). One of the important reasons of this discrepancy may be that the supplemental irrigations mainly occurred during reproductive stages (R2-R7), and this process may increase *WUE* by eliminating irrigation during the vegetative stages (Neyshabouri and Hatfield, 1986). With large variation among years, the average *WUE* of nine soil types in each year ranged from 10.1 kg ha⁻¹ mm⁻¹ in 2006 to 13.1 kg ha⁻¹ mm⁻¹ in 2011. The *WUE* in 2011, 2012 and 2013 was the highest among 13 years, with an average *WUE* ranging from 12.5 to 13.1 kg ha⁻¹ mm⁻¹. Because the Y_p in 2011, 2012 and 2013 was relatively low (Fig. 2), the higher *WUE* in these years may be caused by lower ET_c (Fig. 7) resulting from

the lower accumulative solar radiation (2518 to 2728 MJ m⁻²) during the growing season. The *WUE* in 2003, 2004 and 2006 was lower compared to other years, with average *WUE* from 10.1 to 10.6 kg ha⁻¹ mm⁻¹. The low *WUE* may be due to lower *Y_p* in 2003 and 2004 (Fig. 2), while the higher accumulative solar radiation during the growing season might be responsible for a higher yield in 2006. The average *WUE* in 2002, 2005, 2008, 2009 and 2010 was in the medium ranging from 10.9 to 11.4 kg ha⁻¹ mm⁻¹.

With regards to soil type, *WUE* was the highest in each year for Okolona and Griffith; medium for Vaiden, Brooksville, Kipling and Demopolis; and the lowest for Catalpa, Leeper and Sumter (Fig. 9). Because *Y_p* in each year was the same (Fig. 2), the difference in *WUE* of nine soil types in each year may be attributed to difference in *ET_c*. Furthermore, the simulated LAI during the growing season did not differ in each year, causing no difference in plant water evaporation (Eqs 3-4). Hence, according to the equation of *ET_c* (Eq. 6), the *WUE* of nine soil types in each year was mainly affected by soil water evaporation in relation to soil property including ST, FC and PWP (Eq. 5). Therefore, the low AWC (difference of FC and PWP) of Okolona and Griffith (0.10 and 0.12 m/m, respectively, Table 1), was probably the main reason of the highest *WUE* among nine soil types in each year. These results suggest that *WUE* can be improved by managing soils through conservation tillage, preserving topsoil depth and maintaining soil profile (Tanaka, 1990; Hatfield et al., 2001), which can increase crop yield to meet projected global food needs in 2050.

3.4.2 Irrigation water use efficiency

Data in Fig. 10 shows that the *I_{WUE}* in 2006, 2007, 2008 and 2009 was relatively high, with average *I_{WUE}* of nine soil types of 5.3, 6.0, 5.5 and 5.7 kg ha⁻¹ mm⁻¹, respectively. The *I_{WUE}* in 2003 and 2004 was relatively low, with average of nine soil types of 2.1 and 1.5 kg ha⁻¹ mm⁻¹,

respectively. While, the I_{WUE} in 2002, 2011, 2012 and 2014 was medium, with average of nine soil types ranging from 2.4 to 3.7 kg ha⁻¹ mm⁻¹. The I_{WUE} in 2003 and 2004 was moderately variable, with $\bar{Sd}$ of 0.5 and 0.4 kg ha⁻¹ mm⁻¹, respectively. In the remaining eleven years, I_{WUE} varied largely with $\bar{Sd}$ ranging from 1.7 to 3.8 kg ha⁻¹ mm⁻¹ (Fig. 10), indicating large differences in efficient use of water, yield, or ET_c among the nine soil types.

The average I_{WUE} of 13 years ranged from 1.8 to 7.8 Kg ha⁻¹ mm⁻¹ for the nine soil types (Fig. 11). Griffith, Sumter and Demopolis had relatively higher I_{WUE} across nine soil types, with average I_{WUE} of 5.3, 5.8 and 7.8 kg ha⁻¹ mm⁻¹ respectively. I_{WUE} of Brooksville, Okolona and Kipling was medium, with average I_{WUE} of 2.7, 2.7 and 3.6 kg ha⁻¹ mm⁻¹, respectively. However, Vaiden, Catalpa and Leeper had relatively lower I_{WUE} , with average I_{WUE} of 1.8, 1.8 and 2.1 kg ha⁻¹ mm⁻¹, respectively. The error bar indicated that I_{WUE} of Kipling, Griffith, Sumter and Demopolis varied widely with $\bar{Sd}$ from 2.4 to 3.0 kg ha⁻¹ mm⁻¹. The I_{WUE} of Leeper, Brooksville and Okolona varied slightly, with $\bar{Sd}$ from 1.7 to 1.8 kg ha⁻¹ mm⁻¹, and that of Vaiden and Catalpa had lower variation with $\bar{Sd}$ of 0.7 and 1.2, respectively (Fig. 11). Large difference between the maximum and minimum values of I_{WUE} as well as high $\bar{Sd}$ suggest that these soils are sensitive to climate change, and weather play a critical role in utilization of rain and irrigation water for different soils.

