Global implications of regional grain production through virtual water trade

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Abstract

Crop yields (Y) and virtual water content (VWC) of agricultural production are affected by climate variability and change, and are highly dependent on geographical location, crop type, specific planting and harvesting practice, soil property and moisture, hydro-geologic and climate conditions. This paper assesses and analyzes historical (1985-2009) and future (2040-2064) Y and VWC of three cereal crops (i.e., wheat, barley, and canola) with high spatial resolution in the highly intensive agricultural region of Alberta, Canada, using the Soil and Water Assessment Tool (SWAT). A calibrated and validated SWAT hydrological model is used to supplement agricultural (rainfed and irrigation) models to simulate Y and crop evapotranspiration (ET) at the sub-basin scales. The downscaled climate projections from nine General Climate Models (GCMs) for RCP 2.6 and RCP 8.5 emission scenarios are fed into the calibrated SWAT model. Results from an ensemble average of GCMs show that Y and VWC are projected to change drastically under both RCPs. The trade (export-import) of wheat grain from Alberta to more than a hundred countries around the globe led to the annual saving of ~5 billion m^3 of virtual water (VW) during 1996-2005. Based on the weighted average of VWC for both rainfed and irrigated conditions, future population and consumption, our projections reveal an annual average export potential of ~138 billion m^3 of VW through the flow of these cereal crops in the form of both grain and other processed foods. This amount is expected to outweigh the total historical provincial water yield of 66 billion m^3 and counts for 47% of total historical precipitation and 61% of total historical actual ET. The research outcome highlights the importance of local high-resolution inputs in regional modeling and understanding the local to global water-food trade policy for sustainable agriculture.

Keywords: crop modeling, climate change, virtual water content, virtual water flow, Canada

1. Introduction

Both land and water resources are limited and already under heavy pressure from population growth, economic development, and varying diets, therefore, future agricultural production needs to be highly productive and also sustainable (van der Esch et al., 2017; Porkka et al., 2017). However, climate change is expected to influence the spatial and temporal heterogeneity of water resources worldwide (Schewe et al., 2014). Currently, many regions across the globe are unveiling significant depletion of freshwater resources due to withdrawal for agriculture, which uses 70% of total water withdrawal of global freshwater (Falkenmark, 2013; Wada et al., 2014; Tuninetti et al., 2015; Kaune et al., 2017; Ren et al., 2018). In the 21st century, meeting the increasing water demand of ecosystems and societies is one of the major environmental challenges. Hence, the water-food nexus has drawn much attention in order to understand the effects of global environmental change and provide sustainable development for the ever-increasing global population (Konar et al., 2011).

Many countries could compensate for the limited and uneven distribution of freshwater resources and associated food production by importing virtual water through international trade of agricultural products (Dalin et al., 2017). International trade transfers large amounts of virtual water from one region of production to other regions of consumption, so-called 'Globalization of Water' (Hoekstra and Chapagain, 2008). Virtual water content (VWC) refers to the water that is embedded in the production process of particular goods and services, and virtual water trade (VWT) refers to the amount of water traded through the flow of commodities between and within countries (Allan, 1993). The concept has been evolved over recent decades, and VWT is considered as an alternative solution for water and food security in overpopulated regions with limited water resources and/or regions with a scarcity of fertile lands. The VWT strategy potentially promotes regional and global food security, water savings, and water use efficiency (WUE) (Faramarzi et al., 2010; Carr et al., 2013). There will be a net water saving if the trade direction is from countries with low VWC to countries with high VWC. Countries can benefit from trade if they specialize in the production of goods and services for which they have a comparative advantage while importing goods and services for which they have a relative disadvantage (Chapagain et al., 2006). International trade in staple foods has been estimated to save approximately 238 billion m^3 of water annually, equivalent to 6-7% of global water use in agriculture (Dalin et al., 2012).

Earlier studies discussed the importance of VWT strategy in water resource management (e.g., Hoekstra, 2003; Wichelns, 2005), and subsequent studies emphasized the role of VWT in the globalization of water, world food demand, network of VWT, water savings evolution and regional water systems (Faramarzi et al., 2010; Seekell et al., 2011; Dalin et al., 2012; Carr et al., 2013; Goswami and Nishad, 2015; Oki et al., 2017; Qu et al., 2018). Contemporary to the conceptual evolution of the approach, the methodological advancements of calculating VWC helped reduce uncertainty in VWT analysis (Fader et al., 2011; Hanasaki et al., 2010; Liu et al., 2018; Lovarelli et al., 2016; Qu et al., 2018; Wichelns, 2015; Zhang et al., 2018). However, the majority of the earlier studies conducted at a global scale, only concerning international food trade between countries. Few recent studies considered regional effects of natural and management factors in quantifying VWC (Goswami and Nishad, 2015; Ma and Ma, 2017; Marano and Filippi, 2015; Shtull-Trauring and Bernstein, 2018). Such global scale studies lack reliability in the results since local processes and site-specific data were not considered in the simulation of crop yield and crop water requirements. The VWC of a given commodity in a given geographic location and time depends on location-specific agricultural practices, soil properties, hydro-geologic and climate conditions (Mekonnen and Hoekstra, 2011). For instance, a more significant amount of water is generally required to produce one ton of a cereal crop in the arid region than that in the humid region (Yang and Zehnder, 2007; Goswami and Nishad, 2015). In addition, comparison of the local water renewals was not considered in VWT studies, and the studies of the VWT concept as a policy option for water management were only based on water consumptions (Hoekstra, 2011).

