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Integrated spatial–temporal analysis of crop water productivity of winter wheat in Hai Basin

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ABSTRACT

Achieving higher yield per unit of water is one of the most important challenges in water-limited agriculture. In this paper, crop water productivity (CWP) of winter wheat was calculated and analyzed in the plain of Hai Basin in northeastern China. The average CWP of winter wheat (*Triticumaestivum* L.) in the basin for 2003–2009 was 1.049 kg m^{-3}, with CWP values across the basin ranging between 0.7 and 1.4 kg m^{-3}. The spatial analysis of the relationships among CWP, yield, and evapotranspiration (ET) across the basin showed a strongly linear relationship between ET and yield ($R^2 = 0.86$). The temporal analysis showed increases in yield of between 100.4–211.4 kg ha^{-1} year^{-1} between 1984 and 2002 at eight agro-meteorological research stations across the basin without a corresponding increase in ET, corresponding to an increase in CWP of 0.02–0.1 kg m^{-3} per year. It was concluded that the improvements in CWP have resulted from improvements in crop varieties and crop husbandry rather than reductions in water consumption.

1. Introduction

In recent years, rapid economic development and population growth have increased the consumption of water to meet the additional demand for food, intensifying the competition for water between agriculture, industry, and the environment. Agriculture is the largest water-consuming sector (FAO, 1994; Rosegrant et al., 2002) and in many developing countries irrigated agriculture has been expanding rapidly over recent decades, nearly doubling between 1962 and 1998 (Carruthers et al., 1997; Ali and Talukder, 2008). Irrigated agriculture contributes between 25% and 50% to global food production (FAO, 1994). A 2003 FAO analysis of irrigation in 93 developing countries indicates an expected 81% increase in agricultural production from irrigated areas by 2030 (Ali and Talukder, 2008). These irrigated areas, however, will need to produce more crops with the currently available water resources (Ali and Talukder, 2008). As a result, agriculture—and the irrigated sector in particular—must increase production per unit of water consumed to ensure food security while protecting the environment (Stanhill, 1986; Zhang et al., 2003; Cao et al., 2007; Zwart et al., 2010). Understanding how the productivity of water can be increased is a high priority where water resources are currently scarce and/or over-exploited (Perry, 2011).

The terms "Water Use Efficiency" and "Crop Water Productivity" are commonly used to express production per unit of water used (Howell, 1990; Perry, 2007; Perry et al., 2009; Keller and Seckler, 2005; Li et al., 2009; Zwart and Bastiaanssen, 2004). In this paper, crop water productivity (CWP) is defined as crop yield per unit of water consumed (see Section 2.3, Perry et al., 2009). CWP is a useful indicator for quantifying the impact of irrigation management decisions (Ali and Talukder, 2008) and can be used to assess and compare the effects of water-saving measures at different scales and under various conditions (Cui et al., 2007).

Many papers, have reported a strongly linear relationship between T and above ground biomass (AGB) (Howell, 1990; Keller and Seckler, 2005; Steduto et al., 2007). Others have reported relationships between ET and economic yield or AGB: Zhang et al. (2011) reports that winter wheat biomass had a more linear relationship ($R^2 = 0.64$) with evapotranspiration than did summer maize (*Zea mays* L.) ($R^2 = 0.13$), based on 1979–2009 data for ET and yield at an experimental station. Tolk and Howell (2009) also found a linear relationship between ET and biomass ($R^2 = 0.95$) when studying sorghum (*Sorghum bicolor*) in an experimental setting. Perry et al. (2009) based on a review of the literature, reported that the relationship between biomass and transpiration (T) is essentially linear for a given crop and climate—provided nutrients are adequate.

Other results, however, suggest the relationship between ET and yield is not always linear. Kang et al. (2002) analysing a four year period, reported that yield increased at a greater rate than ET. The experimental results from Zhang et al. (2011) also showed that

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when ET increased by 14%, yield of winter wheat increased by 39.5%, and CWP by 21.8%. Zhang et al. (2011) further noted that biomass and ET had a linear relationship from 1979 to 2009 ($R^2 = 0.64$), but that this relationship did not fully explain a smaller water use increase corresponding to the much greater yield increase over the thirty years. Zwart and Bastiaanssen (2004) using a large set of experimental data, also found the relationship between ET and yield for winter wheat was not straightforward ($R^2 = 0.35$), but this result integrated data from many agro-climatic zones where potential ET was quite different. Any relationship between T and biomass depends on the value of *potential* ET; for example, achieving maximum yield in Egypt requires higher ET than maximum yield for the same crop in the UK, and a relationship between yield and ET that mixes data from both countries would not be particularly meaningful. Keller and Seckler (2005) using experimental station data sets for maize, found a logistic curve relation between ET and AGB. Li et al. (2009) using ET and yield data from surface energy balance algorithm for land (SEBAL) for 83 counties in the North China Plain in 2004, reported a relationship between ET and yield in the form of a parabola. The relationship, however, was not statistically significant.