In the full season irrigated experiment on soybean conducted in a humid region of Georgia, southeastern USA, Garcia y Garcia et al. (2010) reported that the I_{WUE} was as low as 5.5 kg ha⁻¹ mm⁻¹ and as high as 11.4 kg ha⁻¹ mm⁻¹ for maturity group VI, and 2.0 to 9.0 kg ha⁻¹ mm⁻¹ for maturity group V. I_{WUE} was 3.1 to 11.5 kg ha⁻¹ mm⁻¹ for the same region in Mississippi (Heatherly and Elmore, 1986), and Casa and Lo Cascio (2008) reported that I_{WUE} was 3.0 to 7.1 kg ha⁻¹ mm⁻¹ in a 2-year field study in Italy. Thus, the results presented herein had a wider range

and were relatively lower than the previous results, as the I_{WUE} was 0.6 to 11.2 kg ha⁻¹ mm⁻¹ over nine soils across 13 years from 2002 to 2014 (Fig. 11). These wide range and low values for I_{WUE} may be contributed by the simulations with a long-term period of 13 years and nine soils compared with only two or three years' field experiment and only one soil type in the above studies. Differences may be also due to a wider range of irrigation applied in the present study, from 0 to 437 mm over nine soils from 2002 to 2014, while Garcia y Garcia et al. (2010) used only 78 to 137 mm for the entire growing season. Meanwhile, the I_{WUE} was highly correlated with Y_g among nine soil types across 13 years, with R^2 of 0.75 (Fig. 12). Hence, the difference in Y_g was the primary reason for difference in I_{WUE} among nine soil types. Soybean could use available water more efficiently in the soil where Y_g was large.

3.5 Cost-return analysis on irrigation

The data in Table 4 show that the average net return of irrigated soybean can be increased by approximately 93 \$ ha⁻¹ (dollar per hectare) for all nine soil types from 2002 to 2014, as compared to rainfed conditions. On average, irrigation can increase net returns by 195, 58 and 70 \$ ha⁻¹ in dry, normal and wet years, respectively (Table 4). Hence, supplemental irrigation is an effective way to increase net return even in the wet years. The results demonstrate that irrigation can significantly increase soybean grain yield as well as net profits even in a humid region like Mississippi, which are consistent with those reported by Heatherly. (1983) and Salassi et al. (1984).

The average net return of nine soil types varied greatly from 2002 to 2014, ranging from -4 to 292 \$ ha⁻¹. In comparison with rainfed conditions, supplemental irrigation was profitable in all years from 2002 to 2014 except in 2004 (Table 4). The lower Y_g of 0.23 Mg ha⁻¹ and relatively higher I_a of 161 mm were the major reasons that supplemental irrigation was not profitable in

2004. Furthermore, the lower Y_g in 2004 was primarily due to the relatively even rainfall distribution during the growing season. The average net return was the highest in 2006 and 2007, at 249 and 292 \$ ha⁻¹, respectively, indicating supplemental irrigation can eliminate extreme dry conditions, increase grain yield covering the cost of irrigation and enhance net return. Even in a wet year 2008, supplemental irrigation can alleviate water stress caused by uneven rainfall distribution and produced a higher net return of 200 \$ ha⁻¹.

The average net return of 13 years also varied greatly among nine soil types, ranging from 12 to 216 \$ ha⁻¹. Vaiden, Catlapa and Leeper soils had the lowest increase in average net return, ranging from 12 to 39 \$ ha⁻¹. Brooksville, Okolona, and Kipling soils had the middle average net return, of 56 to 79 \$ ha⁻¹. While Griffith, Sumter and Demopolis soils had the highest net return of 172 to 216 \$ ha⁻¹ through irrigation (Table 4). Considering the small difference in average I_a of 170 to 233 mm, the difference in Y_g was the primary reason for net return discrepancy among nine soils. As Y_p didn't depend on soils, the Y_w values related to soil properties resulted differences in net return among nine soils.