Physical and process-based models have been typically utilized to account for spatial and temporal heterogeneity in large-scale VWT analysis. However, various assumptions in large-scale modeling framework such as hydro-climatic inputs, soil water balance, and crop growth simulations often limit the quality of predictions and lack representation of regional or local level processes (Folberth et al., 2016; Xinchun et al., 2018). Liu et al. (2013) and Flach et al. (2016) highlighted the critical importance of using spatially explicit data such as crop-specific fertilizer application rates, crop specific planting and harvesting data, and high-resolution geospatial and hydro-climate input in modeling to capture local variation and avoid significant errors in the estimation of crop yield (Y) and VWC. While large-scale models are efficient tools helping to understand processes and factors affecting VWC, the local scale inputs to the models are inevitable to provide reliable estimates of VWC and related parameters (Goswami and Nishad, 2015; Lovarelli et al., 2016). Reliable estimates of VWC and VWT can provide significant insights into the local/regional dynamics of water resources and the policy implications for global water savings (Tamea et al., 2016; Shtull-Trauring and Bernstein, 2018).

Increased attention has been paid to the consequences of climate change for water and food security through exploring VWT (Konar et al., 2013; Orlowsky et al., 2014). Changing patterns of precipitation and evapotranspiration (ET), and rising CO_2 will impact the relative advantage of countries concerning agricultural production and trade (IPCC, 2013; Konar et al., 2013; Deryng et al., 2016; Zhao et al., 2017). For instance, spring barley Y is projected to decrease by 7-25% in France, while it is expected to increase by 30-70% in the UK during the 21st century (Yawson et al., 2016; Gammans et al., 2017). This will likely induce the shifting of agricultural production in some countries, which will, in turn, change the regional and international patterns of food trade. Importantly, the redistribution of international food trade has been proposed as a potential adaptation measure to a changing climate (Nelson et al., 2009). Thus, it is essential to understand how world food trade system will be impacted by a region-specific climate change, as VWC is highly dependent on the local climate conditions.

In this study, we aimed to address the knowledge gap in understanding global and regional effects of local processes in VWT analysis and food security by utilizing locally adapted high-resolution models and data. We introduced a novel approach in the analysis of future VWF potentials by comparing water consumptions with local water resource renewals. We analyzed future water use of the three water-intensive and major cereal crops, namely wheat, barley, and canola by developing high-resolution (sub-basin scale; used a threshold drainage area of ~200 km^2) agro-hydrological models under both rainfed and irrigated conditions at a provincial scale. We also used a high-resolution, locally adapted hydrology model to account for spatiotemporal variation of water balance components. A primary objective of this study was to use a process-based, transient, biophysical model, Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), to simulate hydrology and soil-plant-water interactions at a daily time step, considering local climate and agricultural management operations using Alberta, Canada as a case study. Canada is known as one of the topmost export-oriented countries, and Alberta is one of the largest provincial exporters (Alberta Agriculture and Forestry, 2017). This study also provides a framework for projecting VWF under various climate change scenarios, which improve our understanding of global implications of VWF to other countries. The methods developed in this paper consists of a step-wise and detailed procedure involving spatially explicit simulation of Y, crop ET, VWC, and VWT of spring wheat (hereafter called as wheat), barley and canola, and calculation of crop demand and supply based on local population and consumption data.

2. Methods

2.1 Study area

Alberta, with an area of about 66 million hectares (Mha), has a highly variable climate with warm summers and cold winters (Fig. 1). Historically, the mean temperatures range from 10 to 20 °C, and the mean precipitation varies from 160 to 400 mm during the crop growing season (May-August) (Masud et al., 2018). The western side of the province receives higher precipitation, while the south-eastern side is drought-prone as it receives less precipitation with higher temperature (Masud et al., 2017a). The province has 17 river basins, where 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 extensively uses irrigation in the southern part (Fig. 1), accounting for 75% of the licensed water allocation (Islam and Gan, 2015), and has one of the world's most productive agricultural economies, contributing 23% of total Canadian farm revenue. Total agricultural land in Alberta is over 21 Mha and represents 31.2% of the Canadian total of 68 Mha. Wheat, barley, and canola are the three topmost farm cash crops. Exporting to over a hundred countries, Alberta's international exports of primary and processed agri-food totaled > $10 billion in 2016. About 74% of the total wheat, barley, and canola produced in 2016 were shipped to the USA, China, Japan, Mexico, and South Korea (Alberta Agriculture and Forestry, 2017).

2.2 Data

Historical climate data including daily precipitation, temperature, solar radiation, humidity, and wind speed were obtained from Faramarzi et al. (2015), who used a suite of four climate time series from local meteorological records, gridded products, and satellite data at a provincial coverage to reproduce historical streamflow records by using a calibrated SWAT hydrologic model. Other hydrological data include vegetation cover, soil characteristics, potholes, daily operation of large reservoirs and dams, and glacial maps in order to better represent natural and human-induced hydrological processes at sub-basin levels (Faramarzi et al., 2017). Agricultural management data such as the date of planting and harvesting, volume, and rate of fertilizer and irrigation application were obtained to develop the SWAT crop models. The crop-specific fertilizer application rate (N:P:K ratio), the maximum amount of annual fertilizer application (kg/ha/year), and the potential heat units required for crops were additionally obtained from the Government of Alberta (Table A1). Yearly Y statistics for irrigated and rainfed crops were taken from Alberta Financial Service Corporation (AFSC) and Alberta Agriculture and Rural Development (AARD) over the period 1980–2009 for model calibration and validation. Here, Y data for irrigated and rainfed crops were collected at the county level from AFSC (Fig. 1b) and at the Census Agricultural Region (CAR) level from AARD (Fig. 1a), respectively. For calibration and validation purposes, simulated data at sub-basin level and measured irrigated data at the county level were aggregated to CAR level to follow the same spatial resolution as the measured rainfed data, i.e., CAR level (see Table A1).

