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

Eun-Mi Hong^{a,b}, Won-Ho Nam^{c,1}, Jin-Yong Choi^d, Yakov A. Pachepsky^a

^a USDA-ARS, Beltsville Agricultural Research Center, Beltsville, MD, USA

^b Oak Ridge Institute of Science and Engineering, Oak Ridge, TN, USA

^c National Drought Mitigation Center, School of Natural Resources, University of Nebraska-Lincoln,
Lincoln, NE, USA

^d Department of Rural Systems Engineering and Research Institute for Agriculture & Life Sciences, Seoul
National University, Seoul, Republic of Korea

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

¹ Corresponding author. Fax: +1-402-472-2946.

E-mail address: wonho.nam@gmail.com (W.H. Nam).

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.

Keyword: Climate change, Evapotranspiration, Irrigation requirement, Soil moisture model, South Korea, Upland crop

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 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., 2015). 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 scarce 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 change. The 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.

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 1,200–1,500 mm. The annual average temperature is 10–15°C, ranging from -6–3°C in January to 23–26°C in August obtained from the Korea Meteorological Administration (KMA, 2014). Figure 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 1,325 10³ ha (1985) to 934 10³ ha (2014); the total upland agricultural area in South Korea is 757 10³ 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 of the KMA for 2000-2100 to generate a time series of future climate data. We generated projected climate change data using a statistical downscaling technique in PRISM (Parameter-elevation Regressions on Independent Slopes Model, Daly et al., 2008) to create two adaptation scenarios from 2011 to 2100. These data have been widely used and verified in previous research using historical observed weather data from 2000 to 2010 in South Korea (Kim et al., 2013; Kim et al., 2015; Seo et al., 2015). Compared to the observed data and the climate change data from each weather station, the bias-corrected data appropriately reflected the temporal trends of the each weather variable (data not shown) (Kim et al., 2013). Because in past work the Had-GEM3-RA shows relatively good correspondence with the modeled dataset (Park et al., 2015). Therefore, in this study the projection climate data are considered appropriate for predicting future irrigation requirements in South Korea. The observed data are historical data from 1981–2010; we created the downscaled climate projections from the RCP 4.5 and 8.5 scenarios for the next 90 years as 2011–2040 (2025s), 2041–2070 (2055s), and 2071–2100 (2085s).

2.2.2. Upland crops

To calculate the IR of upland crops using the soil moisture model, we selected 2 types, 8 groups and 29 upland crops: cereals (barley & wheat; barley, wheat, rye, Pulses; soybean, red beans, green beans, miscellaneous grain crops; millet, sorghum, maize, buckwheat, starch roots; sweet potato, potato) and vegetables (leafy vegetables; Chinese cabbage-spring,

Chinese cabbage-fall, cabbage, spinach, lettuce, seasoning vegetables; red pepper, green onion, onions, garlic, fruits vegetables; watermelon, melons, strawberry, cucumber, pumpkin, tomato, root vegetables; radish, carrot) as shown in Table 2. We collected crop information such as maximum root depth (m) in each crop growth stage, start days and length of different growth stages, soil water depletion fraction for each upland crop, and crop coefficient (Allen et al., 1998; Jung et al., 2011; Han, 2012; Eom et al., 2013).

2.2.3. Soil

Figure 2 shows the spatial distribution of effective soil depth, soil type, and DEM (digital elevation model) in South Korea. The effective soil depth, as shown in Figure 2 (a), represents the depth of soil horizons and is classified from very shallow (less than 20 cm) with poor soil formation to deep (greater than 100 cm) with well-weathered bedrock or well-deposited sediments. Soil type, as shown in Figure 2 (b), is classified into seven categories: sandy, sandy loam, sandy silt, loam, soil clay, clay, and rock soil. The major soil texture of South Korea is sandy loam in the eastern region and loam in the western region. We collected soil series data and information (field capacity and wilting point of soil series, soil type, and effective soil depth) from the Rural Development Administration (RDA) Korean Soil Information System (<http://soil.rda.go.kr>).

2.3. Soil moisture model

2.3.1. Soil water balance model

IR can be affected by variation of precipitation and evapotranspiration and the resultant fluctuations in soil moisture (De Silva et al. 2007; Hunt et al., 2009). To estimate the IR, we developed a daily soil moisture model using the water balance model, as shown in Eq. (1) and Table 3. This model was already verified by Nam et al., (2014) and Hong et al., (2015). The soil moisture model for IR is based on the mass balance of soil water in the crop root zone as a function of evapotranspiration, infiltration, ER, and runoff. We neglect upward capillary rise and determine the key soil water balance model as shown in Eq. (2). To initialize the model, we ran the soil water balance calculations for the first year twice, assuming that after one year the soil water conditions in January are representative of actual conditions (Thomas, 2008).

$$\Delta SM = (P - RO) + I + CR - ET_c - DP \quad (1)$$

$$SM_t = SM_{t-1} + ER_t + IR_t - ET_{ct} \quad (2)$$

where, ΔSM is the daily soil moisture variation (mm day^{-1}), P is the precipitation (mm day^{-1}), RO is the surface runoff (mm day^{-1}), I is the irrigation (mm day^{-1}), CR is the upward capillary rise into the root zone (mm day^{-1}), ET_c is the crop evapotranspiration (mm day^{-1}), DP is the deep percolation out of the root zone (mm day^{-1}), t is the time (day), and ER is the effective rainfall (mm day^{-1}).

2.3.2. Crop evapotranspiration

We estimated the ET_o on a daily basis using the meteorological data and the Penman–Monteith equation, as recommended by the United Nations Food and Agriculture

Organization (Allen et al., 1998; Pereira et al., 2015) and shown in Eq. (3). ET_c is determined by multiplying ET_o and the crop coefficient (K_c) for the same day, as shown in Eq. (4).

$$ET_o = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \left(\frac{900}{T + 273}\right) \cdot U_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot U_2)} \quad (3)$$

$$ET_c = K_c \times ET_o \quad (4)$$

where ET_o is the reference evapotranspiration (mm day^{-1}), K_c is the crop coefficient (dimensionless), R_n is the net radiation available at the crop surface ($\text{MJ m}^{-2}\text{d}^{-1}$), G is the ground heat flux density at the soil surface ($\text{MJ m}^{-2}\text{d}^{-1}$), T is the average air temperature at 2 m height ($^{\circ}\text{C}$), U_2 is the average wind speed at 2 m height (m s^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), Δ is the slope of the saturation vapor pressure versus the air temperature curve ($\text{kPa } ^{\circ}\text{C}^{-1}$), and γ is the psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$). We computed those parameters following the recommendations of Allen et al. (1998). The wind speed data obtained at 10 m height (U_2 , m s^{-1}) were adjusted to the standard height of 2 m using the logarithmic wind speed profile equation.

The crop coefficient (K_c) is related to the crop characteristics and stages of crop growth (initial, mid-season, and late-season). Because the evapotranspiration of upland crops is affected by the surface's dry or wet conditions, we calculated the crop coefficients considering the soil moisture conditions proposed by Jensen et al. (1990), as shown in Eqs. (5) and (6).

$$K_c = K_{co} \times K_{\alpha} \times K_s \quad (5)$$

$$K_{\alpha} = \ln(A_{\omega} + 1) / \ln(101) \quad (6)$$

where K_{α} is the coefficient considering the soil saturated condition by irrigation or rain (dimensionless) with a value between 0 (soil moisture at wilting point) and 1 (soil moisture at field capacity), K_{cb} is the value of the basal crop coefficient considering the canopy and stages of crop growth (dimensionless), as shown in Table 4, K_s is the correlation factor of soil evaporation after irrigation or rainfall (dimensionless), and A_w is the percentage of available soil water (%).