4. Conclusions

The agroecosystem APEX model can be applied to understand the impacts on soybean productivity by interaction of weather conditions, soil types and irrigation management, which was helpful to close the yield gap. The data presented support the following conclusions:

(1) Soybean yield potential (Y_p) without water stress by irrigation on nine soils in each year was similar for 2002 to 2014, with $\bar{Sd}$ ranging from 0 to 0.02 Mg ha⁻¹. The difference in Y_p is attributed to climatic factors such as solar radiation, temperature and wind speed rather than rainfall and soil types.

(2) Compared with rainfed soybean, the yield increase by irrigation (yield gap, Y_g) ranged greatly from 0.17 to 3.35 Mg ha⁻¹. The nine soils had a large average Y_g variance from 0.34 to 1.60 Mg ha⁻¹, and the saturated hydraulic conductivity was an important factor to result in Y_g difference by affecting rainfed productivity.

(3) The supplemental irrigation was primarily applied at R2, R3, R4, R5, R6 and R7 stages, which accounted for 97% of total irrigation events for nine soil types from 2002 to 2014. Growing stages R5 and R6 had the highest probability to receive irrigation, accounting for 31% and 22% of total irrigation events, respectively. The average irrigation amount was 75 mm from R1 to R8. While V3 had an average of only 45 mm of irrigation among nine soils from 2002 to 2014.

(4) Across nine soil types, WUE in each year was the highest for Okolona and Griffith; medium for Vaiden, Brooksville, Kipling and Demopolis; and the least for Catalpa, Leeper and Sumter. The Y_g was the principal reason for the difference in irrigation water use efficiency (I_{WUE}) among nine soil types. The highest I_{WUE} was observed in Griffith, Sumter and Demopolis, with average values of 5.3, 5.8 and 7.8 kg ha⁻¹ mm⁻¹, respectively. On the contrary, I_{WUE} was relatively lower for Vaiden, Leeper and Catalpa soils.

(5) Irrigation can significantly increase soybean grain yield as well as net profits even in a humid region of Mississippi. Relatively lower increase in average net return was observed for Vaiden, Catalpa and Leeper, ranging from 12 to 39 \$ ha⁻¹. In comparison, Griffith, Sumter and Demopolis had a relatively higher increase in average net return, ranging from 172 to 216 \$ ha⁻¹. Considering the small difference in average I_a of 170 to 233 mm, the difference in Y_g was the primary reason for net return discrepancy among nine soils. As Y_p didn't depend on soils, the Y_w values related to soil properties resulted differences in net return among nine soils.

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Reference

- Ashley, D.A., Ethridge, W.J., 1978. Irrigation effects on vegetative and reproductive development of three soybean cultivars. *Agron. J.* 70, 467–471.
- Baier, W., Robertson, G.W., 1965. Estimation of latent evaporation from simple weather observations. *Can. J. Plant Sci.* 45, 276-284.
- Bhatia, V.S., Singh, P., Wani, S.P., Chauhan, G.S., Kesava Rao, A.V.R., Mishra, A.K., Srinivas K., 2008. Analysis of potential yields and yield gaps of rainfed soybean in India using CROPGRO-Soybean model. *Agr. Forest Meteorol.* 148, 1252–1265.
- Borah, D.K., Yagow, G., Saleh, A., Barnes, P.L., Rosenthal, W., Krug, E.C., Hauck, L.M., 2006. Sediment and nutrient modeling for TMDL development and implementation. *Trans. ASABE* 49 (4), 967–986.

651 Bos, M.G., 1980. Irrigation efficiencies at crop production level. *ICID Bull.* 29, 18–25, 60.

652 Bos, M.G., 1985. Summary of ICID definitions of irrigation efficiency. *ICID Bull.* 34, 28–31.

653 Boyer, J.S., 1982. Plant productivity *Environ. Sci.* 218, 443–448.

654 Casa, R., Lo Cascio, B., 2008. Soil conservation tillage effects on yield and water use efficiency
655 on irrigated crops in central Italy. *J. Agron. Crop Sci.* 194, 310–319.

656 Cassman, K.G., Dobermann, A., Walters, D.T., Yang, H.S., 2003. Meeting cereal demand while
657 protecting natural resources and improving environmental quality. *Ann. Rev. Environ.*
658 *Resour.* 28, 315–358.

