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Quantifying the impact of climate change on crop yield and water footprint of rice in the Nam Oon Irrigation Project, Thailand

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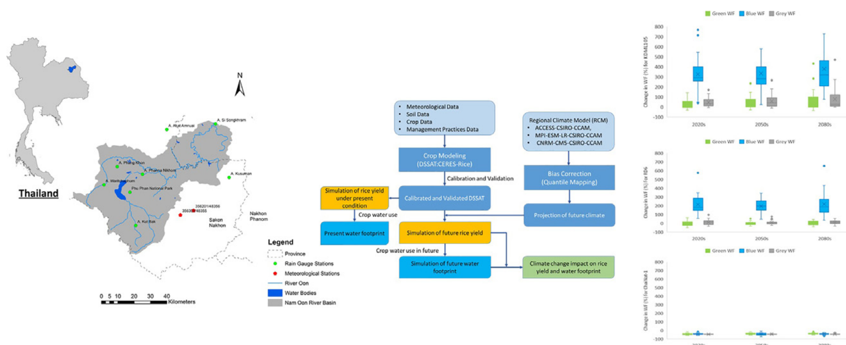
HIGHLIGHTS

- DSSAT (CERES-Rice) model is used to simulate the rice yield.
- Rice yield and water footprint under climate change are assessed.
- Water footprint of KDML-105 and RD-6 rice varieties is expected to increase in future.
- Water footprint of ChaiNat-1 variety is expected to decrease in future.

GRAPHICAL ABSTRACT



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ABSTRACT

Northeast Thailand makes a significant contribution to fragrant and high-quality rice consumed within Thailand and exported to other countries. The majority of rice is produced in rainfed conditions while irrigation water is supplied to rice growers in the dry season. This paper quantifies the potential impact of climate change on the water footprint of rice production using the DSSAT (CERES-Rice) crop growth model for the Nam Oon Irrigation Project located in Northeast Thailand. Crop phenology data was obtained from field experiments and used to set up and validate the CERES-Rice model. The present and future water footprint of rice, the amount of water evaporated during the growing period, was calculated under current and future climatic condition for the irrigation project area. The outputs of three regional climate models (ACCESS-CSIRO-CCAM, CNRM-CM5-CSIRO-CCAM, and MPI-ESM-LR-CSIRO-CCAM) for scenarios RCP 4.5 and RCP 8.5 were downscaled using quantile mapping method. Simulation results show a considerably high increase in the water footprint of KDML-105 and RD-6 rice varieties ranging from 56.5 to 92.2% and 27.5 to 29.7%. respectively for the future period under RCP 4.5, and 71.4 to 76.5% and 27.9 to 37.6%, respectively under RCP 8.5 relative to the simulated baseline water footprint for the period 1976–2005. Conversely, the ChaiNat-1 variety shows a decrease in projected water footprint of 42.1 to 39.4% under RCP 4.5 and 38.5 to 31.7% under RCP 8.5. The results also indicate a huge increase in the future blue water footprint, which will consequently cause a high increment in the irrigation water requirement in order to meet the plant's evaporation demand. The research outcome highlights the importance of proper adaptation strategies to reduce or maintain acceptable water footprints under future climate conditions.

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1. Introduction

Agriculture contributes 10.5% to the GDP of Thailand (World Bank, 2014). Despite its small GDP contribution, the majority of people depend on agriculture for their livelihoods, and hence it plays a vital role in the Thai economy. Crops are vital to the various sub-sectors as they contribute 60% to the total agricultural production. Rice and rubber are the main products, followed by fishery (FFTC-AP, 2014). Rice (*Oryza sativa* L.) is the major crop grown in Thailand. Annually, about 30 million tons of rice has been exported by Thailand in recent years. Approximately 20% of the country's total land area is used for rice production, with the northeast region (also called "Isan") the major contributor. There are two main cropping seasons; the primary rice crop is grown in the wet season (May to October) and the secondary in the dry season (November to April) (ADB, 2012).

Water is absolutely essential for rice production, and on average, rice needs two or three times more water than any other crop (Maclean et al., 2013). In Thailand, for every hectare(ha) of rice, approximately 10,000 m^3 of water is required in each season, while the water required for each kg of rice is about 2 to 3 m^3 (Rahatwal, 2010). Despite the importance of rice production, it also adversely affects the environment (Roger and Joulian, 1998; Tilman et al., 2001; Thanawong et al., 2014). For instance, besides the high water extraction required for rice production, heavy pesticide usage is another burning concern. In addition, when rice is flooded, it undergoes anaerobic processes, resulting in the formation and release of large amounts of methane into the atmosphere (Thanawong et al., 2014).

Climate change exerts an additional pressure on the world's food supply system. It affects food production directly through changes in agro-ecological conditions and, thereby, affects the overall food supply (Ingram et al., 2008). Extensive research indicates that high temperatures, variable rainfall, floods, droughts, and cyclones are likely to cause a significant decrease in world food production, especially for developing countries (Gregory et al., 2005). The increase in temperature shortens the phenological phases of crops (planting, flowering, and harvesting) and affects plant growth and development (Teixeira et al., 2013). Crop yield is expected to have an increment in higher latitudes and a decrement in lower latitudes (Stocker et al., 2013). Various researchers such as Babel et al. (2011), Soora et al. (2013), Luo et al. (2015), and Shrestha et al. (2016) have studied the potential impact of climate change on rice production and concluded that it is pivotal to ascertain how rice production and water use efficiency is affected by climate change in order to formulate plans and policies for adapting the agricultural system against the changing climate.