In fact, non-proportional relationships between ET and CWP are not inconsistent with reported linear relationships between yield and ET: some papers (e.g., Tolk and Howell, 2009; Howell, 1990) report the relationship between ET and yield (or biomass) which had a relatively “fixed” contribution of E to ET, such that the graph of biomass against ET does not intersect the origin. Thus, while the relationship between ET and biomass is linear, it is not necessarily proportional. While varieties, soil type, nutrient status, timing of water stress and the farmer’s skill will all affect CWP, the most commonly reported relationship—other things being constant—is that crop production is linearly related to crop water consumption in a given environment.

Most of the above studies reporting on the relationship between water consumption, yield, and CWP use data obtained over a relatively short period of time, or are based on data obtained in a controlled, experimental environment. The reported differences in relationships among yield, ET, and CWP found in these studies suggest it is important to look more generally at the situation in the field, as findings for a particular location, or in a controlled environment may not adequately capture variations in micro-climate, soil types, nutrient availability, and farmers’ education and decisions. A similar conclusion was suggested by Zwart and Bastiaanssen (2004) who, after reviewing 84 literature resources, wrote that the relations between actual marketable crop yield and actual ET “are only locally valid and cannot be used in macro-scale planning of agricultural water management.”

This paper presents results from an integrated study of temporal and spatial data of winter wheat AGB and yield, ET, and CWP across the Hai Basin in China. The Hai Basin is an important area for winter wheat production and because rainfall in the basin is erratic and limited during the growing stage of winter wheat, the area depends heavily on irrigation (Cao et al., 2007; Li et al., 2008). Winter wheat accounts for about 70% of total agricultural water use in Hebei Province—the province that encompasses most of the Hai Basin. The basin faces serious water-related problems, including water conflicts among sectors, ground water over-exploitation, and environmental damage from reduced and polluted river flows. New government policies encourage sustainable economic and social development, with a focus on saving water and increased CWP.

CWP values across the basin were calculated as the amount of above ground biomass per unit of water evapotranspired, with both ET and AGB derived from remote sensing data. The use of remote sensing data to estimate ET and crop yield has been used extensively over recent decades as an efficient new approach for obtaining water consumption and crop output data on a regional scale (Bastiaanssen and Ali, 2003; Tao et al., 2005; Li et al., 2008, 2009; Ahmada et al., 2009; Zwart et al., 2010; Yan et al., 2011).

In addition to information about yield in 2003–2009 based on remote sensing data, this paper also uses long-term data on measured yield at eight agro-meteorological research stations in the basin. The spatial analysis for CWP for the years 2003–2009 is combined with a temporal analysis of data for 1984–2002 to present a comprehensive picture of the relationships among CWP, ET, and AGB in the Hai Basin in recent years.

2. Data and methods

2.1. Study area

The Hai Basin is located in northeast China, between the longitudes and latitudes of 112.0–119.8°E and 35.0–42.8°N. The basin has a total area of 318,000 km^2, some 28% of China’s total land area. Mountains occupy 189,000 km^2 (60% of the total area), while the plain area is 129,000 km^2 (40%). The Hai Basin belongs to the temperate zone continental monsoon climate and the average annual rainfall across the basin between 1980 and 2005 was 498 mm year^{-1}. About 80% of the annual precipitation is concentrated between June and September. Because of its location and size—the basin encompasses the cities of Beijing and Tianjin and includes approximately 108,000 km^2 of arable land—the Hai Basin is at China’s political, economic, and cultural center; it is also the main production base for grain and cash crops in the country.

The Hai Basin includes three major river systems: the Hai River, Luan River, and Tuhaimajia River, with the Hai River system including the Daqing, the Ziya, Zhangwei, and Beisi rivers. The basin is divided into 15 water resources districts, associated with the main rivers (Fig. 1). The Tuhaimajia River plain is also irrigated by water from the Yellow River, with about 3.34–6.68 billion m^3 diverted annually to this sub-basin.

Eight agro-meteorological stations, at Baodi, Zhuozhou, Luancheng, Feixiang, Guantao, Chen’an, Anyang, and Xinxiang, serve as county-level observation stations. Each representing a certain region, the stations have been established for long-term field observations of soil water content, crop growth, and crop yield for main crops.

2.2. Data

Monthly ET and AGB data for the Hai Basin from 2003 to 2009 were obtained from remote sensing (RS) data. The ET data for eight agro-meteorological stations were also estimated with ETWatch, using AVHRR (advanced very high resolution radiometer) data for the years 1984–2000, and MODIS (moderate-resolution imaging spectra radiometer) data for 2001–2009. In order to make the resolution of the satellite data consistent with the field experiments at the research stations, pixels within the window of 3 × 3 pixels around stations with more than 70% vegetation coverage in May were chosen to calculate the average ET. This extraction method was designed to eliminate the mixed-pixel effect and make ET comparable with yield at stations.

ETWatch is an integration of the “Residual Approach (the energy balance model)” and Penman-Monteith model. Due to cloud cover and satellite overpass intervals, any ET dataset directly from remotely sensed data contains large temporal gaps. ETWatch utilizes the Penman-Monteith method for time integration. The surface resistance, which expressed the status of soil moisture and vegetation stomata, is a key variable which is difficult to measure. A solution is given by Xiong et al, (2008) the modified and optimized energy balance model was applied to calculate surface resistance on cloud free days (r_s) from spectral radiances. The daily surface