659 Cavero, J., Barros, R., Sellam, F., Topcu, S., Isidoro, D., Hartani, T., Lounis, A., Ibrikci, H.,
660 Cetin, M., Williams, J.R., Aragüés, R., 2012. APEX simulation of best irrigation and N
661 management strategies for off-site N pollution control in three Mediterranean irrigated
662 watersheds. *Agric. Water Manage.* 103, 88–89.

663 De Bruin, J.L., Pedersen, P., 2008. Soybean seed yield response to planting date and seeding rate
664 in the Upper Midwest. *Agron. J.* 100, 696–703.

665 Eck, H.V., A.C. Mathers, and J.T. Musick. 1987. Plant water stress at various growth stages and
666 growth and yield of soybeans. *Field Crops Res.* 17, 1–16.

667 Egli, D.B., Hatfield, J.L., 2014. Yield gaps and yield relationships in central U.S. soybean
668 production systems. *Agron. J.* 106:560–566.

669 Elmore, R.W., Eisenhauer, D.E., Spetch, J.A., Williams, J.H., 1988. Soybean yield and yield
670 component response to limited capacity sprinkler irrigation system. *J. Prod. Agric.* 1, 196–
671 201.

672 Evans, L.T., 1993. *Crop Evolution, Adaptation, and Yield.* Cambridge University Press,
673 Cambridge, UK.

674 Evans, L.T., 1998. *Feeding the Ten Billion; Plants and Population Growth.* Cambridge
675 University Press, UK.

676 Garcia y Garcia, A., Persson, T., Guerra, L.C., Hoogenboom, G, 2010. Response of soybean
677 genotypes to different irrigation regimes in a humid region of the southeastern USA.
678 *Agric. Water Manage.* 97, 981–987.

679 Grassini, P., Thorburn, J., Burr, C., Cassman, K.G., 2011. High-yield irrigated maize in the
680 Western U.S. Corn-Belt: I. On-farm yield, yield-potential, and impact of management
681 practices. *Field Crops Res.* 120, 142–150.

682 Grassini, P., Torrión, J.A., Cassman, K.G., Yang, H.S., Specht, J.E., 2014. Drivers of spatial and
683 temporal variation in soybean yield and irrigation requirements. *Field Crops Res.* 163, 32–
684 46.

685 Grassini, P., Torrión, J.A., Yang, H.S., Jennifer Rees, Daryl Andersen, Kenneth G. Cassman,
686 James E. Specht. 2015. Soybean yield gaps and water productivity in the western U.S.
687 Corn Belt. *Field Crops Res.* 179, 150–163.

688 Hargreaves, G.H., Samani, Z.A., 1985. Reference crop evapotranspiration from temperature.
689 Applied Engr. Agric. 1, 96-99.

690 Hatfield, J.L., T.J. Sauer, and J.H. Prueger. 2001. Managing soils for greater water use efficiency:
691 A review. Agron. J. 93:271–280.

692 Hatfield, J.L., Walthall, C. L., 2015. Meeting Global Food Needs: Realizing the Potential via
693 Genetics × Environment × Management Interactions. Agron. J. 107:1215–1226.

694 Heatherly, L.G. 1983. Response of soybean cultivars to irrigation of a clay soil. Agron. J. 75,
695 859–864.

696 Heatherly, L.G., Elmore, C.D., 1986. Irrigation and planting date effects on soybean grown on
697 clay soil. Agron. J. 78, 576–580.

698 Hoogenboom, G., Jones, J.W., Boote, K.J., 1992. Modeling growth, development and yield of
699 grain legumes using Soygro, Pnutgro, and Beangro: A review. Trans. ASAE 35(6), 2043-
700 2056.

701 Hook, J.E., 1994. Using Crop Models to plan water withdrawals for irrigation in drought years.
702 Agric. Syst. 45, 271-289.

703 Howell, T.A., 2001. Enhancing water use efficiency in irrigated agriculture. Agron. J. 93, 281–
704 289.

705 Kadhem, F.A., Specht, J.E., Williams, J.H., 1985. Soybean irrigation serially timed during stages
706 R1 to R6. II. Yield component responses. Agron. J. 77, 299-304.

707 Karam, F., Masaad, R., Sfeir, T., Mounzer, O., Rouphael, Y., 2005. Evapotranspiration and seed
708 yield of field grown soybean under deficit irrigation conditions. Agric. Water Manage. 75
709 (3), 226–244.

710 Korte, L.L., Williams J.H., Specht, J.E., Sorensen, R.C., 1983. Irrigation of soybean genotypes
711 during reproductive ontogeny. I. Agronomic responses. Crop Sci. 23, 521–527.

