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The water-food-energy nexus optimization approach to combat agricultural drought: a case study in the United States ☆

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HIGHLIGHTS

- A spatially-explicit optimization model is developed for drought management.
- A water-food-energy nexus approach is used in the optimization model.
- The Pareto frontier show the optimal crop yield, water applied and energy requirements.
- Significant investments on water and energy are required to limit the negative effects of drought.
- The optimal crop yield does not necessarily correspond to the maximum yield, resulting in potential water and energy savings.

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ABSTRACT

The frequent recent drought events in the Great Plains of United States have led to significant crop yield reductions and crop price surges. Using an integrated water-food-energy nexus modelling and optimization approach, this study laid the basis for developing an effective agricultural drought management system by combining real-time drought monitoring with real-time irrigation management. The proposed water-food-energy simulation and optimization method is spatially explicit and was applied to one major corn region in Nebraska. The crop simulations, validated with yield statistics, showed that a drought year like 2012 can potentially reduce the corn yield by 50% as compared to a wet year like 2009. The simulation results show that irrigation can play a key role in halting crop losses due to drought and in sustaining high yields of up to 20 t/ha. Nevertheless, the water-food-energy relationship shows that significant investments on water and energy are required to limit the negative effects of drought. The multi-criteria optimization problem developed in this study shows that the optimal crop yield does not necessarily correspond to the maximum yield, resulting in potential water and energy savings.

1. Introduction

Climate change, together with population growth and economic development, is substantially threatening water, food and energy security in several regions of the globe. As one of the most important weather-driven natural disasters, drought causes significant economic, social and environmental impacts in different sectors [1]. Drought events can be generally classified as meteorological drought, agricultural drought, hydrological drought, or socioeconomic drought [2]. With the intensification of global warming and the increasing frequency of extreme events, the issue of global drought is becoming more and more pronounced. From 2000 to 2016, drought affected 1.3 billion people, resulting in an economic loss of 83 billion US$ in different sectors [3]. Among these sectors, agriculture is one of the most vulnerable. Despite rising

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agricultural production over the past decades, crop failure due to drought negatively affects the global food market (e.g. food prices, trading) and related carbon emissions, and poses severe threats to food security. In the last decade, the severe droughts in the major agricultural producing countries, such as Australia, Brazil, China, India, Russia, Ukraine, and the United States, were primary factors for the recent crop price surges leading to global food price instability and threatening global food security [4]. The close linkage between crop price and drought events in the United States is depicted in Fig. 1 for corn [4].

Currently, agriculture accounts for 70% of total global freshwater withdrawals, making it the largest sector for freshwater usage [5]. Meanwhile, the food production and supply chains consume about 30% of the total energy consumed globally [5]. According to the Food and Agriculture Organization (FAO), global demand for freshwater, energy and food is projected to increase significantly over the next few decades. Leclère et al. [6] and Vorosmarty [7] studied the effects of climate change on the global agricultural systems and concluded that irrigated areas are likely to greatly increase in the future, requiring huge investments in the irrigation, energy, and water resource management sectors. Fischer et al. [8] modelled the change in global irrigation water requirements based on different IPCC scenarios (A2 and B1). The authors highlighted that with an overall increasing trend of future irrigation requirements around the world, the magnitude is a function of both the rate of future greenhouse gas emissions and future precipitation patterns. This situation is expected to be exacerbated in the near future as 70% more food will be needed to feed the world population in 2050 [9]. Similarly, the total global water withdrawal for irrigation is projected to increase by 10% by 2050 [9].