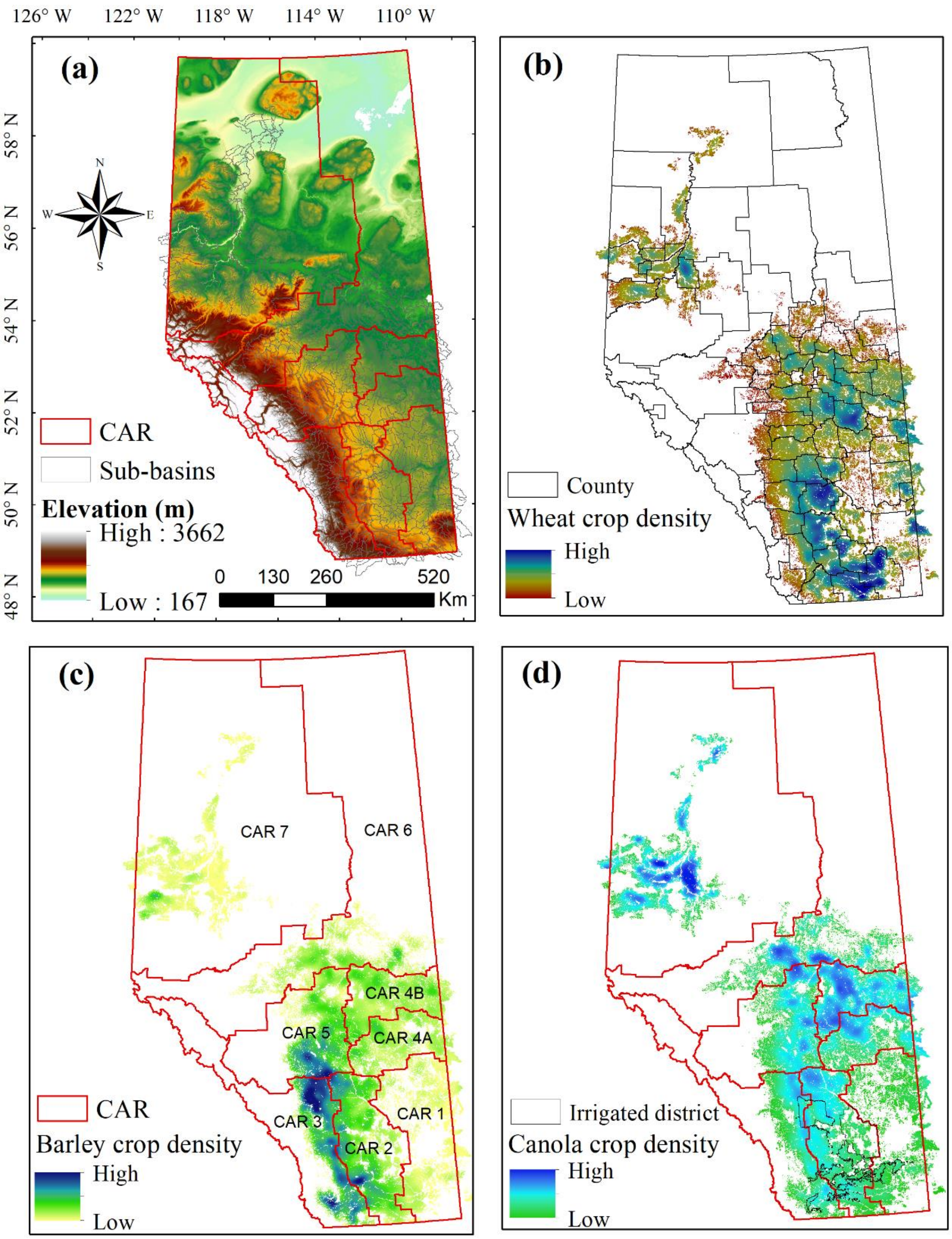

Fig. 1. Study area (a) and crop density maps for different cereal crops wheat (b) barley (c) and canola (d). Here, CAR is Census Agricultural Region.

Table 1. List of General Circulation Models (GCMs) used in this study.

Model	Institution	Center
CanESM2	Canadian Centre for Climate Modeling and Analysis	CCCma
CCSM4	National Center for Atmospheric Research	NCAR
CNRM-CM5	Centre National de Recherches Meteorologiques/Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	CNRM-CERFACS
CSIRO-MK5	Commonwealth Scientific and Industrial Research Organization in collaboration with the Queensland Climate Change Centre of Excellence	CSIRO-QCCCE
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory	NOAA/GFDL
HADGEM2-ES	Met Office Hadley Centre (additional HadGEM2-ES runs by Instituto Nacional de Pesquisas Espaciais)	MOHC (INPE)
MIROC5	Meteorological Research Institute	MIROC
MPI-ESM-LR	Max Planck Institute for Meteorology	MPI-M
MRI-CGCM3	Meteorological Research Institute	MRI

The climate projections of nine General Circulation Models (GCMs) over the period 2040–2064 were obtained under two contrasting emission scenarios of RCP 2.6 and 8.5 (Representative Concentration Pathways) from the Pacific Climate Impacts Consortium (PCIC; Cannon, 2015) at a resolution of 5 arcmin (~10 km) (Table 1). The change factor approach (Chen et al., 2011) was used to downscale the data based on the local climate conditions of Alberta. Overall, an ensemble of eighteen climate projections (9 climate models by 2 scenarios) was downscaled and used in the calibrated SWAT model. We set the CO_2 concentration as 350, 450, and 750 ppm for the historical, RCP 2.6, and RCP 8.5, respectively. For each GCM and RCP combination, a total of 1000 SWAT simulations were performed on a daily basis using the calibrated parameter ranges (see section 2.3). Although the model simulation was performed under each climate model-scenario combination, here we describe the results based on the ensemble average.

Changes in population size are important in determining the future demands for goods and services, particularly for food (Ercin and Hoekstra, 2014). We used the Government of Alberta population projection data for the historic (1985-2009) and future periods (2040-2064). Future population growth is based on historical trends of fertility, mortality, and migration, accounting for possible future patterns of change (Table A1). Per capita food consumption data were taken from FAOSTAT (FAOSTAT, 2018). The best available crop import and export data were collected for the 1996-2005 period from the Statistics and Data Development Section of Alberta Agriculture and Forestry (Alberta Agriculture and Forestry, 2018a). All input data are listed in the supplementary Table A1.