2.3.3. Effective rainfall

ER is the portion of rainfall infiltrated in the soil layer and stored in the root zone and can be used for crop transpiration. It is an important component for investigating IR and has different characteristics depending on crop species, stage of crop growth, rainfall amount, rainfall intensity, soil infiltration rate, antecedent soil moisture, and soil characteristics. We calculated the surface runoff using the NRCS (Natural Resources Conservation Service) CN (curve number) method, as shown in Eqs. (7) and (8).

$$RO = \begin{cases} 0 & \text{for } P < 0.2S \\ \frac{(P-0.2S)^2}{P+0.8S} & \text{for } P \geq 0.2S \end{cases} \quad (7)$$

$$S = \frac{25400}{CN} - 254 \quad (8)$$

where RO is the surface runoff (mm), P is the precipitation (mm), S is the potential maximum soil moisture retention after runoff (mm), and CN is the runoff curve number.

The available water content of the soil is defined as the soil water that can be used for a crop. The available water content of the soil is determined by the differences between field

capacity and wilting point (Hunt et al., 2014). Total available soil water (TAW) is calculated considering the available water content and crop root depth, as shown in Eq. (9).

$$TAW = (\theta_{FC} - \theta_{WP}) \times Z_r \quad (9)$$

where θ_{FC} is the soil moisture content at field capacity ($m^3 m^{-3}$), θ_{WP} is the soil moisture content at the wilting point ($m^3 m^{-3}$), and Z_r is the crop root depth (mm).

Theoretically, the available soil water in the root zone can be used until wilting point. However, as the soil water content decreases, water is more difficult to extract because it becomes more strongly bound to the soil matrix (Allen et al., 1998; 2005; Rudnick and Irmak, 2014b). Therefore, when the soil water content drops below a threshold value, the amount of available water in the effective soil depth decreases gradually from the surface to the lower soil layers before the wilting point is reached. In response, the crop begins to experience water stress (Allen et al., 1998; Allen, 2000). In this study, we calculated readily available soil water (RAW) using the soil water depletion fraction, defined by the fraction of TAW that a crop can extract from the root zone without suffering water stress (Allen, 2000; Rudnick and Irmak, 2014a). RAW takes into account the crop, its root depth, and the coefficient of the soil water depletion fraction under the crop rooting depth (P_{crop}), as shown in Eqs. (10) and (11). FAO-56 contains recommended values for P_{crop} for 60 crops and a numerical approximation for adjusting P for the ET_c rate (Allen et al., 2005), as shown in Eq. (11).

$$RAW = \bar{P} \times TAW \quad (10)$$

$$\bar{P} = P_{crop} + 0.04 \times (5 - ET_c) \quad (11)$$

where, $\bar{P}$ is the average fraction of TAW that can be depleted from the root zone before water stress occurs considering reduction in ET_c rate (Allen et al., 1998).

In this study, we calculated ER using the precipitation, crop evapotranspiration, and soil moisture content of the previous day, as shown in Eqs. (12), (13), and (14). It is calculated based on the residual effective soil moisture content in the root zone from daily rainfall, minus surface runoff loss and consumptive use of crops using the soil water balance model to simulate the value of soil moisture contents. When soil moisture content exceeds the field capacity in effective soil, the soil water over the field capacity is considered to be deep percolation out of the root zone (DP).

$$\overline{ER}_t = P_t - RO_t - DP_t \quad (12)$$

$$ER_t = \begin{cases} 0 & \text{for } SM_{t-1} + \overline{ER}_t - ET_{Ct} > D_{\max} \\ \overline{ER}_t - ET_{Ct} & \text{for } SM_{t-1} + \overline{ER}_t - ET_{Ct} \leq D_{\max} \end{cases} \quad (13)$$

$$D_{\max} = \theta_{FC} \times Z_r \quad (14)$$

where, $\overline{ER}_t$ is the potential effective rainfall on day t, and $D_{\max}$ is the upper threshold of effective soil water.

2.3.4. Estimation of net irrigation requirement

The definition of IR used in this study is the irrigation water that needs to be applied to supplement stored soil water in the crop root zone (Doorenbos and Pruitt, 1977; Sharma and Irmak, 2012), as shown in Eqs. (15) and (16). It was determined by the daily accumulated value of soil water shortage, considering the soil water balance for the root zone when soil moisture content is below the wilting point ($D_{\min}$), which is the lower threshold of effective

soil water (Eq. (15)). As shown in Eq. (16), for example, if the sum of soil moisture on day $t-1$ and effective rainfall on day t exceeds the sum of the D_{min} and ET_c on day t (i.e., the ET_c is possible), the IR on day t was not necessary (i.e., IR on day t is zero). In contrast, if the ET_c on day t is not possible when soil moisture content on day t is lower than the D_{min} , the IR occurs as determined by Eq. (16). After the IR on day t was determined, the soil moisture on day t was calculated by Eq. (17). The NIR is defined as the total amount of IR during the crop growing seasons at the time of irrigation, as shown in Eq. (18).

$$D_{min} = \theta_{WP} \times Z_r \quad (15)$$

$$IR_t = \begin{cases} 0 & \text{for } D_{min} \leq SM_{t-1} + ER_t - ET_{ct} \\ (D_{t-1} - D_{min}) - ER_t + ET_{ct} & \text{for } D_{min} > SM_{t-1} + ER_t - ET_{ct} \end{cases} \quad (16)$$

$$SM_t = \begin{cases} SM_{t-1} + ER_t - ET_{ct} & \text{for } D_{min} \leq SM_{t-1} + ER_t - ET_{ct} \\ D_{min} & \text{for } D_{min} > SM_{t-1} + ER_t - ET_{ct} \end{cases} \quad (17)$$

$$NIR = \int_{t_{planting}}^{t_{harvest}} IR_t \cdot dt \quad (18)$$

3. Results and discussion

3.1. Spatial and temporal weather patterns under climate change

Table 5 shows the average and standard deviation of maximum and minimum temperature and annual total precipitation, and Figure 3 shows the spatial distribution of the maximum temperatures in the historical period (1981–2010) and RCP scenarios for the three periods: 2025s (2011–2040), 2055s (2041–2070), and 2085s (2071–2100). The RCP scenarios predict that the average maximum and minimum temperatures and the standard deviation of the maximum temperature will increase under climate change compared to the

historical period but that the standard deviation of the minimum temperature will decrease. During the historical period, the annual average maximum temperature was 10–18°C in the northern region (zones A, B, C, and D) and 18–20°C in the southern region (zones E, F, G, and H). The maximum average temperature during the 2085s would increase to 20.6 °C (RCP 4.5) and 22.6°C (RCP 8.5). In the central region (zone C), the maximum temperature would increase to 18–21°C under RCP 4.5 and 21–22°C under RCP 8.5, and in the southeastern region (zone H), it would increase to 23–24°C under RCP 8.5.

