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Modeling future water footprint of barley production in Alberta, Canada: Implications for water use and yields to 2064

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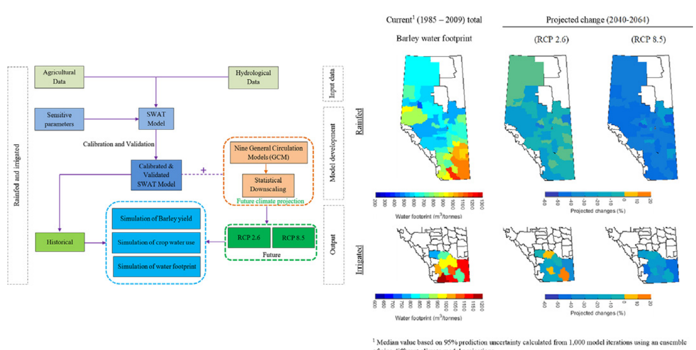
HIGHLIGHTS

- A framework is developed to model barley yield, water use and water footprint.
- Yield and water footprint of barley is assessed under climate change.
- Rainfed yield is projected to increase and irrigated yield is expected to remain unchanged.
- Water footprint is projected to decrease in future.
- Water footprint is adjusted based on water-stress conditions.

GRAPHICAL ABSTRACT



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ABSTRACT

Despite the perception of being one of the most agriculturally productive regions globally, crop production in Alberta, a western province of Canada, is strongly dependent on highly variable climate and water resources. We developed agro-hydrological models to assess the water footprint (WF) of barley by simulating future crop yield (Y) and consumptive water use (CWU) within the agricultural region of Alberta. The Soil and Water Assessment Tool (SWAT) was used to develop rainfed and irrigated barley Y simulation models adapted to sixty-seven and eleven counties, respectively through extensive calibration, validation, sensitivity, and uncertainty analysis. Eighteen downscaled climate projections from nine General Circulation Models (GCMs) under the Representative Concentration Pathways 2.6 and 8.5 for the 2040–2064 period were incorporated into the calibrated SWAT model. Based on the ensemble of GCMs, rainfed barley yield is projected to increase while irrigated barley is projected to remain unchanged in Alberta. Results revealed a considerable decrease (maximum 60%) in WF to 2064 relative to the simulated baseline 1985–2009 WF. Less water will also be required to produce barley in northern Alberta (rainfed barley) than southern Alberta (irrigated barley) due to reduced water consumption. The modeled WF data adjusted for water stress conditions and found a remarkable change (increase/decrease) in the irrigated counties. Overall, the research framework and the locally adapted regional model results will facilitate the development of future water policies in support of better climate adaptation strategies by providing improved WF projections.

1. Introduction

Canada is home to ~12 million head of cattle with the majority of beef production occurring in Alberta (Farm Credit Canada, 2012). Alberta is globally recognized for its large oil and agricultural exports

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including beef and live cattle to over 50 countries around the world (Alberta Cattle Feeders' Association, 2017). Beef production in this province depends largely on annual feed crops such as wheat, canola, and barley, with barley being the principal feed. Given that global beef production is expected to increase 74% by 2050 (FAO, 2017), there will be an increased need to produce barley to sustain Alberta beef exports. Water use intensity of beef production in Canada indicates that feed and pasture production are responsible for the majority of water consumption (Legesse et al., 2017). However, unreliable precipitation patterns, potentially adverse impacts due to climate change, and increasing conflicts among different water users represent serious challenges to the availability of this critical resource for Alberta's beef industry (Islam and Gan, 2014; de Souza et al., 2017). Thus, an assessment of barley production in the future in light of the uncertainties in water availability arising from climate change is needed in order to prepare the beef industry for potential issues that can compromise its sustainability in Alberta and its contribution to global food security.

A usable metric for assessing current and future crop water use is water footprint (WF) accounting, which offers a quantifiable indicator to measure the volume of consumptive water use (CWU) per unit crop yield (Y). The WF of crops can be quantified as being composed of blue, green, and grey forms (Hoekstra et al., 2011). The blue WF of crops is based on freshwater consumption (e.g., lakes, river, and aquifers), while green WF is based on effective precipitation that is consumed in the form of soil moisture. The grey WF is quantified based on the amount of freshwater required to assimilate pollutants to meet specific water quality standards. Application of the water footprint concept has been particularly challenging at large-scale studies (Marano and Filippi, 2015; Ma and Ma, 2017; Shrestha et al., 2017a), due to uncertainties in representing soil-plant-water-atmosphere relationships at the regional scale, where changes in water consumption and crop yields are influenced by both natural and anthropogenic factors. In this context, future projections of crop production in relation to climate change involve interactive and dynamic soil-plant-atmosphere processes that are assessed with integrated system models (Ahuja et al., 2007).