Hoekstra and Hung (2002) introduced the water footprint (WF) theory which was later elaborated by Hoekstra and Chapagain (2008). A framework for assessing the utilisation of water during the agricultural production process is provided by this concept. The WF is an index showing the direct and indirect use of freshwater, establishing a consumptive relationship with the impact on related resources. The WF may be defined as the amount of water required to produce a particular goods or services (Aldaya et al., 2012). There are three distinguishable components of WF: (1) green WF: amount of rainwater evaporated to form a product; (2) blue WF: amount of irrigation water evaporated to form a product; and (3) grey WF: amount of water to dilute the pollutants from agricultural sources (fertilisers, pesticides, etc.) so that the existing water quality standards and natural concentration of water sources are maintained (Hoekstra et al., 2012). Various studies have been conducted on the assessment of a product's WF from a consumption point of view at global as well as national level (Long et al., 2005; Chapagain and Hoekstra, 2007; Chapagain and Orr, 2009; Bulsink et al., 2009; Liu and Yang, 2010; Mekonnen and Hoekstra, 2011; Lamastra et al., 2014). However, some recent studies have estimated the WF of a particular crop on a smaller scale (district and provincial) from the point of view of production, regional climate change impact, or both (Chapagain and Hoekstra, 2011; Mekonnen and Hoekstra, 2011; Hoekstra et al., 2012; Sun et al., 2012, 2013; Bocchiola et al., 2013, Bocchiola, 2015).

The main objective of this study is to quantify the WF of rice production in the Nam Oon Irrigation Project in both wet seasons (rainfed conditions) and dry seasons (irrigated conditions). The specific objectives of the study are: (1) to project the future climate of the Nam Oon River Basin; (2) to simulate rice yield under current and future climatic conditions; and (3) to quantify the climate change impact on the WF of rice production in the Nam Oon Irrigation Project.

2. Materials and methods

2.1. Study area description

The Nam Oon Irrigation Project is located in Northeast Thailand and covers most of the Sakon Nakhon Province and a small part of the Nakhon Phanom Province. It diverts water from the Nam Oon River (Fig. 1), which originates in the Phu Pan Mountain range and empties into the Nam Songkran River at Sri Songkran. The Nam Oon Irrigation Project has two main purposes: to reduce flood damage by reservoir construction and to supply sufficient irrigation water for crops. Both functions are aimed at increasing agricultural production and social security.

The project area is 32,480 ha and the irrigation area in the wet and dry seasons is 29, 728 ha and 16,000 ha, respectively. The project distribution system consists of two main canals: the right measuring 45.70 km and the left 28.04 km, 79 lateral and sublateral with a total length of 239.63 km, together with 1455 canal-related structures and four electric pumping stations (Fig. 1).

The climate of the region is tropical where the maximum and minimum temperature ranges from 28.5 to 35 °C and 14.73 to 25.08 °C, respectively and average rainfall is 1400 mm/year. Since seasonal rainfall (June to October) accounts for 85% of the annual total, farmers opt for rainfed rice cultivation: planting in June and harvesting in November. The soil has a salinity problem and is generally comprised of silty clay.

KDML 105 and RD6 are the common rice varieties grown in the region. Due to the short growing period for rice varieties, a second cropping season (dry season) also exists which usually starts in January and ends in May; about 14% of rice is cultivated in the dry season. However, irrigation water is supplied for growing rice in the dry season and the ChaiNat-1 variety is becoming more preferable for the dry season due to its drought resistant properties.

2.2. Data collection

There are eight rainfall stations but no temperature station in the Nam Oon River Basin. Hence, two nearby meteorological stations at Sakon Nakhon Province were used for climate analysis. Meteorological data for Sakon Nakhon was collected from the Thai Meteorological Department (TMD). The daily weather data comprised precipitation, maximum and minimum temperature, sunshine hours, relative humidity, and wind speed for the period 1976–2014. Precipitation and maximum and minimum temperature were the only climate variables taken into consideration for the future. These variables were taken from the outputs of three regional climate models (ACCESS-CSIRO-CCAM, CNRM-CM5-CSIRO-CCAM, and MPI-ESM-LR-CSIRO-CCAM) for the future periods (2020s, 2050s, and 2080s). Representative Concentration Pathways (RCPs), embraced in the Fifth Assessment Report (AR5) of the IPCC, outline changes in the atmosphere's net balance between incoming and outgoing radiation (IPCC, 2013). Four RCPs (RCP 2.6, RCP 4.5, RCP 6, and RCP 8.5) comprise the scenario set, based on their radiating forces. These four RCPs consists range of greenhouse emission scenarios with or without climate policies. The RCP 2.6 is the low emission scenario which leads to very low forcing level. It is possible to achieve RCP 2.6 pathway, only if proper mitigation policies and efforts are made to

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