2.3 Model set-up and performance indicators

In this study, a calibrated hydrological model of the province (Faramarzi et al., 2017, 2015) was utilized to develop a crop growth model using the ArcSWAT 2012 (Rev. 632). The SWAT crop growth model was built to simulate Y and crop ET for both historical (1980-2009) and future (2040-2064) periods. In the hydrological model, a threshold drainage area of 200 km^2 was used to delineate the study area into a total of 2255 sub-basins, based on a 10 m Digital Elevation Model (DEM). The sub-basins were characterized based on soil, land use, slope, and associated physical parameters available from local sources, and further processed to meet the model requirements (Faramarzi et al., 2017). To simulate crop growth in this study, we developed and calibrated two separate models for each crop simulations (wheat, barley, and canola) to represent rainfed and irrigated conditions, respectively. In general, setting up a crop growth model based on a calibrated hydrological model has been recommended to improve soil-water dynamics in crop growth simulations (Faramarzi et al., 2010; Vaghefi et al., 2014). Heat unit requirements were optimized in the model through our calibration procedure to represent different varieties of crops that differ in growing degree-days across the province. Auto fertilizer and auto irrigation options of the SWAT model were used to represent the management calendar and were controlled by nutrient stress factor and plant-water-stress threshold, respectively. Planting and harvesting dates were obtained from available sources and communication with local experts. Since the cropping calendar did not fully cover the study domain, the suggested dates by local experts were further tuned through our calibration scheme over our study area.

For the model sensitivity, calibration, validation and uncertainty analysis, the Sequential Uncertainty Fitting (SUFI-2) program of the SWAT-CUP software was used (Abbaspour, 2015). The SUFI-2 was used to calibrate the model for the 1995–2009 and to validate it for the 1983–1994 period. A three-year window was considered as a spin-up period for both calibration and validation to mitigate the effect of initial conditions in the model. The inverse time periods were used for calibration and validation since better data were available in the later period. Based on an extensive literature review and author's judgment, a total of 14 to 30 physical and phenological parameters sensitive to water balance and crop growth was selected for each CAR under rainfed and irrigated conditions (Table A2). A global sensitivity analysis (GSA) was applied through the SWAT-CUP tool to screen the most sensitive parameters. The parameters were then sampled within a physically meaningful range using a Latin Hypercube Sampling (LHS) approach (Mckay et al., 1979) for 1000 model runs of each model simulation (under the historical period and 18 climate model-scenario combinations). The mean square error (MSE) was used as an objective function to compare simulated versus observed Y on a yearly basis for each CAR and parameter tuning for the next calibration iteration. In SUFI-2, the 95% prediction uncertainty (95PPU) of the output variables was considered to evaluate the model performance. The 95PPU has been calculated at 2.5% and 97.5% levels of the cumulative distribution functions of an output variable that was generated through the propagation of the parameter uncertainties using LHS. Simulation results for Y and VWC are shown as of median of 1000 runs and indicated as M95PPU hereafter.

The p-factor and r-factor have been used to quantify the calibration performance of the model (Abbaspour et al., 2015; Faramarzi et al., 2017). The p-factor is the percentage of observed data covered by the 95PPU, and the r-factor is the thickness of the 95PPU, which is calculated as the ratio of the average width of the 95PPU to the standard deviation of the measured variable. A p-factor value of 1 (100%) and a r-factor value of zero is ideal. However, due to inherent uncertainties in input data, physical parameters, and model conceptualization in large-scale studies, the p-factor of above 0.5 (50%) and r-factor of around 1-2 and 3-5 is considered satisfactory in hydrologic and crop Y simulations, respectively (Abbaspour et al., 2015). Importantly, our calibration approach does not search for an optimal parameter set as a single solution to replicate historical data, rather an envelope of best solutions represented by the 95PPU. In other words, observed data for a specific year should fall within the 95PPU band.

The crop ET is simulated based on crop biomass development, soil water dynamics in different soil layers, and potential crop ET on a daily basis. The Penman-Monteith approach is generally considered reliable and was used to estimate potential ET. Y and ET were simulated on a daily basis and aggregated for the growing season (planting to harvesting period; May to August). These output variables were simulated at sub-basin scale and then aggregated to CAR scale for calibration and validation purposes.

2.4 Virtual water content (VWC) accounting

The VWC (m^3/tonne) is the volume of water required to produce a unit of mass production and is defined as the ratio of crop water consumption (ET; mm) during a crop growing period to the crop yield (Y; tonne/ha).

$$VWC = \frac{ET}{Y} \times 10 \quad (1)$$

where, 10 is the factor used to convert ET (mm) into m^3/ha. A larger value of VWC indicates a higher amount of water used for a unit mass production and a lower WUE. We used M95PPU of simulated Y and ET to compute the VWC of wheat, barley, and canola for the historical (1985-2009) and future (2040-2064) periods for each sub-basin.

The sub-basins with simulated crop-specific VWC were then aggregated to a provincial level as follow:

$$VWC_p = \frac{\sum_s(VWC \times Y \times A)}{\sum_s(Y \times A)} \qquad (2)$$

where VWC_p is the virtual water content at the provincial level (m^3/tonne), s is the sub-basin number within the province and A is the area under cultivation (ha). However, sub-basins located in the southern Alberta consist of both rainfed and irrigated production. In this case, the VWC of a specific sub-basin is calculated as:

$$VWC_s = \frac{\sum_s((VWC_R \times Y_R \times A_R) + (VWC_I \times Y_I \times A_I))}{\sum_s((Y_R \times A_R) + (Y_I \times A_I))} \qquad (3)$$

Where, R denotes rainfed and I denotes irrigated crop production. This provincial level calculation of VWC is helping us to analyze the VWT of a specific crop and corresponding water saving (see section 2.5).