Figure 4 shows the spatial distribution of the annual total precipitation in the historical period (1981–2010) and RCP scenarios for the three periods: 2025s, 2055s, and 2085s. The annual total precipitation during the 2025s under RCP 4.5 is projected to be generally less than in the historical period, from 1,331 to 1,270 mm. The annual total precipitation increases in the 2055s under RCP 4.5 and 2025s and 2055s under RCP 8.5 in the central and northwestern regions (zones B and C). During the 2085s, annual total precipitation would increase to 1,300–1,600 mm in zones B and C and to greater than 1,700 mm in the southern region (zones E, F, G, and H).

Figure 5 shows the relationship between the rate of precipitation changes from historical data and the rate of runoff changes from historical data (a) and the rate of ER changes from the historical data (b) under climate change for 29 different upland crops during their cropping periods. The average precipitation and runoff of the 29 upland crops during each cropping period would decrease in the 2025s but increase during the other periods. The precipitation on upland crops during the 2025s, except for 7 crops (barley, strawberries, pumpkins, etc.) under RCP 4.5 and 14 crops (Chinese cabbage-spring, melons, rye, etc.) under RCP 8.5, is projected to decrease in a range from -0.25% (garlic under RCP 8.5) to -29.55% (spinach under RCP 8.5) compared to the historical period. On the other hand, in the 2055s and 2085s under both RCP scenarios, the precipitation on upland crops except for

spinach, potatoes, tomatoes, and several other crops during the same cropping period, would increase by up to 37.45% (Chinese cabbage-spring, 2055s under RCP 4.5). The average rate of precipitation changes for the 29 upland crops is from -4.81% (in the 2025s under RCP 4.5) to 8.67% (in the 2085s under RCP 8.5), and the rate of runoff changes from the 29 upland crops is from -5.14% (in the 2025s under RCP 4.5) to 11.49% (in the 2055s under RCP 4.5). In general, as the precipitation decreases, runoff also decreases, and when precipitation increases, runoff also increases. However, the rate of increase in runoff is higher than the rate of increase in precipitation for most crops. Even though the precipitation increases, some of the water is not used for crop growth but lost as runoff, as shown in the analysis of the rate of ER changes under climate change. The average ER during each cropping period decreases under climate change. The average rate of ER changes for the 29 upland crops was from -25.93% (in the 2085s under RCP 4.5) to -21.45% (in the 2055s under RCP 8.5). The rate of ER changes for pumpkins and barley has positive values or decreases of less than 10%, but those for soybeans, red peppers, spinach, red beans, and garlic decrease by up to 30% under climate change. The rate of ER and precipitation decreases is highest for the spinach crop.

3.2. Spatial and temporal trends of projected irrigation requirements for upland crops under climate change

3.2.1. Changes in the crop evapotranspiration

Figure 6 shows the spatial distribution of ET_o in the historical period (1981–2010) and the RCP scenarios for the three periods: 2025s, 2055s, and 2085s. Only small differences are found in the standard deviation of ET_o (43–46 mm) between the historical period and climate change scenarios, as shown in Table 5. The average ET_o during the historical period was 911

mm year⁻¹, which is projected to increase to 995 mm year⁻¹ (the 2085s under RCP 4.5) and 1,054 mm year⁻¹ (the 2085s under RCP 8.5) over the whole of South Korea. The ET_o of the northwestern region (zone B) was 800–900 mm year⁻¹ in the historical period and would increase to 900–950 mm year⁻¹ in the 2085s under RCP 4.5 and to 950–1,050 mm year⁻¹ in the 2085s under RCP 8.5. The ET_o of the eastern region (zone A) was less than 800–850 mm year⁻¹ in the historical period and is projected to increase to 800–1,000 mm year⁻¹ in the 2085s. The ET_o of the southeastern region (zone H) is projected to increase from 900–1,050 mm year⁻¹ (historical period) to more than 1,050 mm year⁻¹ in the 2085s.

In the historical period (Table 6), the total ET_c during each cropping period ranged from 119 mm season⁻¹ (melons, cultivation period from Sep-E to Nov-L) to 632 mm season⁻¹ (onions, cultivation period from Apr.-L to Feb.-E). The total ET_c of spinach, which has the shortest cultivation period, was 179 mm season⁻¹, and the ET_c of wheat, which has the longest cultivation period, was 407 mm season⁻¹. The daily ET_c ranged from 0.8 mm day⁻¹ (barley, cultivation period from Oct.-E to May-L) to 4.4 mm day⁻¹ (maize, cultivation period from Apr.-L to Aug.-M). The ET_c is affected by the cropping period, duration, weather condition, and crop species and characteristics.

Under the RCP 4.5 scenarios (Table 7), ET_c would increase from the historical period. We estimate the total ET_c during each cropping period to range from 134 mm season⁻¹ (melons) to 669 mm season⁻¹ (onions) in the 2025s, from 135 mm season⁻¹ (melons) to 674 mm season⁻¹ (onions) in the 2055s, and from 140 mm season⁻¹ (melons) to 694 mm season⁻¹ (onions) in the 2085s. We estimate the daily average ET_c to range from 0.9 mm day⁻¹ (barley) to 4.4 mm day⁻¹ (maize) in the 2025s, from 1.0 mm day⁻¹ (barley) to 4.5 mm day⁻¹ (maize) in the 2055s, and from 1.0 mm day⁻¹ (barley) to 4.6 mm day⁻¹ (maize) in the 2085s. We found that the average rate of ET_c changes across the 29 crops from historical values to predicted ones would be 4.4% in the 2025s (-2.0% in buckwheat to 13% in Chinese cabbage-fall), 5.4%

in the 2055s (-1.0% in sorghum to 14.3% in Chinese cabbage-fall), and 8.4% in the 2085s (1.7% in buckwheat to 18.5% in Chinese cabbage-fall).

Under the RCP 8.5 scenarios (Table 8), the total ET_c during each cropping period ranges in the 2025s from an estimated 134 mm season⁻¹ (melons) to 663 mm season⁻¹ (onions), in the 2055s from 144 mm season⁻¹ (melons) to 709 mm season⁻¹ (onions), and in the 2985s from 148 mm season⁻¹ (melons) to 739 mm season⁻¹ (onions). We estimate the daily average ET_c to range from 0.9 mm day⁻¹ (barley) to 4.4 mm day⁻¹ (maize) in the 2025s, from 1.0 mm day⁻¹ (barley) to 4.7 mm day⁻¹ (maize) in the 2055s, and from 1.0 mm day⁻¹ (barley) to 4.9 mm day⁻¹ (maize) in the 2085s, all clear increases from the historical period. ET_c under RCP 8.5 shows a significant average increase across the 29 crops compared to the historical period: 3.4% in the 2025s (-3.1% in buckwheat to 13.3% in Chinese cabbage-fall), 10.1% in the 2055s (1.7% in buckwheat to 21.6% in Chinese cabbage-fall), and 15.1% in the 2085s (8.7% in buckwheat to 24.8% in Chinese cabbage-fall). We found that under climate change, onions have the highest total ET_c , maize has the highest daily ET_c , and Chinese cabbage-fall has the highest rate of increase for ET_c among the 29 crops.

