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Projected irrigation requirements for upland crops using soil moisture model under climate change in South Korea

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ABSTRACT

An increase in abnormal climate change patterns and unsustainable irrigation in uplands cause drought and affect agricultural water security, crop productivity, and price fluctuations. In this study, we developed a soil moisture model to project irrigation requirements (IR) for upland crops under climate change using estimated effective rainfall (ER), crop evapotranspiration (ET_c) and the IR of 29 major upland crops in South Korea. The temperature and precipitation will increase, but the ER is projected to decrease under climate change. ET_c and the net irrigation requirement (NIR) are expected to increase under climate change. Vegetable crops have less ER and more NIR than cereal crops with a similar amount of ET_c, which means they are more sensitive to water scarcity and IR than cereal crops. In addition, we found that barley has the smallest daily ET_c and IR but the highest increase rate in NIR under climate change, especially in the central part of South Korea. The NIR of Chinese cabbage-fall is the lowest in the northern region and increases moving southwards. The NIR of spinach is projected to increase gradually from the southern and eastern coastlines to the northern inland area. Onions have the largest ET_c and NIR of the 29 upland crops, but they show small changes compared to other crops under climate change. Water scarcity is a major limiting factor for sustainable agricultural production. The variation of IR and ET_c values for each crop under different climate change scenarios depends on the crop, soil, space, and meteorological characteristics. The results of this study can be used as a guideline for irrigation and soil water management for upland crops under climate change.

1. Introduction

Climate change greatly affects global and regional agriculture and irrigation (Puma and Cook, 2010; Calzadilla et al., 2013). The increase in abnormally high or low temperatures, changes of precipitation and climate patterns, extreme weather events, and unsustainable irrigation in uplands can give rise to drought and floods and affect the security of water resources, crop productivity, and crop yields (Mo et al., 2013; Saadi et al., 2015). In recent years, drought has caused agricultural damage throughout the world (Wilhite et al., 2014). Russia experienced its worst drought in 2010 (Hoerling, 2010). The Russia government suspended exports of wheat, barley, and corn, which affected the whole world's grain supply and price. China has experienced a severe drought and crop damage every year: 12% of cropland in the northern region was affected by drought in 2006, and more than 1 million hectares of cropland were damaged by a severe drought during the winter and spring of 2012 (Yang et al., 2013; Xu et al., 2015). A lack of precipitation and warmer temperatures in Europe during most of 2012 caused severe drought across parts of southeastern Europe and greatly affected harvest yields and water supplies (Spinoni et al., 2015). In 2013–2014, South Africa experienced its worst drought since 1933 (Lewis et al., 2011). Nearly two-thirds of the contiguous United States experienced drought in 2012, which resulted in a multi-billion dollar agricultural disaster (WMO, 2015). In 2012–2015, California has been experiencing an extreme drought, causing the prices of vegetables to more than double in a month (Hatchett et al., 2015; Mao et al., 2015; Seager et al., 2015).

Agricultural water crises and droughts are a critical challenge for agricultural production and have recently received considerable attention (Hayes et al., 2004; Li et al., 2010; Yang et al., 2010). In

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facing irrigation in South Korea, the self-sufficiency rate for paddy rice is more than 90%, and 80.6% of paddy fields in 2013 used irrigation from a reservoir, well, pump, and etc. (MAFRA, 2014). In contrast, most upland crops are cultivated in rainfed or irrigated fields that depend on groundwater, which is unstable. In addition, the regional drought pattern affected crops and periods differ every year make planning difficult (Hong et al., 2015). Future water security depends on climate change and the water requirements for irrigation (Holst et al., 2014; Mainuddin et al., 2015). Therefore, it is necessary to know how much irrigation water is required to support agricultural sustainability and productivity under present and climate-change conditions (Kousari et al., 2013).

It is important to investigate variations in crop evapotranspiration and irrigation requirements (IR) and predict which crops can be affected by drought and which areas are vulnerable under climate change (Allen et al., 2011; Shahid, 2011; Shen et al., 2013). Several studies have investigated the IR for upland crops under climate change. Most research predicts that IR will increase even though precipitation will also increase because of changes in other meteorological variables. Sav'e et al. (2012) investigated potential changes of IR under climate change. They found that changes in the environmental conditions will affect IR, which will increase throughout the century by 40–250% depending on the crop. Gondim et al. (2012) in Jaguaribe, Brazil, and Mo et al. (2013) in North China found the effect of climate change to be increasing IR and a change in crop evapotranspiration (ET_c). Tanasijevic et al. (2014) investigated the effect of climate change on olive crops in the Mediterranean region. They predicted that the net irrigation requirement (NIR) will increase, though the effective evapotranspiration of rainfed olives could decrease in most areas because of a reduction in precipitation and increase in evapotranspiration demand.