2.5 Virtual water trade (VWT)

Although Alberta is considered as a net exporting province, small amounts of wheat, barley, and canola are also imported (Figure 2). In order to account for water savings in this province, the trade was analyzed based on the actual import and export data that are available only for the 1996-2005 period. Therefore, the net virtual water export associated with the production of a given crop is calculated as:

$$NVWE_p = (EXP_p \times VWC_p) - (IMP_p \times VWC_{sc}) \qquad (4)$$

where, EXP and IMP denote for export and import of a crop in tonne/year, respectively. For import, the VWC_{sc} is considered from the respective source country based on the study of Hoekstra and Chapagain, (2006) and Mekonnen and Hoekstra (2011).

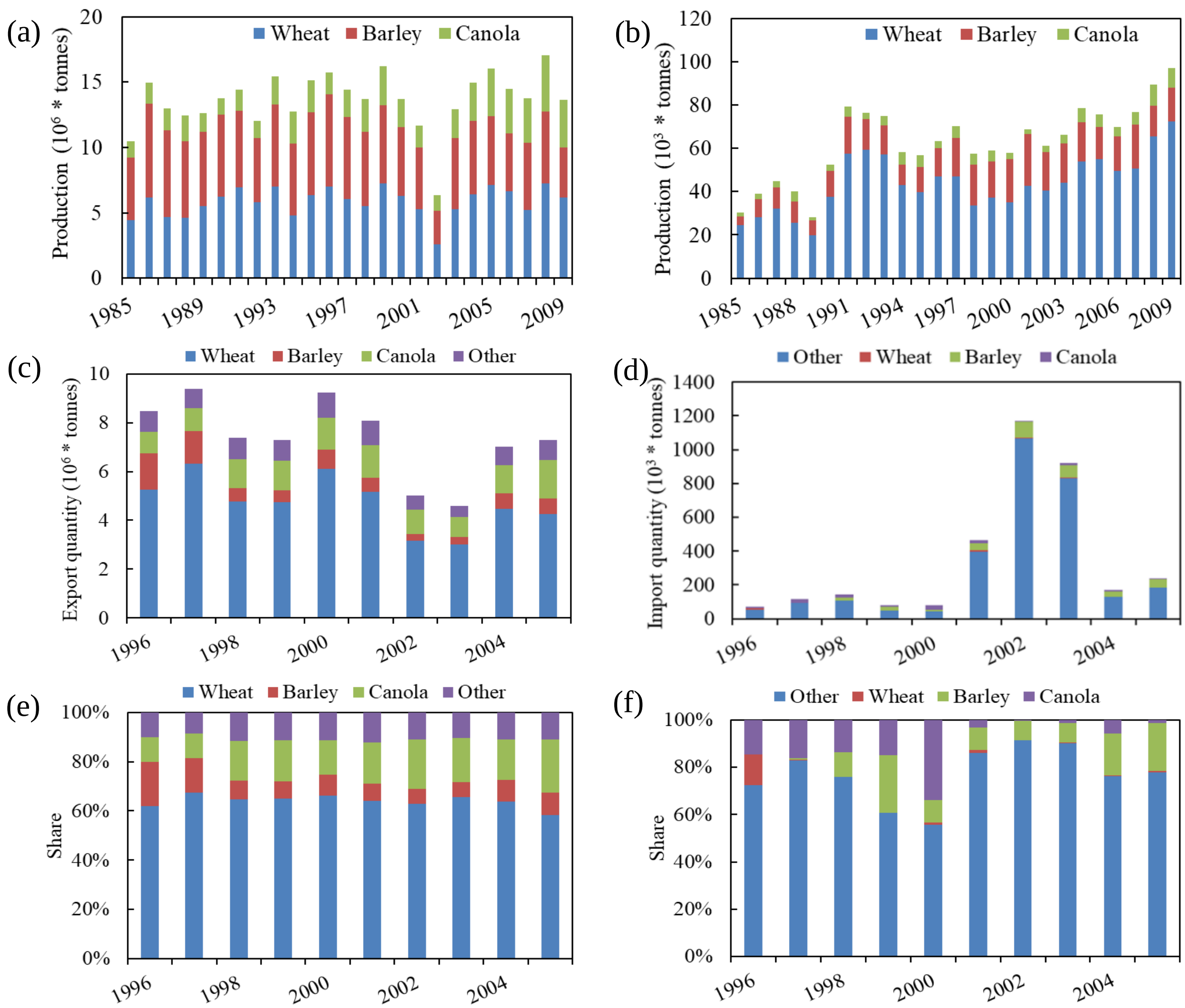

Fig. 2. Rainfed (a) and irrigated (b) cereal production during the historical period. Annual crop import (c), export (d), and their corresponding shares (%) in (e) and (f), respectively in the province.

Based on the per capita consumption and total population, the required production (P_r in tonne) of a crop in Alberta in a year is defined as (Ercin and Hoekstra, 2014; Karandish et al., 2015):

$$P_r = 1.2 \times \text{per capita crop consumption} \times \text{Total population} \quad (5)$$

where, the crop consumption is in kg/capita/day. The actual crop production (P_a in tonne) is computed as:

$$P_a = \sum_s ((Y_R \times A_R) + (Y_I \times A_I)) \quad (6)$$

In this study, we estimated the P_r and P_a for each year but averaged the results for the entire period. We assumed the area under cultivation (A) in the future period is the same as that of the historic period. There is no measured data available for the area under cultivation at the sub-basin scale. We used the crop density raster maps (Fig. 1b,c,d), with a spatial resolution of 230 m × 230 m, to estimate the area under cultivation for each sub-basin. As higher crop density values represent higher likelihood for crop production, we calculated P_a by omitting low crop density cells. Here, we developed a hypothetical scenario by considering cells with >10% crop density values (Fig. A1) for cropping areas.