3.2.2. Changes in the net irrigation requirement

The crop NIR in the historical period (Table 6) ranged from 55 mm (melons, cultivation period from Sep.-E to Nov.-L) to 439 mm (onions, cultivation period from Apr.-L to Feb.-E). The NIR of spinach, which has the shortest cultivation period, was 138 mm, and the NIR of wheat, which has the longest cultivation period, was 143 mm. The daily crop IR ranged from 0.3 mm day⁻¹ (barley, cultivation period from Oct.-E to May-L) to 2.8 mm day⁻¹ (spinach, cultivation period from May-E to June-M). We found that the crop NIR generally

increased under climate change, which is similar to the results of earlier studies (Gondim et al., 2012; Sav'e et al., 2012).

Under the RCP 4.5 scenarios (Table 7), the crop NIR would range from 69 mm (melons) to 439 mm (onions) in the 2025s, from 74 mm (sorghum) to 437 mm (onions) in the 2055s, and from 81 mm (melons) to 459 mm (onions) in the 2085s. The daily crop IR would range from 0.41 mm day⁻¹ (barley) to 2.99 mm day⁻¹ (spinach) in the 2025s, from 0.47 mm day⁻¹ (barley) to 2.94 mm day⁻¹ (spinach) in the 2055s, and from 0.50 mm day⁻¹ (barley) to 3.00 mm day⁻¹ (spinach) in the 2085s. We estimate the average rate of NIR changes across the 29 crops from the historical values to the predicted ones to be 12.1% in the 2025s (-1.1% in garlic to 41.3% in barley), 11.9% in the 2055s (-6.8% in red peppers to 60.6% in barley), and 19.8% in the 2085s (0.4% in red peppers to 70.8% in barley), which is higher than the rate predicted for ET_c.

Under the RCP 8.5 scenarios (Table 8), the crop NIR would range from 68 mm (melons) to 426 mm (onions) in the 2025s, from 75 mm (sorghum) to 463 mm (onions) in the 2055s, and from 78 mm (melons) to 476 mm (onions) in the 2085s. The daily crop IR would range from 0.40 mm day⁻¹ (barley) to 3.09 mm day⁻¹ (spinach) in the 2025s, from 0.42 mm day⁻¹ (barley) to 3.12 mm day⁻¹ (spinach) in the 2055s, and from 0.47 mm day⁻¹ (barley) to 3.38 mm day⁻¹ (spinach) in the 2085s, which are not higher than the historical period but are higher than in the RCP 4.5 scenarios. We estimate the average rate of NIR changes across the 29 crops from the historical period to the predicted ones to be 9.6% in the 2025s (-6.4% in soybeans to 37.9% in barley), 18.3% in the 2055s (2.5% in garlic to 45.4% in barley), and 25.0% in the 2085s (3.0% in soybean to 62.1% in barley), which is higher than the rate of increase of ET_c under RCP 8.5 and the rate of increase of crop NIR in the 2055s and 2085s under RCP 4.5.

In the 2055s under RCP 4.5 and the 2025s under RCP 8.5, the crop NIR of 6 crops decreased, even though the ET_c of carrots, garlic, green beans, radishes, red peppers, and soybeans increased under climate change. Except for those 6 crops, however, both the ET_c and NIR increase under climate change. In addition, in crops such as buckwheat, Chinese cabbage-spring, maize, potatoes, sorghum, sweet potatoes, tomatoes, and watermelons, our results predict an increase in crop NIR under climate change, even though our results show that ET_c will decrease in the 2025s under the RCP 8.5 scenario. We assume that the effects on crop NIR under climate change in each scenario vary because of different crop responses to different thresholds of precipitation, temperature, and crop growing characteristics (Valverde et al., 2015). From these results, we found that onions have the highest NIR, spinach has the highest daily IR, and barley has the highest increase rate of NIR among the 29 crops.

3.2.3. Comparison of projected ET_c , ER and NIR for upland crops

Figure 7 compares the ratio of ET_c to ER ($ET_c ER^{-1}$) and the ratio of ET_c to NIR ($ET_c NIR^{-1}$). The average ratio $ET_c ER^{-1}$ across the 29 crops in the historical period is 3.9. It increases to 5.32 (2025s), 5.43 (2055s), and 5.77 (2095s) under the RCP 4.5 scenarios (Figure 7 (a)) and to 5.38 (2025s), 5.59 (2055s), and 5.95 (2085s) under the RCP 8.5 scenarios (Figure 7 (b)). The average ratio $ET_c NIR^{-1}$ across the 29 crops in the historical period is 2.00. It decreases to 1.85 (2025s), 1.89 (2055s), and 1.80 (2095s) under the RCP 4.5 scenarios (Figure 7 (a)) and to 1.88 (2025s), 1.84 (2055s), and 1.83 (2085s) under the RCP 8.5 scenarios (Figure 7 (b)). The ratio $ET_c ER^{-1}$ has a tendency to increase, and the ratio $ET_c NIR^{-1}$ has a tendency to decrease under climate change. The ratio $ET_c ER^{-1}$ increases, even though the precipitation is projected to increase in general, because the ET_c has been increased by the increased temperature (Ye et al., 2015), as shown in Table 5 and Figure 3. Thus, the ER of all

29 crops decreases, and the NIR would increase in all of South Korea. In the case of ratio ET_c
 NIR^{-1} , both ET_c and NIR tend to increase, but the increase rate of NIR is higher than that of
 ET_c .

In general, we project that the ratio $ET_c NIR^{-1}$ of cereal crops will be higher than the
ratio $ET_c NIR^{-1}$ of vegetable crops, as shown in Figure 7, and we project that the ratio ET_c
 ER^{-1} of cereal crops will be smaller than that of vegetable crops. The results show that
vegetable crops have less ER and more IR with a similar amount of ET_c compared with cereal
crops. Thus, vegetable crops have more sensitivity to required irrigation water than cereal
crops.

Among cereal crops, the barley & wheat crop group has the steepest decrease gradient
between ratio $ET_c ER^{-1}$ and ratio $ET_c NIR^{-1}$, which means that ET_c changes little per ER, but
the requirement ratio for irrigation water increases rapidly. The ratio $ET_c NIR^{-1}$ of the pulses,
miscellaneous grain, and starch root crop groups decreased but with little sensitivity to the
water requirement compared to the barley & wheat crop group. Among the vegetable crops,
the ratio $ET_c ER^{-1}$ versus ratio $ET_c NIR^{-1}$ of the leafy vegetable group generally decreased
steeply with high sensitivity under climate change compared to other vegetable crop groups.
In particular, even though the spinach crop, from the leafy vegetable group, has the smallest
NIR because of its short cropping period, it has the highest daily IR, the highest ratio $ET_c ER^{-1}$,
and the smallest ratio $ET_c NIR^{-1}$ both in the historical period and under climate change. The
ratio $ET_c NIR^{-1}$ of the crops in the seasoning and root vegetable group, however, increased or
had small differences compared to the other groups of vegetable crops; thus, the seasoning
and root vegetable group has little sensitivity to IR under climate change. The fruits vegetable
group has within-group ratio $ET_c ER^{-1}$ and ratio $ET_c NIR^{-1}$ pattern differences under climate
change. Melons, strawberries, and pumpkins have a steeper decreasing gradient between ratio
 $ET_c ER^{-1}$ and ratio $ET_c NIR^{-1}$ than the other fruit vegetables under climate change.