712 Licker, R., Johnston, M., Foley, J.A., Barford, C., Kucharik, C.J., Monfreda, C., Ramankutty, N.,
713 2010. Mind the gap: how do climate and agricultural management explain the ‘yield gap’
714 of croplands around the world?. Global Ecol. Biogeogr. 19, 769–782.

715 Liu, Y., Jiang, H., Li, C., Huang, H., Pan, Z., Chai, C., 2013. Analysis of irrigation water
716 requirement and irrigation requirement index for cotton of Hebei province. Transactions
717 of the CSAE. 29(19), 98–104.

718 Lobell, D.B., Cassman, K.G., Field, C.B., 2009. Crop yield gaps: their importance, magnitudes,
719 and causes. Ann. Rev. Environ. Resour. 34, 179–204.

720 Lv, S., Yang, X., Lin, X., Liu, Z., Zhao, J., Li, K., Mu, C., Chen, X., Chen, F., Mi, G., 2015.
721 Yield gap simulations using ten maize cultivars commonly planted in Northeast China
722 during the past five decades. Agr. Forest Meteorol. 205, 1–10.

723 Ma, L., Malone, R.W., Heilman, P., Jaynes, D.B., Ahuja, L.R., Saseendran, S.A., Kanwar, R.S.,
724 Ascough II, J.C, 2007. RZWQM simulated effects of crop rotation, tillage, and controlled
725 drainage on crop yield and nitrate-N loss in drain flow. Geoderma. 140, 260–271.

726 Monteith, J.L., 1965. Evaporation and environment. *Symp. Soc. Exp. Biol.* 19, 205-234.

727 MSU, 2015. Soybeans 2015 planning budget: Mississippi State University, Department of
728 Agricultural Economics, Budget Report. 2014.

729 Mullen, J.D., Yu, Y., Hoogenboom, G., 2009. Estimating the demand for irrigation water in a
730 humid climate: A case study from the southeastern United States. *Agric. Water Manage.*
731 96, 1421–1428.

732 NASS, 1999. ‘1997 census of agriculture, farm and ranch irrigation survey’, Vol. 3, 1998, AC-
733 97-SP-1, US Department of Agric. National Agricultural Statistics Service, Washington,
734 DC.

735 NASS, 2010. ‘2007 census of agriculture, farm and ranch irrigation survey’, Vol. 3. 2008, AC-
736 07-SS-1, US Department of Agric. National Agricultural Statistics Service, Washington,
737 DC.

738 NASS, 2014. 2012 Census of Agriculture, 2012 Census Ag Atlas Maps.
739 Maps http://www.agcensus.usda.gov/Publications/2012/Online_Resources/Ag_Atlas_Maps/Crops_and_Plants/. US Department of Agric. National Agricultural Statistics Service,
740 Washington, DC.

741

742 NASS, 2015. Mississippi Crop Values Report.
743 http://www.nass.usda.gov/Statistics_by_State/Mississippi/Publications/Crop_Releases/Crop_Values/2014/mscrpval14.pdf. United States Department of Agriculture, National
744 Agricultural Statistics Service, Cooperating with the Mississippi Department of
745 Agriculture and Commerce. Jackson, MS.

746

747 Neyshabouri, M.R., Hatfield J.L., 1986. Soil water deficit effects on semi-determinate and
748 indeterminate soybean growth and yield. *Field Crops Res.* 15, 73–84.

749 Nijbroek, R., Hoogenboom, G., Jones, J.W., 2003. Optimizing irrigation management for a
750 spatially variable soybean field. *Agric. Syst.* 76 (1), 359–377.

751 NRCS, 2015. Geospatial Data Gateway. USDA Natural Resource Conservation Service.
752 Available at: <https://gdg.sc.egov.usda.gov/>. Accessed 19 March 2015.

753 Payero, J.O., Tarkalson, D.D., Irmak, S., Davison, D., Petersen, J.L., 2008. Effect of irrigation
754 amounts applied with subsurface drip irrigation on corn evapotranspiration, yield, water
755 use efficiency, and dry matter production in a semiarid climate. *Agric. Water Manage.* 95,
756 895-908.

757 Paz, J.O., Fraisse, C.W., Hatch, L.U., Garcia y Garcia, A., Guerra, L.C., Uryasev, O.,
758 Bellow, J.G., Jones, J.W., Hoogenboom, G., 2007. Development of an ENSO-based
759 irrigation decision support tool for peanut production in the southeastern US. *Comput.*
760 *Electron. Agric.* 55 (1), 28–35.