Next, we calculated the "potential" net virtual water export (NVWE) for future period as follows:

$$NVWE = (P_a - P_r) \times VWC_p \quad (7)$$

With the above formulation, any crop production that is not directly consumed by local population was considered as crop surplus and potential for export to outside. It is noteworthy that a large share of crop surplus is 'indirectly' exported through production and export of meat (e.g., beef), live animals (e.g., cattle, calve), dairy products and beverage under status quo situation in Alberta (Alberta Agriculture and Forestry, 2017). In this study, we did not explicitly calculate VWC and VWF of these commodities, but assumed all crop surplus could be exported directly in the form of grain (i.e., no processed production). Thus, our estimates are the first order estimates of VWC and VWF of agricultural production in Alberta.

3. Results

3.1 Model set-up and performance statistics

Calibration and validation were performed for 67 counties (barley) and 8 CAR (wheat and canola). For brevity, we only present the results of our analysis at the provincial level for both irrigated and rainfed crops in Table 2. For details on the calibration and validation of the crop models, we refer to the supplementary information (Tables A3-A6). The model performed well for all rainfed crops over the calibration period. The average p-factor of the calibrated rainfed crop model is mostly >90% (88-99%), which indicated the percentage of observed Y data bracketed well by simulated 95PPU, with an average r-factor of 2.69, 4.48 and 3.46 for wheat, barley and canola, respectively (Table 2). The average MSE values for all rainfed crop models were less than 1 at the provincial scale. Similar statistical performance was obtained for the validation period. For all rainfed crops, the minimum and maximum statistics of all counties and CARs indicated an overall satisfactory performance. In general, irrigated crop models statistically performed slightly better than those of rainfed crops for the calibration period, since irrigated crops are grown under controlled conditions, and rainfall variability is attenuated by irrigation. Relatively poor model performance of irrigated crop models for validation period is due to the limited availability of historical or transient management data over time such as cropping, harvesting, and fertilizer at the county and CAR levels. It is important to note that the performance of p-factor improved at the expense of a larger r-factor and higher MSE in some areas. Therefore, a right balance needs to be reached between the p-factor and r-factor through a calibration procedure. A larger uncertainty (greater r-factor) in some areas was obtained for some of the crops, e.g., rainfed barley and canola, and irrigated canola during both calibration and validation. This inherent uncertainty is not uncommon in large-scale models due to errors in the model input data, process simplification and variation in historical management practices. Overall, model performance was satisfactory for most of the regions and times in the study area.

Table 2. The minimum and maximum statistics for the county and CAR-based calibration and validation. The provincial average statistics are also provided.

	Calibration			Validation			Calibration			Validation		
	p-factor	r-factor	MSE	p-factor	r-factor	MSE	p-factor	r-factor	MSE	p-factor	r-factor	MSE
				Rainfed Wheat						Irrigated Wheat		
Minimum	0.93	1.5	0.03	0.6	1.4	0.03	0.87	2.08	0.05	0.2	2.58	0.59
Maximum	1	4.17	0.15	1	5.67	0.23	1	2.71	0.66	0.43	2.69	0.71
Average	0.99	2.69	0.07	0.83	3.88	0.1	0.96	2.45	0.26	0.32	2.64	0.65
				Rainfed Barley						Irrigated Barley		
Minimum	0.53	1.91	0	0.55	1.65	0.11	0.8	1.21	0.01	0.5	0.61	0.17
Maximum	1	8.04	2.1	1	8.93	2.3	1	3.22	0.61	0.93	3.66	1.9
Average	0.88	4.48	0.6	0.85	5.35	0.59	0.92	2.13	0.23	0.82	2.34	0.68
				Rainfed Canola						Irrigated Canola		
Minimum	0.93	2.62	0.04	0.7	3.43	0.01	1	4.64	0.06	0.7	3.85	0.03
Maximum	1	5.06	0.12	1	8.2	0.17	1	7.5	0.06	1	7.3	0.14
Average	0.97	3.46	0.07	0.91	5.97	0.06	1	5.99	0.06	0.9	5.88	0.09

3.2 Spatially explicit distribution of Y and VWC

Historical and future Y, and the projected changes for rainfed wheat, barley, and canola in Alberta are shown in Fig. 3. Overall, simulated average canola Y was lower (1.68 tonnes/ha) for the historic period, followed by barley (2.93 tonnes/ha) and wheat (3.15 tonnes/ha), although there were some sub-basins where barley Y is projected to be more than 5 tonnes/ha in the future period. Simulated Y of all rainfed crops for the historic period was higher in the central and northern parts of Alberta followed by low Y in the south-eastern province. Rainfed Y is projected to substantially increase for both RCP scenarios (2.6 and 8.5) by up to 80% in many sub-basins with some others decreasing by up to 20%. On average, wheat, barley, and canola Y are projected to increase by 11, 25 and 33% for RCP 2.6 and 31, 65 and 69% for RCP 8.5, respectively. The spatial pattern showed that wheat Y is expected to increase more uniformly over the study domain than other crops, and such results are in agreement with other global scale studies on wheat production (e.g., Iizumi et al., 2017). Canola Y was projected to increase less than the other two crops, however, the projected Y differences were noticeable between RCP 2.6 and 8.5 having significantly higher magnitudes for the latter scenario.