The conceptual models for investigating IR are based on the soil water balance model in the crop root zone (Hlavinka et al., 2011; Ma et al., 2013; Tanasijevic et al., 2014). It is based on gains by precipitation and irrigation and losses by evapotranspiration and deep percolation in the crop root zone (Ma et al., 2013; Trnka et al., 2015). Such soil water balance model is useful for agricultural water management because it needs fewer parameters than other models and considers the soil water quantity in the root zone without considering the detailed mechanism of soil water flow at the field scale (Panigrahi and Panda, 2003; Trnka et al., 2009).

Several studies in Korea have investigated the effects of climate change on paddy rice fields by estimating evapotranspiration, IR, and paddy rice productivity (Hong et al., 2009; Yoo et al., 2012; Chung, 2013; Nam et al., 2015a). Even though evapotranspiration and NIR are crop-specific, the water mechanisms in the soil are complex, and the kinds of crops grown in South Korea are diverse. Research is scare that considers different crops, cropping systems, and soil moisture balance under climate change. In this study, we focus on changes in the temporal and spatial trends in the IR of 29 major upland crops in South Korea under climate changeThe primary purpose of this study was to develop a soil moisture model based on the water balance equation for the upland crops. To investigate the IR for upland crops, we constructed a database of historical meteorological data for 30 years (1981–2010), future climate data (2011–2100) using the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathways (RCPs) 4.5 and 8.5 scenarios, and crop and soil characteristics. This study includes (1) calculating the reference evapotranspiration (ET_o) and ET_c, effective rainfall (ER), and NIR in each crop's growing season using soil moisture model, (2) analyzing and quantifying changes of the spatial and temporal variation of ET_c and NIR for each crop, and (3) evaluating which crops and regions are vulnerable to climate change.

Table 1
Classification of observed data and climate change data from RCP scenarios.

Classification	Period	Source	Climate model
Observed	1981–2010	KMA (Korea Meteorological Administration)	Observed data
2025s 2055s 2085s	2011–2040 2041–2070 2071–2100	RCP 4.5, RCP 8.5	HadGEM3-RA

2. Materials and methods

2.1. Study area

We conducted this study in South Korea, which is located between China and the Japanese Islands in East Asia (35°50′N, 127°00′W). The climate in South Korea is influenced by the East Asian monsoon system, has complex spatial and temporal variations because of topographical characteristics from mountain terrain, and has four clear seasons. Between 50% and 60% of the country's annual precipitation falls during the summer, and the annual average total precipitation is 1200–1500 mm. The annual average temperature is 10–15 °C, ranging from −6 to 3 °C in January to 23–26 °C in August obtained from the Korea Meteorological Administration (KMA, 2014). Fig. 1 shows the spatial distribution of the country's 54 meteorological stations and an agricultural land cover map. The total cultivated paddy rice area has decreased from 1325×10^3 ha (1985) to 934×10^3 ha (2014); the total upland agricultural area in South Korea is 757×10^3 ha, accounting for around 45% of the total farmland area in 2014, and that area has changed little during the past 30 years obtained from the Korea Statistical Information Service (MAFRA, 2014).

2.2. Data

2.2.1. Meteorological and climate change data

For analysis, we divided the time domain into two periods, current (1981–2010) and future (2011–2100). The Korea Meteorological Administration (KMA) collected daily historical meteorological data (e.g. average, minimum and maximum temperature, relative humidity, wind speed, sunshine hours, and precipitation) from 54 meteorological stations (Fig. 1) for a 30-year period (1981–2010), as shown in Table 1.

In our research, we used a range of future climate change scenarios projected by the IPCC (2013). The RCPs form a set of greenhouse gas concentrations and emissions pathways designed to support research on the effects and potential policy responses to climate change (Moss et al., 2010). Rather than using the peak-and-decline scenario (RCP 2.6) or stabilization scenario (RCP 6.0) in which the total radiative force stabilizes shortly after 2100, we used RCP 4.5, which stabilizes the radiative force at 4.5 W m^{-2} in the year 2100 without ever exceeding that value (Thomson et al., 2011), and RCP 8.5, which assumes that greenhouse gases continue to rise according to current trends (Riahi et al., 2011).

The KMA and National Institute of Meteorological Research produced part of the fifth phase of the Coupled Model Intercomparison Project (CMIP5) and Coordinated Regional Climate Downscaling Experiment (CORDEX) simulations using the Hadley Center Global Environmental Model (HadGEM) (Nam et al., 2015b). KMA produced regional climate projections and the atmospheric regional climate model HadGEM3-RA (Hewitt et al., 2011) using the dynamical downscaling method from a coupled atmosphere–ocean general circulation model, HadGEM2-AO, for its weather stations on a daily time scale (Baek et al., 2013; Park et al., 2015). In this study, we used projected climate change data from the high-resolution (1 km) climate change scenario by the Climate Change Information Center