761 Penman, H.L., 1948. Natural evaporation from open, bare soil and grass. *Proc. Soc. London Ser.*
762 A193, 120-145.

763 Powers, S.E., Ascoug, J.C., Nelsonc, R.G., Larocque, G.R., 2011. Modeling water and soil
 764 quality environmental impacts associated with bioenergy crop production and biomass
 765 removal in the Midwest USA. *Ecol. Model.* 222, 2430–2447.

766 Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation
 767 using large-scale parameters. *Mon. Weather Rev.* 100, 81-92.

768 Ritchie, J.T., 1972. A model for predicting evaporation from a row crop with incomplete cover.
 769 *Water Resources Res.* 8, 1204-1213.

770 Salassi, M.E., Musick, J.A., Heatherly, L.G., Hamill, J.G., 1984. An economic analysis of
 771 soybean yield response to irrigation of Mississippi River Delta soils. *Mississippi Agric.*

772 Sincik, M., Candogan, B.N., Demirtas, C., Büyükacangaz, H., Yazgan, S., Göksoy, A.T., 2008.
 773 Deficit irrigation of soybean [*Glycine max* (L.) Merr.] in a sub-humid climate. *J. Agron.*
 774 *Crop Sci.* 194, 200–205.

775 Sinclair, T.R., Rufty, T.W., 2012. Nitrogen and water resources commonly limit crop yield
 776 increases, not necessarily plant genetics. *Global Food Secur.* 1, 94–98.

777 Sionet, N., Kramer, P.J., 1977. Effect of water stress during different stages of growth of
 778 soybean. *Agron J.* 69, 274-278

779 Spaeth, S.C., Sinclair, T.R., Ohnuma, T., Konno, S., 1987. Temperature, radiation, and duration
 780 dependence of high soybean yields: measurement and simulation. *Field Crops Res.* 16,
 781 297–307.

782 Specht, J.E., Hume, D.J., Kumudini, S.V., 1999. Soybean yield potential—a genetic and
 783 physiological perspective. *Crop Sci.* 39, 1560–1570.

784 Spetch, J.E., Elmore, R.W., Enseihauer, D.E., Klocke, N.W., 1989. Growth stage scheduling
 785 criteria for sprinkler-irrigated soybeans. *Irrig. Sci.* 10, 99–111.

786 Stegman, E.C., Schatz B.G., and Gardner J.C., 1990. Yield sensitivities of short season soybeans
 787 to irrigation management. *Irrig. Sci.* 11:111–119.

788 Sweeney, D.W., Long, J.H., Kirkham, M.B., 2003. A single irrigation to improve early maturing
 789 soybean yield and quality. *Soil Sci. Soc. Am. J.* 67, 235–240.

790 Tanaka, D.L., 1990. Topsoil removal influences on spring wheat water- use efficiency and
 791 nutrient concentration and content. *Trans ASAE.* 33:1518–1524.

792 Thomas, J.G., Blaine, A., 2014. Extension Service of Mississippi State University, cooperating
 793 with USDA. <http://msucare.com/pubs/publications/p2185.htm>.

794 Ucan, K., Killi, F., Gencoglan, C., Merdun, H., 2007. Effects of irrigation frequency and amount
 795 on water use efficiency and yield of sesame under field conditions. *Agric. Water Manage.*
 796 101, 249–258.

797 USDA–NASS, 2014. Crops U.S. State and County Databases. USDA–NASS, Washington, DC.
 798 Available from <http://www.nass.usda.gov/index.asp> (accessed Aug 1, 2014).

799 USDA-NASS, 2015. United States Department of Agriculture–National Agricultural Statistics
800 Service, http://www.nass.usda.gov/Statistics_by_State/Mississippi/Publications/Crop_Releases/Crop_Values/2014/mscrpvall4.pdf (Accessed February 24, 2015).
801

802 Van Ittersum, M.K., Cassman, K.G., 2013. Yield gap analysis-Rationale, methods and
803 application-introduction to the special issue. *Field Crops Res.* 143, 1-3.

804 Van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Titttonell, P., Hochman, Z., 2013.
805 Yield gap analysis with local to global relevance-A review. *Field Crops Res.* 143, 4–17.

806 Van Ittersum, M.K., Donatelli, M., 2003. Cropping system models: science, software and
807 applications special issue. *Eur. J. Agron.* 18, 187–393.

