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Spatio-temporal distribution of irrigation water productivity and its driving factors for cereal crops in Hexi Corridor, Northwest China

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ABSTRACT

The analysis of irrigation water productivity (IWP) can provide insights into taking measures to improve water-efficient irrigation. This study examines the temporal IWP trend of cereal crops over the Hexi Corridor in Northwest China by employing descriptive analysis, trend analysis, and change-point analysis. Spatial patterns of different typical years (dry, average and wet year) are analyzed by the spatial interpolation method and spatial autocorrelation method. The regional average IWP significantly increased from 0.51 kg/m^3 to 1.29 kg/m^3 during the period of 1981–2012 and no change point was detected. Spatial distribution of IWP reveals that IWP was higher in the plain oasis region, while lower in the mountainous and desert oasis region. The IWP ranged from 0.72 to 1.60 kg/m^3 for the dry year 2004, 0.77–1.66 kg/m^3 for the average year 2008, and 0.81–1.93 kg/m^3 for the wet year 2011, respectively. No significant spatial autocorrelation was observed. By 2012, there were still 3.9% of the area with IWP less than 1.0 kg/m^3, which implied an opportunity to increase IWP through better water management practices. The grey relational analysis of the influences of major driving factors (area supported by unit of irrigation water use, fertilization, agricultural film, agricultural pesticide, and annual mean temperature) on IWP showed that area supported by unit of irrigation water use, fertilization, and agricultural film had dominant impacts during the whole period.

1. Introduction

Water is a vital factor in agricultural production, and water shortage is seriously affecting China's agricultural production (Brown and Halweil, 1998; Oweis and Hachum, 2003; Kang et al., 2016). Under the pressure of water scarcity and the increasing population growth, agriculture is being challenged by producing more agricultural products with limited water resources (Zwart and Bastiaanssen, 2004). For irrigated agriculture in Northwest China, a step towards meeting this challenge is to improve irrigation water productivity (Molden, 1997; Molden et al., 2003).

Irrigation water productivity (IWP) is defined as the production per unit of irrigation water application (Molden, 1997; Playán and Mateos, 2006). It reflects the relationship between irrigation input and output, and represents not only water-use efficiency but also benefits of irrigation, which is a useful indicator for revealing the level of agricultural irrigation and crop management (Seckler et al., 2003; Abdullaev and Molden, 2004; Zoebl, 2006). Increased IWP is the result of comprehensive improvements in agricultural production and irrigation water-use efficiency (Ali and Talukder, 2008; Molden et al., 2010). Application of regional IWP assessment and analysis can provide insight for exploring macroscopically agricultural water-saving management practices (Ines et al., 2003). Increasing lower IWP values can greatly contribute to food production (Cai et al., 2009). Thus the analysis of IWP is attracting more attention. So far, two major procedures for assessing regional scale water productivity are widely applied. One is using statistical or model-simulated yield and water use data to assess water productivity (Droogers and Kite, 2001; Abdullaev and Molden, 2004; Garg et al., 2012), and the other is integrating RS/GIS technology with models to obtain spatio-temporal expression of yield and water use, and then assess water productivity (Ines et al., 2002; Bastiaanssen et al., 2003; Wesseling and Feddes, 2006; Zwart and Bastiaanssen, 2007; Immerzeel et al., 2008; Li et al., 2008; Zwart et al., 2010; Cai et al., 2012; Yan and Wu, 2014).

Many spatio-temporal studies on regional or basin-scale water productivity have been reported in literature, but they mainly focus on crop water productivity (CWP, ratio of yield to evapotranspiration). Abdullaev and Molden (2004) provided the analysis of CWP for different farm types and different basin segments in Syr Darya Basin of central Asia for three hydrological years. The ratio of the highest to lowest CWP was about 2. CWP in water-deficient years

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was higher than that in water-abundant years. Mainuddin and Kirby (2009) considered provincial administrative boundaries as the spatial units and analyzed spatial and temporal trends of CWP in Lower Mekong Basin comprising Laos, Thailand, Cambodia and Vietnam, and the results showed that CWP increased over time. There is a significant spatial variation among countries but not for provinces within a country. Lower CWP is attributed to the lower rainfall, longer drought period, poorer soil nutrition, and less fertilizer application. Cai et al. (2012) analyzed spatial and temporal variability of CWP in Limpopo River Basin of Southern Africa, and concluded that the basin CWP was very low with great variation, mainly due to the low yield, variable water availability, and variant water management levels. Yan and Wu (2014) analyzed CWP of winter wheat based on remote sensing data, and found a steady increase of CWP in recent years.

The spatial and temporal studies on regional IWP are relatively less reported. Droogers and Kite (2001) simulated IWP at basin scale for the Gediz River of Turkey with annual precipitation of 500–1000 mm in the basin, and found IWP in the dry years was much higher than that in the wet years. Irrigation water productivity of spring wheat in an irrigation district of Heihe River Basin, Gansu Province, China, was analyzed from 1995 to 2006, where the average IWP increased by 8.9% from the period of 1995–2000 to the period of 2001–2006 (Hu et al., 2010).