A range of recent studies have focused on drought monitoring and assessment. Typically, drought monitoring has been performed using station-based meteorological observations. The commonly used meteorological drought indicators include the Standardized Precipitation Index (SPI) [10], the Standardized Precipitation Evapotranspiration Index (SPEI) [11], and the Palmer Drought Severity Index (PDSI) [12]. Satellite observations play a key role in large-scale drought monitoring because they can provide cost-effective, spatially explicit, and continuous information over large regions. Several drought indicators based on satellite observations have been proposed such as the Vegetation Condition Index (VCI) [13], the Temperature Condition Index (TCI) [13], the Vegetation Health Index (VHI), the Temperature Vegetation Drought Index (TVDI) [13,14], and the Evaporative Stress Index (ESI) [15]. Aghakouchak et al. have recently reviewed the state-of-the-art of drought monitoring approaches through satellite observations focusing on climatological and ecosystem aspects [16]. The review has also highlighted the research gaps, challenges and opportunities, such as developing new drought indicators to better quantify the effects of drought and improving satellites observations. Besides those studies focused on drought monitoring, several studies have dealt with drought impact analysis using crop modelling. Using the WOFOST crop model, Song and Dong assessed the impact of drought on the winter wheat yield in China [17], revealing more severe drought impact in the period 1961–1980 than 1981–2000 (4.6% and 12% decrease for entire China and northern China respectively from 1961 to 1980). Similarly, using the Environmental Policy Integrated Climate (EPIC) model, Jia et al. assessed the drought impact on maize yield in North China [18] and Southwest China [19], showing a gradually decreasing maize drought risk from northwest to southeast of China. Recent studies have carried out large-scale agricultural drought impact assessment using remote sensing data. Zhang et al. evaluated the drought impact on winter wheat during the growing season both in the United States [20] and China [21], highlighting the crop growth stages that are more affected from drought.

Several studies have focused on crop modelling, even at a large scale, and irrigation management. Liu developed the geographic information system (GIS) version of the EPIC model to analyze the crop yield response to water for three major crops (wheat, corn, and rice) at the global scale [22]. The model was developed to perform simulations, however, system optimizations, as well as the energy aspects of irrigation, were not included. Similarly, Balkovic et al. performed large-scale crop yield simulations in European countries using an updated GIS version of EPIC [23], aiming to implement and validate EPIC at a large scale. Optimization and energy aspects were also not considered in the study. Thorp and Bronson [24] developed the Geospatial Simulation (GeoSim) tool to perform spatial simulations in QGIS software. The authors combined GeoSim with AquaCrop and the DSSAT Cropping System Model to simulate the crop yield response to water, nitrogen, and soil texture in Texas. The developed tool also has an embedded optimization procedure for calibration to minimize the error between model outputs and observed data. However, the energy aspects of irrigation and the analysis of the water-food-energy nexus, especially during drought conditions, were not addressed in the study. Fang et al. used the Root Zone Water Quality Model (RZWQM2) to simulate the corn yields under different irrigation levels, thus analyzing the effect of limited irrigation or deficit irrigation at different crop stages to achieve both high yields and high water use efficiencies [25]. The simulations showed that high crop yield and water use efficiency can be achieved by satisfying the water requirement during the crop reproductive stage. Saseendran et al. investigated the long-term corn yield responses to water (precipitation and irrigation) to provide guidelines for planning deficit irrigation by combining RZWQM2 model, short-term limited irrigation trials, and long-term weather data for different locations and soil types [26]. A recent study conducted by Cheviron

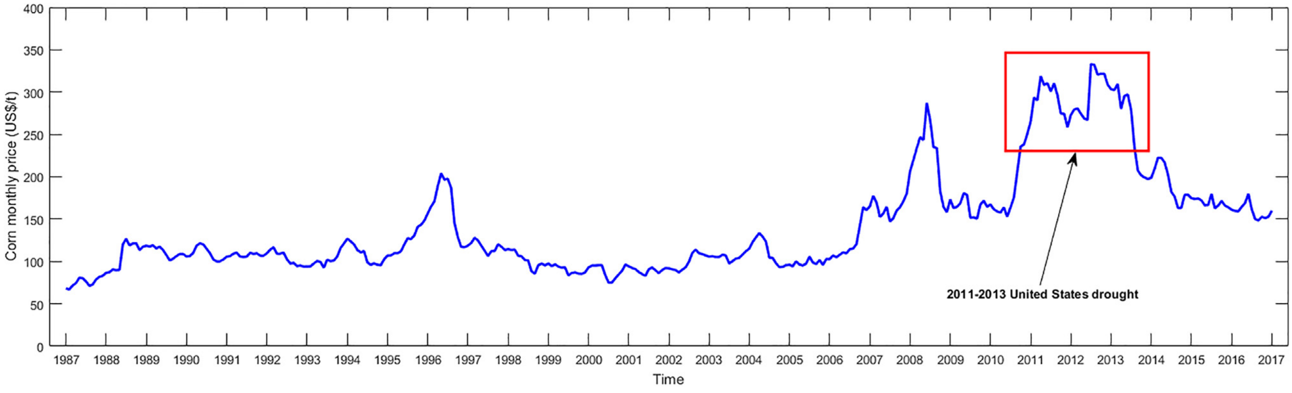

Fig. 1. Global corn price volatility [4].

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