3.3. Spatial and temporal water availability of major crops

The spatial patterns of NIR in the historical period and under the RCP 4.5 and 8.5 scenarios are illustrated in Figure 8. We selected 4 major crops to investigate the spatial and temporal variations of NIR: 1) barley, which has the smallest daily ET_c and daily IR but with the highest increase rate of NIR; 2) Chinese cabbage-fall, which has the highest increase rate of ET_c ; 3) spinach, which has the highest amount of daily IR; and 4) onions, which have the highest amount of ET_c and NIR.

Barley, mainly cultivated in the winter and spring (from Oct.-E to May-L), is a cereal with high ET_c NIR^{-1} and small ET_c ER^{-1} characteristics. It has less water sensitivity than vegetable crops but a relatively high sensitivity among the cereal crops. Its NIR in RCP 4.5 is higher than in RCP 8.5. Its ET_c under the RCP 8.5 scenario is higher than in RCP 4.5 because of high temperatures. The precipitation and ER in RCP 8.5 are also higher than in RCP 4.5, and they have a greater effect on IR than temperature during the barley cropping period. The NIR was between 47.1 mm (zone E) and 93.5 mm (zone G) in the historical period, and we project an increase ranging from 102.5 mm (zone A) to 131.3 mm (zone H) in the 2085s under RCP 4.5 and from 91.0 mm (zone E) to 130.4 mm (zone G) in the 2085s under RCP 8.5. Barley in South Korea is mainly cultivated in the middle and southern regions (zones D, E, F, G, and H in Fig. (1)), but Kim et al. (2012) predict that it will be cultivated throughout South Korea under climate change. In the midwestern part of South Korea (zones D and E), the NIR in the historical period was 30–50 mm, and we project that to increase to more than 100 mm under climate change. That NIR is smaller than what we project for other regions of South Korea, but the rate of change is higher and the amount of increase is greater than that predicted for other regions. In the mid- and southeastern region (zones G and H), the NIR in

the historical period was 80–94 mm, and we predict increases to 110 mm (2025s), 120 mm (2055s), and 130 mm (2085s) under climate change. That region has the largest NIR, but its rate of change is the lowest, and the amount of increase is smaller than that predicted for other regions. In the southwestern region (zone F), the NIR in the historical period was 82.4 mm, and we predict increases to 116 mm in the 2085s under RCP 8.5 and 126 mm in the 2085s under RCP 4.5.

Chinese cabbage-fall and spinach are leafy vegetable crops. This group has high sensitivity for water security under climate change (Fig. 7). The NIR in the RCP 8.5 scenarios would be higher than in the RCP 4.5 scenarios. For the Chinese cabbage-fall crop (Sep.-E to Nov.-E), we expect the NIR to increase under climate change. However, for spinach, cultivated in the late spring and early summer (from May-E to June-M), we expect that the NIR under RCP 4.5 would be the higher in the 2025s than in the 2055s and in some areas even higher than in the 2085s. The NIR under the RCP 8.5 scenarios increases in some regions from the historical period to the 2085s, but in other regions the NIR remains mostly stable.

Chinese cabbage-fall has the highest increase rate of ET_c and is ranked 8–10th in the increase rate of NIR under climate change. The NIR in the RCP 8.5 scenarios would be higher than in the RCP 4.5 scenarios. The NIR ranged between 78.0 mm (zone A) and 110.1 mm (zone F) in the historical period, and we project it to increase to between 82.7 mm (zone A) and 144.8 mm (zone F) in the 2085s under RCP 4.5 and to between 86.9 mm (zone A) and 146.5 mm (zone F) in the 2085s under RCP 8.5. The NIR in the northern part of South Korea is the lowest, and it gets increasingly high values at an increasing rate moving southward. The northeastern region (zone A) will see fewer changes in NIR under climate change than other regions. NIR in that region will decrease 4% in the 2025s and increase 3% (2055s) and 6% (2085s) under RCP 4.5. It will increase 11% in the 2085s under the RCP 8.5 scenario. In

the southeastern region (zone F), which has the highest NIR value, the increase rate will be between 16% (2025s under RCP 8.5) and 33% (2085s under RCP 8.5), and in the southwestern region (zone H), which has the highest NIR increase rate, the increase rate will be between 20% (2025s under RCP 4.5) and 40% (2085s under RCP 8.5).

The regional NIR of spinach was mainly between 127.0 mm (zone F) and 148.7 mm (zone G) in the historical period, and we project it to range between 129.1 mm (zone F) and 162.4 mm (zone C) in the 2085s under RCP 4.5 and between 147.2 mm (zone F) and 182.5 mm (zone C) in the 2085s under RCP 8.5. Unlike other crops, we project that the NIR for spinach will increase gradually from the southern and eastern coastlines to the northern inland areas. In the central and some inland regions (zones C, E, and F), NIR was approximately 140 mm in the historical period and will increase to approximately 165 mm in the 2085s under RCP 4.5 and 180 mm in the 2085s under RCP 8.5. The NIR in the central inland region of South Korea (zone C) has the highest value, whereas we expect the NIR of other crops in region C to be below the average under climate change. We expect that the amount and increase rate of NIR in the southwestern and southeastern coastal regions (zones F and H) will remain the smallest. In the mideastern region (region G), the NIR showed the smallest increase, even though it was the highest in the historical period. In zones F, G, and H, we expect only small differences in NIR under climate change in the RCP 4.5 scenarios. The NIR increase rates in the RCP 8.5 scenarios are 6% (2025s), 7% (2055s), and 16% (2085s).

The onions, cultivated from Apr.-L to Feb.-E, are in the seasoning vegetable group. We found that it has less sensitivity than crops from other groups to water security under climate change. Thus, we found that even though the onion has the largest ET_c and NIR among the 29 upland crops, those values would change less than those of other crops under climate change. The regional NIR for onions was between 390.6 mm (zone A) and 467.3 mm (zone G) in the historical period, and we project that it will increase to between 403.7 mm

(zone A) and 479.3 mm (zone G) in the 2085s under RCP 4.5 and between 429.1 mm (zone A) and 498.5 mm (zone D) mm in the 2085s under RCP 8.5. The NIR of onions in the northwestern and southeastern regions (zones B, D, G, and H) will be higher than the NIR in the northeastern and southwestern regions (zones A, E, and F). Zones B and D have the highest increase rate of NIR, from 8% (2055s in zone B) to 19% (2085s in zone D) under RCP 4.5 and from 10% (2025s in zone D) to 23% (2085s in zone D) under RCP 8.5. Zones G and H have and will continue to have the highest NIR; we project that the NIR will decrease 2–6% in the 2025s under the RCP 4.5 and 8.5 scenarios, with small increases of 4–9% under further climate change. In zones A and F, we project the NIR to decrease in the 2025s under both RCP 4.5 and 8.5 and in the 2055s under RCP 4.5.

3.4. Discussion

In South Korea, the average maximum temperature will increase under climate change. The total annual precipitation will also generally increase under climate change. However, even though the precipitation increases, much of it is not used for crop growth but instead lost as runoff. We thus project that the average ER during each cropping period will decrease under climate change. In general, the vegetable crops have less ER and more IR with a similar amount of ET_c compared with cereal crops and have more sensitivity to required irrigation water than cereal crops. We found that barley has the smallest daily ET_c and daily IR but with the highest increase rate of NIR, Chinese cabbage-fall has the highest increase rate of ET_c , spinach has the highest amount of daily IR, and onions have the highest amount of ET_c and NIR among the 29 crops. ET_c and IR depend on the type of crop, cropping periods, temperature, and precipitation. Our results show that rainfall increases will not reduce crop IR. In addition, the projected temperature increase will increase ET_c and IR,

which could raise the water deficit problem already present for several upland crops. Water scarcity is already becoming a major limiting factor in sustainable agricultural production (Faramarzi et al., 2010). The variation of IR and ET_c values under different climate change scenarios and crops can be used as an indicator of crop response under climate change.