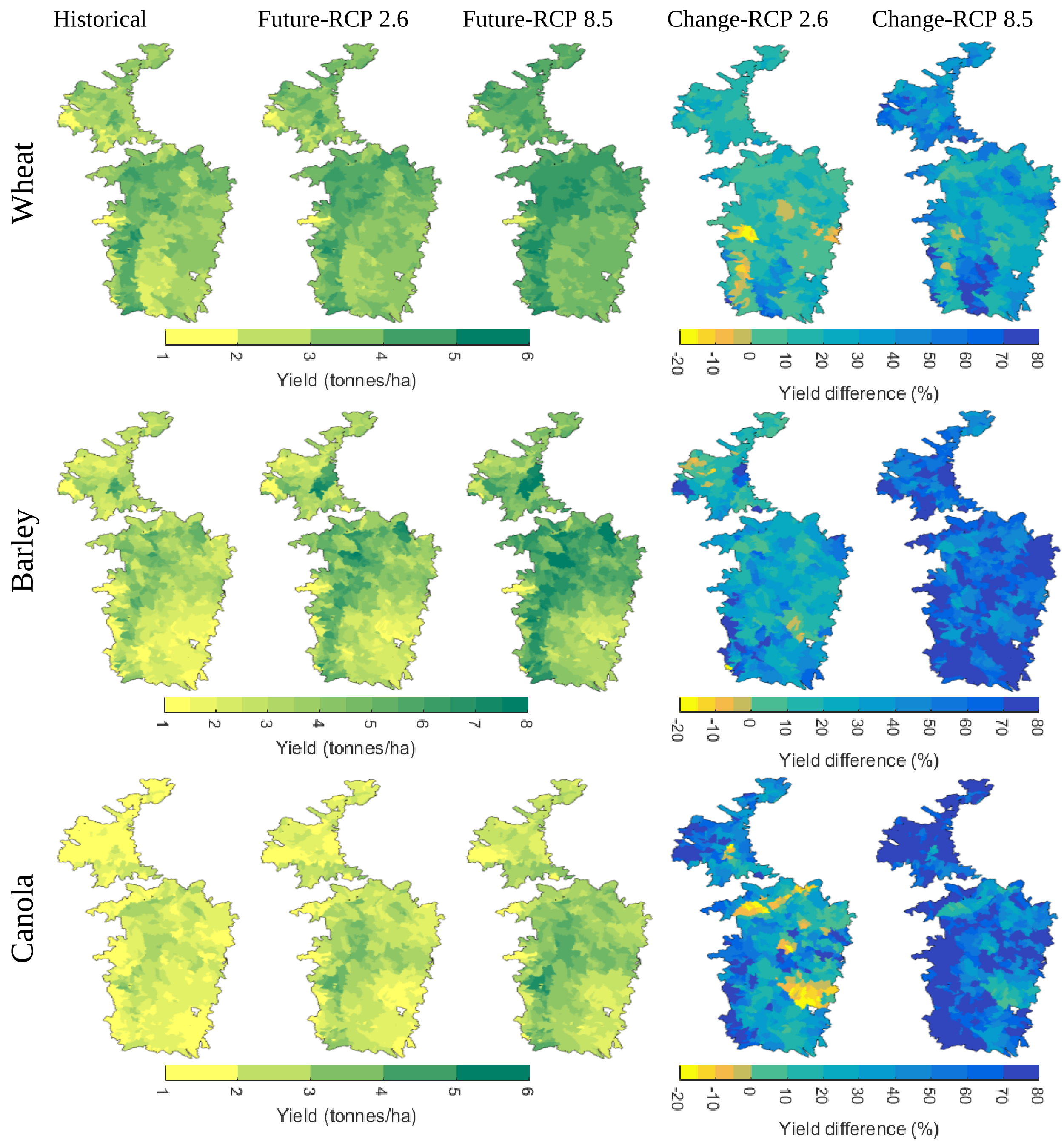

Fig. 3. Simulated long-term average rainfed yield (Y) (tonnes/ha) for historical (1985-2009) and future (2040-2064) periods and their projected changes (%).

Our results suggest a larger increase in wheat and canola yield under irrigated conditions as compared to rainfed Y. However, this is opposite for barley (Fig. A2). A possible reason could be a larger Y gap in Wheat and Canola under the irrigated condition that is the difference between actual and potential Y. The large historical Y gap can then be closed in the future due to more favorable conditions (Schierhorn et al., 2014). On the other hand, historical barley Y gap is already meager, therefore, more water or temperature may not help to boost up yield under irrigated conditions. Overall, the complex interaction of growing season precipitation, temperature, antecedent spring and winter soil moisture status influence the Y difference in the future (Kukal and Irmak, 2018). These results are consistent with Lu et al. (2018) who used empirical models to study crop Y response to climate variability.

Simulated VWC of rainfed crops for the historical period shows that canola has the highest VWC followed by wheat and barley (Fig. 4), implying a higher volume of water to produce a unit of canola than the other two crops. In general, maximum VWC was found in southern parts of the province as this area experienced higher temperature inducing higher ET. Projected future VWC shows a decreasing trend from RCP 2.6 to RCP 8.5. One possible reason could be the lower ET under RCP 8.5 scenario, where a higher CO_2 concentration reduces crop stomatal closure, hence decreases actual crop ET by reducing plant transpiration (Deryng et al., 2016). Similar to rainfed crops, the VWC of irrigated crops is projected to decrease in the future (Fig. A3). The magnitude of VWC in irrigated crops is more than rainfed crops in southern Alberta. This is due to a higher (atmospheric) evaporative demand in the southern part of the province that needs to be supplemented by irrigation. Overall, the magnitude of VWC and the projected changes (i.e., decrease) are highest for canola followed by barley and wheat.