808 Van Ittersum, M.K., Rabbinge, R., 1997. Concepts in production ecology for analysis and
809 quantification of agricultural input-output combinations. *Field Crops Res.* 52, 197–208.

810 Vories, E.D., Evett S.R., 2014. Irrigation challenges in the sub-humid US Mid-South. *Int. J.*
811 *Water*, 8(3), 259-274.

812 Wang, X., Gassman, P.W., Williams, J.R., Potter, S., Kemanian, A.R., 2008. Modeling the
813 impacts of soil management practices on runoff, sediment yield, maize productivity, and
814 soil organic carbon using APEX. *Soil & Till. Res.* 101, 78-88.

815 Williams, J.R., Arnold, J.G., Kiniry, J.R., Gassman, P.W., Green, C.H., 2008. History of model
816 development at Temple, Texas. *Hydrol. Sci. J.* 53(5), 948–960.

817 Williams, J.R., Izaurralde, R.C., Steglich, E.M., 2012. Agricultural Policy/Environmental
818 eXtender Model: Theoretical documentation version 0806 (Draft). BREC Report # 2008-
819 17. Temple, TX: Texas AgriLIFE Research, Texas A&M University, Blackland Research
820 and Extension Center.

821 Zhang, B., Feng, G., Read, J.J., Kong X., Ouyang, Y., Adeli, A., Jenkins N.J., 2016. Simulating
822 soybean productivity under rainfed conditions for major soil types using APEX model in
823 East Central Mississippi. *Agric. Water Manage* (Accept).

827 **Tables:**

828 Table 1 Properties in 0.5 m depth of dominant soils in Noxubee county, Mississippi

Soil layer thickness	Vaiden	Catalpa	Leeper	Brooksville	Okolona	Kipling	Griffith	Sumter	Demopolis	$\bar{x} \pm S_d$
Field capacity (m/m)	0.46	0.38	0.39	0.40	0.36	0.38	0.37	0.40	0.31	0.38±0.04
Permanent wilting point (m/m)	0.28	0.21	0.22	0.24	0.26	0.20	0.25	0.25	0.16	0.23±0.04
Available water content (m/m)	0.18	0.17	0.17	0.16	0.10	0.18	0.12	0.15	0.15	0.15±0.03
Saturated hydraulic conductivity (mm/h)	1.75	2.87	2.67	1.95	2.45	3.77	1.84	2.45	6.85	2.95±1.59
Sand content (%)	9.40	7.77	7.61	7.00	6.72	10.20	7.00	6.24	28.06	10.00±6.89

Silt content (%)	31.70	50.25	49.24	48.00	48.44	48.56	50.00	49.85	33.02	45.45±7.47
Clay content (%)	58.90	41.98	43.15	45.00	44.84	41.24	43.00	43.91	38.92	44.55±5.70
Soil texture	Clay	Silty clay	Silty clay	Silty clay	Silty clay	Silty clay	Silty clay	Silty clay	Clay loam	

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830 †Soil properties were taken from USDA-NRCS (<http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx>)

831 $\bar{x}$ and S_d is the mean and standard deviation of nine soils.

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Table 2 Statistics on yield gap of nine soil types in different category year

Category years	Rainfall during soybean growing season (mm)	The number of simulations	Average	Median	Minimum	Maximum	Standard deviation
			Mg ha ⁻¹				
2007	218	9	2.22	2.00	1.11	3.35	0.88
2002	267	9	0.54	0.24	0.19	1.27	0.43
2006	272	9	1.97	1.89	0.74	3.35	1.01
Dry years	252	27	1.58	1.27	0.19	3.35	1.09
2011	330	9	0.48	0.19	0.19	1.18	0.45
2014	379	9	0.32	0.21	0.21	0.73	0.18
2010	390	9	0.80	0.28	0.17	2.04	0.83
2004	406	9	0.23	0.19	0.19	0.36	0.07
2009	410	9	1.58	1.49	0.37	2.85	0.99
2013	464	9	0.19	0.19	0.19	0.20	0.00
Normal years	397	54	0.60	0.21	0.17	2.85	0.73
2008	508	9	1.59	1.21	0.38	2.96	0.98
2003	566	9	0.22	0.20	0.19	0.31	0.04
2005	595	9	0.66	0.43	0.25	1.40	0.49
2012	627	9	0.38	0.20	0.19	0.91	0.28
Wet years	574	36	0.71	0.35	0.19	2.96	0.76

Table 3 Statistics on amount of irrigation required for soybean to achieve water non-limiting potential productivity in different category years.