One example of such models is the Soil and Water Assessment Tool (SWAT), a process-based, time-continuous, bio-physical model (Arnold et al., 1998) that simulates hydrology and soil-water dynamics at a daily time step (Vigiak et al., 2015). It is widely used to simulate the impacts of climate, water, and agricultural management practices on hydrology, vegetation growth, and related bio-physical processes in small and large basins (Tuo et al., 2016). SWAT has been used in a number of large and regional scale studies (Abbaspour et al., 2015; Vigiak et al., 2015; Palazzoli et al., 2015; Liu et al., 2017; Faramarzi et al., 2017; Shrestha et al., 2017a).

It is hypothesized that barley production and its water use in Alberta can satisfactorily be projected by considering the key influential factors and adapting to the regional/local conditions using the SWAT model. The main objective of this study is to assess the WF of barley as the principal feed crop used in beef cattle production. The specific objectives are: 1) to set up a high-resolution crop model of Alberta for rainfed and irrigated barley by utilizing available local agro-hydrologic data and information; 2) to adjust physical parameters of the rainfed and irrigated models to local conditions by calibration and validation of annual crop yields; 3) to project future climate change impacts on Y, CWU, and blue and green WF of rainfed and irrigated barley; and to address the most influential bio-physical factors affecting the likely changes; and 4) to adjust the results to local water stress conditions.

2. Methods and data

2.1. Study area

Alberta is a semi-arid western province in Canada with an area spanning 661,000 km^2 (Fig. 1a,b). It has a highly variable climate with mean annual precipitation ranging from ≈280 mm in the south to ≈1000 mm at the higher elevations of the Rocky Mountains (Masud et al., 2015). Mean winter temperatures usually range from −25.1 to −9.6 °C while mean summer temperatures vary between 8.7 and 18.5 °C with the mean annual temperature ranging from 3.6 to 4.4 °C (Jiang et al., 2017). The province has 17 river basins (Fig.1a). Most of the southern river basins are snowmelt dominated in their upstream highland areas, and glacier melt plays a major role in supplying downstream water needs in late summer.

Alberta is the home of 65% irrigation in Canada (Alberta WaterPortal, 2017). With 6% of Alberta's total water availability (Faramarzi et al., 2017), the southern river basins provide nearly 57% of the irrigation water in 13 irrigation districts (Fig. 1c). The government of Alberta is seeking means of improving water use efficiency, and reducing the water footprint to meet water supply-demand constraints during periods of high water shortages (Faramarzi et al., 2017). Irrigation districts are spread in 11 out of 67 counties (Fig. 1c) in the southern part of the province, where there is often not sufficient precipitation and soil moisture to naturally meet crop requirements. In the central and northern areas of the province crop production relies on precipitation. Barley is one of the most commonly grown crops in the province, and its production and Y is dependent on the availability of water resources and influenced by other climate and phenological factors. For instance, rainfed barley had an average annual yield of 2.5 t/ha, dropped to its lowest level (1.5 t/ha) in 2002, due to drought, generating the lowest yield during the 25-year period (1983–2007). While irrigated yield sustained around 4.5 t/ha with sufficient irrigation to compensate climate variations (Fig. 1d,e).

2.2. SWAT overview

The SWAT model divides each river basin into sub-basins based on topography and subsequently into Hydrologic Response Unit (HRU) according to the soil, land use, and slope characteristics. The plant growth component of SWAT, which is a simplified version of the Erosion Productivity Impact Calculator (EPIC; ref. Williams, 1995), is capable of simulating a wide range of crops, grassland, and pasture. In the SWAT model, crop biomass development (above- and- under ground) is simulated on a daily time-step based on light interception and conversion of CO_2 to biomass. Actual crop yield is then calculated as a product of actual above ground biomass and the actual harvest index. Actual harvest index is calculated, on a daily basis, as a fraction of above ground plant dry biomass removed as dry economic yield. A plant is assumed to start growing once the temperature exceeds its base temperature (T_b). The portion of the mean daily temperature exceeding T_b will contribute to growth over the growing period. If the temperature falls below T_b then the plant is assumed to enter dormancy. The actual crop water uptake is simulated in a daily time step. It is based on soil water dynamics in different soil layers and crop potential evapotranspiration (PET). There are three different methods (i.e. Penman-Monteith, Priestley-Taylor, and Hargreaves) available in the model to calculate PET, with the Penman-Monteith being the most comprehensive as it considers various climatic factors (Allen et al., 1989). The Penman-Monteith approach was considered in this study as the base to simulate CWU.

In this study, four and five management practices were selected for rainfed and irrigated condition, respectively. The practices were ploughing, fertilizer application, irrigation, planting operation and harvest and kill operations. Two options are available for application of irrigation water and timing of fertilizer application: user specified and automatic. In the automatic option, an irrigation event is triggered by water stress threshold and fertilizer is applied based on nutrients stress factor. The total amount of fertilizer applied during the growing season is specified by the user. More details are given by Neitsch et al. (2011).

2.3. Input data, model development and parameterization

In this study, ArcSWAT 2012 (Rev. 632) was used to set up the model. A hydrology model of the province, developed and calibrated in an