To improve IWP, it is essential to understand correlations between IWP and its driving factors. The factors influencing yield and irrigation water use certainly influence IWP (Zwart and Bastiaanssen, 2004; Ali and Talukder, 2008; Molden et al., 2010; Descheemaeker et al., 2011). The controllable and uncontrollable factors include: (1)climate factors, such as temperature, vapor pressure deficit, and precipitation (Zwart and Bastiaanssen, 2004), (2) agronomic management practices, such as irrigation management (Molden, 1997; Kang et al., 2000; Yazar et al., 2002; Oktem et al., 2003; Zwart and Bastiaanssen, 2004; Geerts and Raes, 2009), soil management (Hatfield et al., 2001; Molden et al., 2010), and crop management (Molden, 1997; Zwart and Bastiaanssen, 2004; Passioura, 2006) (3) crop species and varieties (Zwart and Bastiaanssen, 2004; Ali and Talukder, 2008), and (4) soil factors such as soil texture and organic matter(Hatfield et al., 2001; Ali and Talukder, 2008). Driving factors of IWP vary with regional differences and also depend on socioeconomic conditions. Thus, it is necessary to analyze the influences of driving factors for improving IWP.

The Hexi Corridor is located in the arid region of Northwest China, which is characterized as an irrigation district of "no irrigation, no agriculture". It is an important grain production base in Northwest China to fulfill crop demands in the region. In this region, water problems are being aggravated by the arid continental climate, water scarcity, competition among water-consuming sectors, and groundwater overexploitation (Bao and Fang, 2007; Su et al., 2007). Ensuring or increasing agricultural production with reduced or currently available irrigation water, in other words, improving irrigation water productivity, is increasingly important for the region. In order to improve IWP, the spatio-temporal analysis of IWP in Hexi Corridor and its major driving factors are necessary, and will provide insights for exploring measures to improve irrigation water-use efficiency and water saving management.

The previous studies on IWP and its driving factors in Hexi Corridor were limited to the field scale or a part of Hexi Corridor for a short time period, and to a single driving factor. None of them comprehensively analyzed IWP in the whole Hexi Corridor while considering long-term temporal trends, change points, spatial variations, and the influences of major driving factors on IWP. This study aims to examine spatio-temporal trends and the major driving factors of irrigation water productivity of cereal crops in Hexi Corridor for the period of 1981–2012. Therefore, the objectives of this study are to: (1) reveal the temporal trend of IWP over the past 32 years; (2) choose a relatively optimal method for interpolating IWP in terms of interpolation accuracy, by comparing the inverse distance weighed method, local polynomial interpolation method, and ordinary kriging method; (3) analyze spatial pattern and spatial autocorrelation of IWP in different typical years (i.e. dry (75% hydrologic frequency of annual precipitation), average (50%) and wet (25%) year); (4) evaluate major driving factors of IWP, analyze their influences on IWP in different periods, and provide valuable insights for improving IWP.

2. Materials and methods

2.1. Study area

Hexi Corridor lies in an arid region of Northwest China, between longitudes 92°12′E and 104°20′E and latitudes 37°17′N and 42°48′N, with a total area of 270,000 km^2. It is a long corridor and the distance from east to west is about 1000 km (Fig. 1). It can be approximately divided into three parts: the Qilian Mountain area, plain oasis, and mountainous region in the north, according to geomorphic features and ecological factors. There are three river systems, the Shiyang River, Hei River, and Shule River, from east to west (Bao and Fang, 2007).

In the Hexi Corridor, land, light and heat resources are abundant, but precipitation is limited and evaporation is high, with the annual mean precipitation of 50–150 mm, and the annual average evaporation of 1500–2500 mm. The crop water requirement is much greater than precipitation. Thus, agricultural production relies on irrigation. The main cereal crops are maize (*Zea mays* L.) and wheat especially spring wheat (*Triticum aestivum* L.), and high value crops are mainly oil crops, such as sunflower (*Helianthus annuus*), rapeseed (*Brassica napus*), and sesame (*Sesamum indicum*).

2.2. Data collection

The data, including cereal crops yield, the amount of irrigation, planting proportions of cereal crops, fertilization, agricultural film, agricultural pesticide, and disaster area, were obtained from field investigation and statistical data from the China Economic and Social Development Statistics Database (http://tongji.cnki.net/kns55/index.aspx), Gansu Water Statistical Yearbook, Gansu Development Yearbook and Gansu Rural Yearbook, collected by department of water management, agriculture. Data were available for the period of 1981–2012, and the county administrative boundaries were considered as the spatial unit basis. The data of fertilization, agricultural film and agricultural pesticide were collected in terms of the total use amount of each county. Irrigation water use for cereal crops were calculated by combing the synthetical irrigation quotas and the planting proportions of cereal crops. The disaster area means the area of yield reduction due to natural disaster. Daily climate data, including precipitation and mean temperature, were obtained from China Meteorological Data Sharing Service System (http://data.cma.cn). Descriptions about the indicators are listed in Table 1.

2.3. Methodology

2.3.1. Irrigation water productivity

Irrigation water productivity is defined as the yield per unit of irrigation water use, which can be expressed as:

$$IWP = Y/I \quad (1)$$

where IWP is irrigation water productivity, in kg/m^3, Y is yield, in kg/ha, I is irrigation water use, in m^3/ha.