Category year	Average	Median	Maximum	Minimum	Standard deviation
	mm				
Wet years	192	189	370	86	96
Normal years	157	167	333	0	87
Dry years	308	363	437	163	94

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857 Table 4 Average net return by irrigation on nine soils from 2002 to 2014 by irrigation (\$ ha⁻¹, dollar per hectare)

Category years	Year	Vaiden	Catalpa	Leeper	Brooksville	Okolona	Kipling	Griffith	Sumter	Demopolis	Average net return		
											Nine soils	category years & soils	nine soils and 13 years
Dry years	2002	-17	-15	-11	-15	119	-8	69	111	165	44	195	93
	2006	42	75	60	236	198	314	398	442	478	249		
	2007	116	253	392	175	132	220	401	467	469	292		
Normal years	2004	-2	-14	-13	-12	-9	-8	12	-2	17	-4	58	
	2009	12	26	24	186	163	239	374	381	411	202		
	2010	-15	-18	-30	0	-8	24	259	231	292	82		
	2011	-9	-15	-15	-12	-13	3	102	151	154	38		
	2013	15	15	15	17	11	15	-4	17	15	13		
	2014	4	-5	-7	7	0	3	20	38	91	17		
Wet years	2003	0	1	3	0	-4	1	8	3	20	4	70	
	2005	-7	-23	-20	10	4	15	165	143	154	49		
	2008	13	19	101	139	136	211	368	384	428	200		
	2012	1	1	2	1	-4	1	68	70	120	29		
Average net return (13 years)		12	23	39	56	56	79	172	187	216			

Figure Legends

Fig. 1. Location of Noxubee county and soybean field in 2014, Mississippi

Fig. 2. Simulated average yield potential and standard deviation of nine soil types in each year

Fig. 3. Correlation of yield potential without water stress and accumulative solar radiation during soybean growing season

Fig. 4. Statistics on yield gap of 13 years from 2002 to 2014 on each of nine soil type

Fig. 5. The yield potential, rainfed yield and yield gap of nine soil types from 2002 to 2014

Fig. 6. The box plot and standard deviation of irrigation amount (I_a) of nine soil types in each year from 2002 to 2014

Fig. 7. Water balance components and the amount of irrigation to achieve yield potential in nine soil types from 2002 to 2014

Fig. 8. Average amount of irrigation, number of irrigation and probability of irrigation occurred at soybean different growing stage

Fig. 9. Water use efficiency of nine soil types from 2002 to 2014

Fig. 10. The average irrigation water use efficiency of nine soil types in each year

Fig. 11. The Statistics on irrigation water use efficiency (I_{WUE}) from 2002 to 2014 of nine soil types

Fig. 12. The Relationship between irrigation water use efficiency and yield gap on nine soil types from 2002 to 2014

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891 Fig. 1 Location of Noxubee county and soybean field in 2014, Mississippi

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Fig. 2. Simulated average yield potential and standard deviation of nine soil types in each year

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932 Fig. 3. Correlation of yield potential without water stress and accumulative solar radiation during
933 soybean growing season

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Fig. 7. Water balance components and the amount of irrigation to achieve yield potential in nine soil types from 2002 to 2014

Note: ET_c , rainfall, runoff and percolation are all the accumulative value during soybean growing season from May 8 to September 10; The amount of irrigation is the total water demand to achieve yield potential without any water stress, which was simulated by APEX model. Effective rainfall = Rainfall - Runoff - Percolation; Deficit is the difference between ET_c and effective rainfall.

Fig. 8. Average amount of irrigation, the number of irrigation and probability of irrigation occurred at different growing stage of soybean

Note: Average amount of irrigation in each growing stage was calculated as the total amount of irrigation divided by total number of irrigation from 2002 to 2014 across nine soil types.

Total number of irrigation in each growing stage express the sum of irrigation times from 2002 to 2014 over nine soil types.

Probability of irrigation was calculated as the number of irrigation in each growing stage divided by total number of irrigation in soybean growing season.

Fig. 9. Water use efficiency of nine soil types from 2002 to 2014

Fig. 10. The average irrigation water use efficiency of nine soil types in each year.

The error bars represent standard deviation (Sd).

Fig. 11. The Statistics on irrigation water use efficiency (I_{WUE}) from 2002 to 2014 of nine soil types.

The error bars express the standard deviation of I_{WUE} over 13 years.

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Fig. 12. The Relationship between irrigation water use efficiency and yield gap on nine soil types from 2002 to 2014