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Estimation of the effects of climate variability on crop yield in the Midwest USA

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ABSTRACT

Crop yield is strongly affected by climate variability. When applying ecohydrologic models to study climate impacts on crop yield, especially interannual yield responses to climate stresses, the model simulation of plant available soil moisture must be constrained in order to reproduce plant production variation via moisture related bio-climate variables. In this study, the Soil and Water Assessment Tool (SWAT) is used to investigate the relationship between climate variability and crop yield at four sites (Boone, Woodbury, Madison, and Mason) in the Midwestern USA. The model was first calibrated for soil moisture at the plot scale. The calibrated model was then used to extend the observational records between 1991 and 2010 to better capture the effect of climate variability on crop yield over a longer period (1941–2010). We also explored the relative yield reduction due to individual stresses. Our results indicated that annual observed yield from 1991 to 2010 is correlated with drought stress intensity in the early and middle reproductive stage at most sites. The early and middle reproductive periods were thought more critical than other stages, because severe drought stress in those periods is substantially correlated with low observed yields. No significant relationship between crop yield and aeration stress was found at any of the four sites, due to their different impacts under different spatial scales, as well as low frequency of events in the historical record. Long term simulation of yield reduction indicates that drought stress was the dominant factor affecting yield in the historical period when compared with aeration stress both at short and long return periods (high/low probability of exceedance). For a 70-year period, the total yield reduction due to drought stress is 8.1%, 17.5%, 15.2% and 9.7% respectively for Boone, Woodbury, Madison and Mason.

1. Introduction

Crop yield is of great concern all over the world. The Food and Agriculture Organization of the United Nations (FAO) has predicted that "although the growth of food demands are expected to slow to 1.2% a year over the period 2015 to 2030, by 2030, an extra billion tons of cereals will still be needed each year" (FAO, 2002). The increasing food demands have to be matched by a corresponding increase of food supply. An unbalanced supply–demand relation can lead to tight food markets and rising food prices. To release the pressure in food supply, increased exploitation of arable land, crop productivity growth and increases in cropping intensity are often employed (Rosegrant et al., 2012). Productivity growth is the most critical component of agricultural supply increases. However, there are many factors that can affect crop yields negatively. Annual crop yields are strongly controlled by specific hybrids and specific growing conditions, including weather and nutrient availability. Further, at different growth stages, the magnitude of influence could be different for each factor.

Among all of the factors, soil moisture could have the most complicated relationship with crop development. We can subcategorize the impact of this factor into two parts. One is water deficiency, and the other is excess water stress. Both of them will negatively affect plant growth and threaten crop yields. Limited soil moisture results in a decrease of plant water uptake. Drought will also cause plant tissue dehydration and in turn reduce shoot and root growth, membrane integrity and decrease crop production. Drought-induced crop yield reduction is well documented by many researchers. In the 1930s in the southern Great Plains of the US, drought caused as much as a 50% reduction in corn and wheat yields (Warrick, 1984). The 1988 Midwest US drought led to a 30% reduction in US corn production and cost three billion dollars in direct relief payments to farmers (Rosenzweig and Hillel, 1998). The recent 2012 drought

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affected at least 60% of farms in the US, and caused the lowest national yield value since 1995, 123.4 bu/acre (Crutchfiled, 2012)

Limited water supply (drought) is not the only factor affecting crop growth. If soil water is oversupplied, oxygen transport rates in the soil are reduced, adversely affecting root metabolism and retarding root development. In such cases, a paradoxical phenomenon may occur where the plant wilts not due to lack of water but due to a lack of oxygen. The relative proportion of water to air plays an important role in plant health. The optimum moisture content for healthy growth recommended by Kirkham and Powers (1972) is 25% of total soil pore space for both water and air content. Boyer (1982) found that 41% of crop losses in the United States are caused by drought, while excess water causes crop losses of 16% on average. In the United States, 25% of the soils are threatened by drought, and 16% are too wet, both resulting in a limit to crop production (Boyer, 1982).

Historically, much of the Midwestern U.S. has been faced with excess water. Due to previous glacial activities, dense till restricts water infiltration, which means much of this area maintains a high water table and is very poorly drained (Thompson and Bell, 1988; Muenich, 2011). Under such conditions, organic matter is easily accumulated, resulting in some of the most fertile lands in the world (Blann et al., 2009), but also requiring drainage to make the region workable. Without drainage improvements, this region is subject to delayed planting, denitrification, manganese deficiency, poor root development, depressed nodule activity in legumes, and serious root diseases (Ohio Agronomy Guide, 14th Edition). These soils can be the most or least productive ones, depending on how they are managed. Therefore, in the Midwestern U.S., croplands in poorly drained condition are likely to be drained using subsurface tile lines to release excess water problems and guarantee the healthy growth of crops (Naz et al., 2009).