The NIR of barley under RCP 4.5 is the highest than RCP 8.5 scenario. In the central region, the NIR would be the highest rate of increasing and in the eastern and southeastern region, the NIR would be the largest but has the lowest rate and amount of increasing compared to other region. The NIR of Chinese cabbage-fall and spinach on RCP 8.5 scenarios would be higher than on RCP 4.5 scenarios. The NIR of Chinese cabbage-fall in northern region shows the lowest and gets increasingly high value in southwards. The increasing rate of NIR is also higher in southern than northern region. The NIR of spinach is especially projected to increase gradually from southern and eastern coastline to northern inland area and NIR in central and some inland region has the highest value. Even though the onions have the largest ET_c and NIR in 29 upland crops, there would be little increasing or decreasing compared to other crops under climate change. The NIR of north-western and south-eastern region would be higher than the NIR in the north-eastern and south-western region.

4. Conclusions

An increase in abnormal changes of climate patterns and extreme weather events along with unsustainable irrigation in the uplands can give rise to drought and damage water security, crop productivity, yields, and price fluctuations. Thus, such subjects have recently received considerable attention. It is important to investigate ET_c and IR and to predict which crops are vulnerable to water requirement under climate change. This study provided a

quantitative approach for estimating and quantifying the irrigation water requirements for upland crops under climate change. We developed a soil moisture model and estimated the ER, ET_c, and NIR of 29 upland crops under climate change in South Korea. We constructed our database of crop, soil, and meteorological data and conducted our study using climate data from the past (1981–2010) and predictions for the future (2011–2100) using the RCP 4.5 and RCP 8.5 climate change scenarios. We analyzed and evaluated the spatial and temporal variations of crop IR for each crop to determine which crops and regions are vulnerable to climate change.

Although this study is focused solely on the upland crops, it is important that climate change consequences on irrigation water requirements in order to support the future water planning, management policy development, and monitoring. The results of this study can be used as a predictor of crop response under climate change and a guideline for optimizing cropping patterns, adjusting irrigation systems, and soil water management of upland crops under climate change. Future studies are needed for focusing on: the comparison among the different multi-climate change scenarios, the changes in irrigation requirements at various regional scale, and the consideration of future crop patterns.

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Figure 1. Locations of meteorological stations and land cover map (Ministry of Environment).

Figure 2. Spatial distribution of (a) effective soil depth, (b) soil type, and (c) digital elevation model.

Figure 3. Spatial distribution of maximum temperatures using the RCP 4.5 and 8.5 scenarios.

Figure 4. Spatial distribution of precipitation using the RCP 4.5 and 8.5 scenarios.

(a) The rate of precipitation changes and the rate of runoff changes

(b) The rate of precipitation changes and the rate of effective rainfall changes

Figure 5. Comparison between the rate of precipitation changes and effective rainfall or runoff changes during each cropping period from historical data.

Figure 6. Spatial distribution of reference evapotranspiration using the RCP 4.5 and 8.5 scenarios.

Figure 7. Comparison between the ratio of crop evapotranspiration to effective rainfall and the ratio of crop evapotranspiration to net irrigation requirement using the RCP 4.5 and 8.5 scenarios.

Figure 8. Spatial distribution of the difference values of the net irrigation requirement for upland crops between historical data and climate change data using the RCP 4.5 and RCP 8.5 scenarios.

1 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	2011-2040	RCP 4.5, RCP 8.5	HadGEM3-RA
2055s	2041-2070		
2085s	2071-2100		

3 Table 2 Root depth and cropping patterns (Allen et al., 1998; Jung et al., 2011; Han, 2012; Eom et al., 2013).

Crops			Root depth (m)	Month												
				Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	
Cereals	Barley & Wheat	Barley	1.0-1.2													
		Wheat	1.0-1.5													
		Rye	0.5-0.8													
	Pulses	Soybeans	0.6-0.8													
		Red Beans	0.5-0.7													
		Green Beans	0.5-0.7													
	Miscellaneous grain crop	Millet	1.0-1.5													
		Sorghum	1.0-1.5													
		Maize	1.0-1.7													
		Buckwheat	1.0-1.5													
	Starch roots	Sweet potato	1.0-1.5													
		Potato	0.4-0.6													
	Vegetables	Leafy vegetables	Chinese Cabbage (Spring)	0.5-0.8												
			Chinese Cabbage (fall)	0.5-0.8												
Cabbage			0.5-0.8													
Spinach			0.3-0.5													

		Lettuce	0.3-0.5	
	Seasoning vegetables	Red Pepper	0.5-1.0	
		Green Onion	0.3-0.6	
		Onions	0.3-0.6	
		Garlic	0.3-0.5	
	Fruits vegetables	Watermelon	0.8-1.5	
		Melons	0.8-1.5	
		Strawberry	0.2-0.3	
		Cucumber	0.7-1.2	
		Pumpkin	1.0-1.5	
		Tomato	0.7-1.2	
	Root vegetables	Radish	0.4-0.5	
		Carrot	0.5-1.0	

5 Table 3 Data and model description of soil moisture simulation.

	Categories	Data and model description
a. Input data		
	Meteorological data	Observation station data, temperature, rainfall, relative humidity, wind speed, sunshine hours
	Soil data	Reference soil depth by growth stages, coefficient of soil water depletion fraction for no stress, field capacity and wilting point of soil texture, soil type, effective soil depth
	Crop data	Date of growing period, maximum root depth
b. Evapotranspiration model		
	Reference evapotranspiration	Penman-Monteith equation by FAO
	Crop coefficients	10-days crop coefficients
c. Soil water balance model		
	Effective rainfall	Total available soil water, available soil water capacity
	Soil water balance	Simulation of soil water content in the root zone
	Net irrigation requirement	Accumulated soil moisture deficit

7 Table 4 Basal crop coefficient for use with the FAO Penman-Monteith (Allen et al., 1998; Jung et al., 2011; Han, 2012; Eom et al., 2013).

Crops			K _{cb}		
			Initial	Middle	End
Cereals	Barley & Wheat	Barley	0.15	1.10	0.15
		Wheat	0.15	1.10	0.15
		Rye	0.15	1.10	0.30
	Pulses	Soybeans	0.15	1.10	0.30
		Red Beans	0.15	1.10	0.30
		Green Beans	0.15	1.10	0.80
	Miscellaneous grain crop	Millet	0.15	0.95	0.20
		Sorghum	0.15	1.05	0.35
		Maize	0.15	1.15	0.50
		Buckwheat	0.15	1.10	0.15
	Starch roots	Sweet potato	0.15	1.10	0.55
		Potato	0.15	1.10	0.65
Vegetables	Leafy vegetables	Chinese Cabbage (Spring)	0.15	1.11	0.95
		Chinese Cabbage (fall)	0.15	1.25	0.95
		Cabbage	0.15	0.95	0.85
		Spinach	0.15	0.90	0.85
		Lettuce	0.15	0.90	0.90
	Seasoning	Red Pepper	0.15	1.06	0.82

	vegetables	Green Onion	0.15	0.90	0.90
		Onions	0.15	0.95	0.65
		Garlic	0.15	0.90	0.60
	Fruits vegetables	Watermelon	0.15	0.95	0.70
		Melons	0.15	1.00	0.70
		Strawberry	0.30	0.80	0.70
		Cucumber	0.15	0.95	0.70
		Pumpkin	0.15	0.95	0.70
		Tomato	0.15	1.10	0.70
	Root vegetables	Radish	0.15	0.85	0.75
		Carrot	0.15	0.95	0.85

9 Table 5 Average and standard deviation (in parentheses) of (a) daily maximum temperatures, (b) daily minimum temperature, (c) daily
10 precipitation, (d) reference evapotranspiration as determined by the daily weather data for 54 meteorological stations.