Understanding the role of soil moisture in crop yield variation will bring great benefits to a range of users in the Midwestern U.S., including farmers and crop marketing agencies. Many studies have investigated the close relationship between soil moisture or moisture related bioclimatic indices and plant yields (Torell et al., 2011; Singh et al., 1998). Bioclimatic or agro-meteorological indices are preferred over meteorological metrics by land managers, because of their clearer association with crop phenology and management practices (Matthews et al., 2008). Bioclimatic indices used in previous research to explore drought effects include annual maximum soil moisture deficit (Brown, 2013), Soil Moisture Percentile (SMP) (Mishra and Cherkauer, 2010), and the Evapotranspiration Deficit Index (ETDI) (Narasimhan and Srinivasan, 2005). When soil water is oversupplied, the soil aeration capacity (SAC) (Visser, 1977) and the Least Limiting Water Range (LLWR) (Benjamin et al., 2003) metrics are often employed to evaluate crop yield response. All of these indices have been found to be good indicators of crop yield under dry or wet conditions, respectively.

To explore the response of crop growth to climate variability and estimate crop yield under various climate conditions, crop growth modeling is often employed. A good model should be able to capture soil moisture dynamics under various climate conditions. The response of crops to both oversupplied and limited moisture conditions must also be clearly reflected. Thus the close relationship between crop production and moisture related bioclimatic variables (physical–physiological index) should be addressed by the model for serious analysis of future climate impacts. Although there are many crop modeling studies and most of the models used have water balance modules, only a few of them evaluate model performance for both soil moisture and yield prediction (Saseendran et al., 2004; Mkhabela and Bullock, 2012). Furthermore, not all models consider crop response under excess water conditions. For example, Hybrid-Maize (Yang et al., 2004), AquaCrop (Steduto et al., 2009) and Cropsyst (Stockle et al., 1994) only consider yield reduction under drought stress, which limits use in areas that suffer from excess water problems, such as fields with limited drainage in the Midwest U.S.

The main objective of this paper is to study the role of climate variability on crop yield at four sites across the Midwestern U.S. with extended data sets of climate observation and crop yield. The Soil and Water Assessment Tool (SWAT) is used in this study because of its robustness in water quantity simulation and the availability of modules to represent plant response in both dry and wet soil conditions. SWAT's ability to capture daily soil moisture was first tested at four Natural Resources Conservation Service (NRCS) – Soil Climate Analysis Network (SCAN) sites. The model's ability to represent historical corn production using observed climate (1991–2010) was then evaluated at the same sites. The response of simulated crop yields to the timing and duration of different bio-climate extremes (related to drought and aeration stress) was explored. Finally, yield reduction due to individual stresses for a longer historical period (1941–2010) was investigated through frequency analysis.

2. Methods

2.1. SWAT model overview and modification

The Soil and Water Assessment Tool (SWAT) was developed by USDA-ARS and is widely used to assess the impact of climate variability on hydrologic process and crop production. The Hydrologic Response Unit (HRU) is the basic spatial unit required for simulation. It is a lumped land area, possessing unique combinations of land use, soil and slope within a subbasin. The hydrologic cycle is simulated based on a water balance equation of soil water content, including evapotranspiration, surface runoff, infiltration, percolation, shallow and deep aquifer flow (Arnold et al., 1998). A detailed description of SWAT hydrological simulation can be found in Neitsch et al. (2009).

Plant growth is also simulated at the HRU level. The growth cycle of each plant is regulated by specific attributes in the SWAT plant database, as well as the timing of operations in the management files. Growing Degree Days are often used to define crop growth period and schedule management operations, but SWAT makes use of a variant, the heat unit or *PHU*. Crop planting date is decided by the fraction (fr_{PHU_0}) of annual total PHU_0 (heat unit accumulation above 0 °C). The plant begins to accumulate *PHU* (heat unit accumulation above the plant specific base temperature T_{base}) after planting until it reaches PHU_{mat} (heat unit accumulation to maturity), which is also defined by crop type and cultivar. The value of fr_{PHU} is the ratio of current *PHU* to PHU_{mat} and is used to decide the timing of other management operations, such as fertilizer/pesticide application (<1.00), and harvest (>1.00). The crop has reached maturity when $fr_{PHU} = 1.00$.

Under optimal conditions (no growth stress), daily biomass accumulation (Δbio; kg/ha) is regulated by leaf area index (*LAI*) development, light interception (k_l), photosynthetically active radiation (H_{day}; MJ m^{-2}), and radiation-use efficiency (*RUE*; 10^{-1} g/MJ).

$$\Delta bio = 0.5 H_{day} \cdot (1 - \exp(-k_l \cdot LAI)) \cdot RUE \tag{1}$$

For annual crops, *LAI* accumulates each day following an optimal leaf area development curve, with similar shape, but different parameters for different plants. *LAI* increases from the planting date until it reaches the maximum *LAI* value and is then stable until the senescence point (*DLAI*) is attained. *LAI* drops from this point until the crop reaches maturity.

Actual daily growth varies from the optimal growth rate due to an accumulation of stresses, which include water deficit or excess, nutrient limitation, extreme temperature, pests, and diseases. The