Classification		Maximum temperature (°C)	Minimum temperature (°C)	Precipitation (mm)	Reference evapotranspiration (mm)
Observed		18.1 (0.62)	7.6 (0.69)	1331 (326)	911 (46)
RCP 4.5	2025s	19.0 (0.83)	8.4 (0.71)	1270 (282)	955 (43)
	2055s	20.0 (0.71)	9.6 (0.67)	1406 (290)	968 (46)
	2085s	20.6 (0.62)	10.1 (0.42)	1476 (350)	995 (43)
RCP 8.5	2025s	18.9 (0.75)	8.4 (0.67)	1352 (294)	945 (43)
	2055s	20.6 (0.77)	10.1 (0.70)	1431 (263)	1008 (45)
	2085s	22.6 (0.84)	11.8 (0.53)	1487 (341)	1054 (44)

- 12 Table 6 Temporal changes in crop evapotranspiration, effective rainfall, and net irrigation requirement for upland crops as determined by
- 13 the soil water balance model for 54 meteorological stations using historical data.

Crops			1981-2010 [*]		
			ETc ^a	ER ^b	NIR ^c
Cereals	Barley & Wheat	Barley	202 (13)	103 (20)	70 (27)
		Wheat	407 (19)	194 (29)	143 (42)
		Rye	226 (14)	89 (18)	105 (28)
	Pulses	Soybeans	433 (22)	123 (24)	213 (53)
		Red Beans	347 (18)	115 (19)	165 (41)
		Green Beans	371 (18)	104 (17)	201 (40)
	Miscellaneous grain crop	Millet	570 (25)	239 (33)	209 (62)
		Sorghum	223 (12)	110 (21)	74 (35)
		Maize	534 (26)	185 (34)	233 (63)
		Buckwheat	193 (10)	76 (21)	89 (31)
	Starch roots	Sweet potato	366 (16)	163 (24)	135 (41)
		Potato	259 (11)	50 (14)	175 (26)
Vegetables	Leafy vegetables	Chinese Cabbage (Spring)	295 (14)	63 (17)	185 (34)
		Chinese Cabbage (fall)	150 (9)	34 (13)	92 (24)
		Cabbage	373 (18)	79 (20)	251 (38)
		Spinach	179 (8)	22 (8)	138 (16)

		Lettuce	215 (14)	35 (12)	157 (25)
	Seasoning vegetables	Red Pepper	460 (22)	129 (24)	235 (51)
		Green Onion	330 (17)	58 (13)	226 (30)
		Onions	632 (26)	112 (19)	425 (48)
		Garlic	567 (24)	101 (17)	377 (49)
	Fruits vegetables	Watermelon	350 (17)	143 (23)	134 (42)
		Melons	119 (7)	46 (15)	55 (23)
		Strawberry	327 (16)	45 (11)	251 (26)
		Cucumber	606 (26)	208 (31)	284 (62)
		Pumpkin	209 (14)	83 (23)	89 (33)
		Tomato	290 (14)	95 (22)	144 (41)
	Root vegetables	Radish	328 (17)	54 (13)	221 (34)
		Carrot	353 (18)	93 (20)	195 (42)

14 ^a ETc: crop evapotranspiration (mm).

15 ^b ER: effective rainfall (mm).

16 ^c NIR: net irrigation requirement (mm).

17 * Units: average, standard deviation in parentheses.

18 Table 7 Temporal changes in crop evapotranspiration, effective rainfall, and net irrigation requirement for upland crops as determined by
19 the soil water balance model for 54 meteorological stations using the RCP 4.5 scenario.

Crops			RCP 4.5 scenario								
			2011-2040 [*]			2041-2070 [*]			2071-2100 [*]		
			ETc ^a	ER ^b	NIR ^c	ETc	ER	NIR	ETc	ER	NIR
Cereals	Barley & Wheat	Barley	221 (10)	95 (23)	99 (29)	229 (9)	90 (26)	112 (33)	233 (10)	89 (24)	119 (34)
		Wheat	443 (22)	168 (28)	179 (39)	449 (14)	159 (30)	187 (40)	463 (24)	157 (33)	202 (54)
		Rye	247 (10)	79 (19)	142 (28)	256 (10)	75 (22)	154 (32)	261 (11)	73 (20)	162 (32)
	Pulses	Soybeans	456 (33)	83 (20)	214 (55)	455 (24)	81 (15)	204 (34)	473 (34)	78 (18)	221 (49)
		Red Beans	353 (25)	81 (17)	179 (42)	350 (22)	83 (17)	166 (42)	363 (27)	80 (18)	184 (49)
		Green Beans	375 (22)	74 (14)	209 (37)	371 (22)	78 (16)	192 (43)	384 (26)	75 (17)	210 (48)
	Miscellaneous grain crop	Millet	587 (35)	176 (33)	242 (65)	588 (27)	177 (33)	232 (57)	607 (37)	169 (35)	257 (75)
		Sorghum	225 (16)	84 (20)	86 (33)	221 (16)	84 (21)	74 (37)	229 (18)	84 (22)	87 (40)
		Maize	539 (34)	129 (31)	264 (67)	536 (30)	135 (35)	243 (65)	552 (38)	130 (33)	267 (76)
		Buckwheat	189 (9)	61 (22)	102 (33)	193 (10)	63 (26)	102 (41)	197 (12)	61 (24)	109 (40)
	Starch roots	Sweet potato	369 (22)	122 (23)	159 (44)	368 (19)	126 (26)	147 (48)	378 (23)	123 (28)	161 (54)
		Potato	258 (16)	38 (14)	189 (33)	261 (15)	40 (17)	188 (39)	265 (16)	38 (16)	194 (37)
Vegetables	Leafy vegetables	Chinese Cabbage (Spring)	296 (17)	47 (16)	201 (34)	292 (19)	50 (17)	186 (43)	301 (20)	49 (16)	199 (42)
		Chinese Cabbage (fall)	169 (10)	27 (13)	107 (22)	171 (8)	24 (13)	113 (20)	178 (11)	24 (12)	119 (23)

		Cabbage	375 (18)	63 (21)	275 (44)	383 (18)	63 (23)	281 (48)	390 (19)	61 (23)	290 (50)
		Spinach	181 (13)	15 (8)	149 (23)	181 (12)	16 (8)	147 (26)	185 (12)	16 (8)	150 (23)
		Lettuce	216 (10)	30 (12)	165 (26)	224 (10)	30 (13)	174 (26)	228 (12)	29 (13)	179 (30)
	Seasoning vegetables	Red Pepper	474 (32)	88 (19)	236 (51)	471 (25)	91 (17)	219 (41)	487 (33)	89 (20)	236 (54)
		Green Onion	366 (19)	51 (13)	237 (28)	372 (14)	47 (15)	242 (28)	383 (21)	45 (15)	254 (36)
		Onions	669 (34)	83 (16)	439 (48)	674 (24)	81 (17)	437 (37)	694 (38)	77 (18)	459 (58)
		Garlic	578 (32)	70 (15)	373 (49)	579 (26)	71 (14)	362 (42)	596 (36)	70 (16)	380 (59)
	Fruits vegetables	Watermelon	357 (24)	101 (21)	153 (43)	354 (21)	105 (21)	138 (42)	366 (26)	100 (23)	156 (49)
		Melons	134 (8)	41 (15)	69 (22)	135 (6)	36 (17)	75 (21)	140 (9)	33 (16)	81 (24)
		Strawberry	339 (13)	38 (11)	273 (27)	349 (13)	36 (10)	286 (28)	355 (16)	35 (11)	292 (31)
		Cucumber	619 (32)	152 (30)	311 (61)	622 (27)	155 (31)	300 (60)	640 (37)	153 (33)	320 (76)
		Pumpkin	222 (10)	81 (26)	108 (38)	231 (10)	76 (28)	125 (38)	235 (10)	73 (26)	134 (39)
		Tomato	317 (20)	73 (19)	164 (37)	321 (14)	70 (21)	167 (31)	331 (21)	67 (20)	177 (39)
	Root vegetables	Radish	356 (24)	38 (11)	221 (35)	359 (17)	36 (10)	221 (26)	372 (24)	35 (11)	232 (35)
		Carrot	380 (25)	67 (17)	201 (41)	381 (17)	64 (15)	196 (29)	395 (26)	63 (16)	212 (40)

20 ^a ETc: crop evapotranspiration (mm).

21 ^b ER: effective rainfall (mm).

22 ^c NIR: net irrigation requirement (mm).

23 ^{*} Units: average, standard deviation in parentheses.

24 Table 8 Temporal changes in crop evapotranspiration, effective rainfall, and net irrigation requirement for upland crops as determined by
25 the soil water balance model for 54 meteorological stations using the RCP 8.5 scenario.

Crops			RCP 8.5 scenario								
			2011-2040*			2041-2070*			2071-2100*		
			ETc ^a	ER ^b	NIR ^c	ETc	ER	NIR	ETc	ER	NIR
Cereals	Barley & Wheat	Barley	219 (9)	93 (22)	96 (25)	234 (9)	101 (23)	102 (28)	245 (12)	101 (27)	113 (44)
		Wheat	440 (19)	167 (31)	176 (45)	471 (20)	172 (28)	198 (41)	489 (22)	174 (32)	205 (47)
		Rye	245 (10)	78 (20)	137 (28)	261 (10)	84 (20)	145 (28)	274 (13)	83 (23)	160 (42)
	Pulses	Soybeans	451 (27)	84 (17)	200 (43)	485 (30)	83 (17)	223 (48)	503 (34)	86 (17)	220 (49)
		Red Beans	346 (19)	78 (17)	167 (39)	371 (21)	76 (18)	187 (44)	386 (25)	78 (17)	189 (45)
		Green Beans	367 (16)	72 (15)	199 (36)	391 (20)	71 (17)	216 (43)	410 (25)	71 (15)	226 (43)
	Miscellaneous grain crop	Millet	579 (27)	171 (33)	232 (59)	620 (30)	174 (31)	259 (62)	646 (35)	177 (32)	267 (62)
		Sorghum	219 (12)	76 (22)	91 (38)	235 (15)	77 (22)	102 (40)	245 (17)	80 (21)	102 (41)
		Maize	529 (26)	125 (32)	250 (61)	564 (32)	128 (34)	275 (76)	591 (37)	127 (31)	285 (71)
		Buckwheat	187 (9)	58 (24)	101 (38)	197 (10)	65 (24)	102 (38)	210 (14)	60 (23)	124 (42)
	Starch roots	Sweet potato	364 (16)	115 (24)	160 (42)	386 (21)	118 (24)	171 (50)	405 (23)	118 (25)	182 (49)
		Potato	257 (12)	34 (15)	195 (32)	267 (15)	37 (16)	198 (37)	284 (17)	33 (14)	222 (35)
Vegetables	Leafy vegetables	Chinese Cabbage (Spring)	291 (14)	44 (17)	202 (38)	307 (20)	45 (18)	213 (47)	322 (20)	44 (16)	226 (40)
		Chinese Cabbage (fall)	170 (10)	29 (12)	109 (24)	182 (10)	28 (11)	119 (22)	187 (11)	28 (12)	122 (22)

		Cabbage	372 (14)	60 (21)	277 (42)	390 (20)	66 (24)	283 (51)	414 (24)	61 (20)	315 (51)
		Spinach	180 (9)	12 (8)	154 (20)	187 (12)	14 (8)	156 (26)	198 (13)	13 (8)	169 (23)
		Lettuce	213 (10)	32 (14)	159 (29)	226 (12)	35 (13)	166 (28)	240 (17)	31 (12)	186 (34)
	Seasoning vegetables	Red Pepper	467 (25)	87 (19)	224 (45)	499 (28)	85 (18)	247 (49)	521 (31)	90 (18)	247 (50)
		Green Onion	365 (18)	53 (15)	235 (32)	392 (21)	53 (14)	256 (33)	407 (22)	53 (16)	263 (39)
		Onions	663 (28)	84 (16)	426 (46)	709 (30)	81 (16)	463 (47)	739 (33)	84 (17)	476 (50)
		Garlic	570 (23)	70 (15)	360 (42)	607 (27)	68 (15)	386 (48)	635 (32)	68 (13)	402 (47)
	Fruits vegetables	Watermelon	349 (19)	97 (21)	142 (40)	374 (21)	96 (22)	159 (47)	391 (25)	99 (22)	162 (46)
		Melons	134 (8)	44 (16)	68 (23)	144 (8)	44 (14)	75 (20)	148 (9)	42 (16)	78 (23)
		Strawberry	336 (12)	37 (12)	271 (28)	355 (16)	39 (12)	284 (31)	375 (19)	37 (11)	308 (35)
		Cucumber	612 (24)	149 (29)	302 (57)	651 (28)	152 (29)	326 (61)	682 (33)	151 (27)	346 (60)
		Pumpkin	220 (10)	81 (27)	106 (36)	234 (11)	85 (24)	112 (34)	247 (14)	84 (29)	128 (50)
		Tomato	317 (18)	79 (19)	156 (36)	341 (20)	77 (18)	175 (36)	352 (21)	78 (19)	175 (37)
	Root vegetables	Radish	355 (21)	42 (11)	209 (32)	381 (22)	39 (9)	230 (32)	395 (25)	40 (10)	232 (34)
		Carrot	378 (22)	73 (16)	187 (36)	405 (23)	70 (15)	207 (37)	420 (26)	71 (15)	209 (39)

26 ^a ETc: crop evapotranspiration (mm).

27 ^b ER: effective rainfall (mm).

28 ^c NIR: net irrigation requirement (mm).

29 ^{*} Units: average, standard deviation in parentheses.