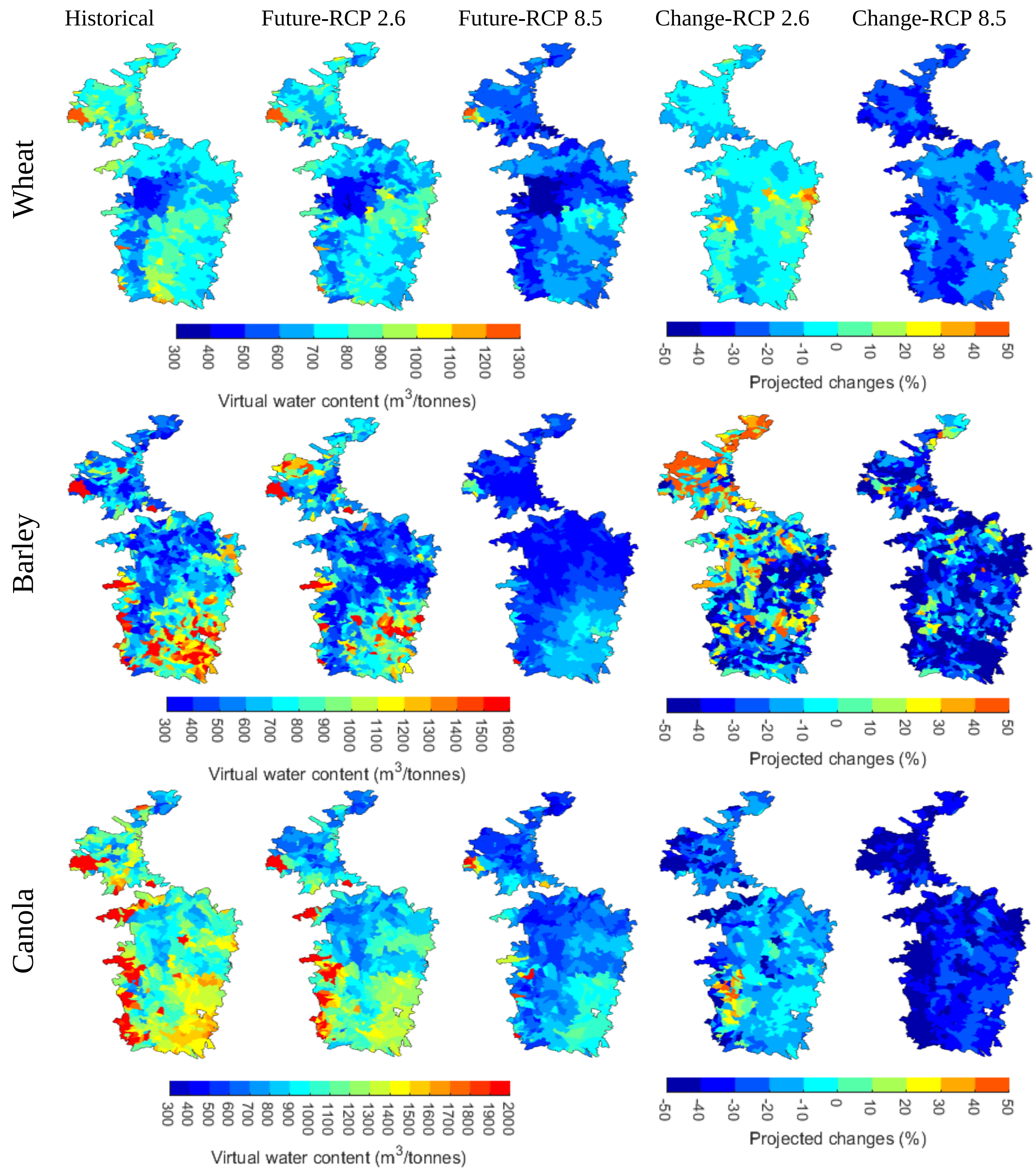

Fig. 4. Simulated long-term average pattern of virtual water content (VWC) for historical (1985-2009) and future (2040-2064) periods for the rainfed crops (m^3/tonnes) and their projected changes (%).

3.3 VWC at the provincial level

Temporal variation of simulated VWC at the provincial level is shown in Fig. 5 for wheat, barley, and canola for the 1985-2009 period. VWC exhibits substantial temporal variation in the historical period. It is noticeable from Fig. 5 and 6 that VWC varied for different crop types (wheat, barley, and canola), production conditions (rainfed vs. irrigated), and geographical locations in different parts of the province (north vs. south). Our models captured the temporal fluctuation of VWC due to interactive feedback between local agro-hydrologic, climate, and management factors. In global studies (e.g., Mekonnen and Hoekstra, 2010; Konar et al., 2013), such variation in rainfed and irrigated conditions may not be adequately considered, since global models are not adopted to represent the regional/local conditions. This often causes large uncertainty in the overall estimation of crop Y, ET, and VWC. Further, we aggregated our sub-basin based simulated data and calculated the weighted average VWC (Prov_AVG) of wheat, barley, and canola at the provincial level (see Eq. 2). The time-averaged provincial VWC of wheat, barley, and canola, weighted for both rainfed and irrigated conditions, are 797, 835 and 1239 m^3/tonnes, respectively (Fig. 6). Hereafter, we will discuss VWT and VWF based on the weighted average of VWC.

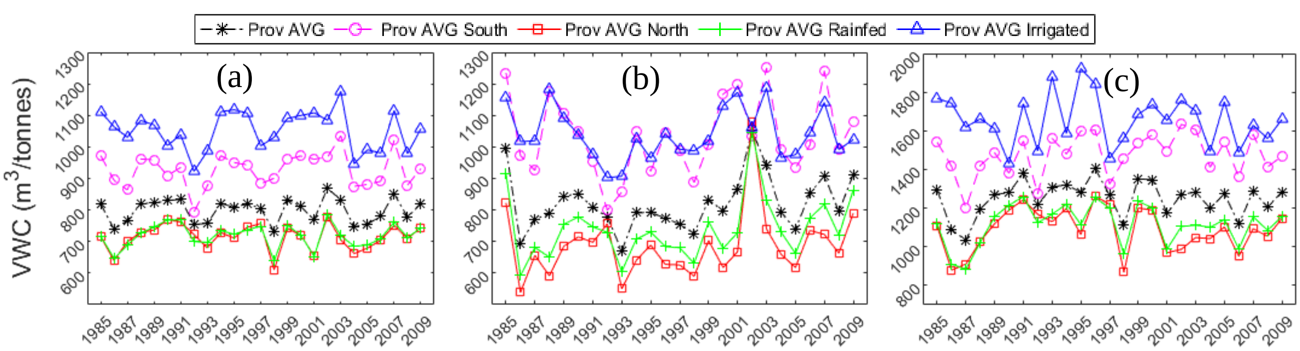

Fig. 5. Temporal variation of virtual water content (VWC) of wheat (a), barley (b), and canola (c) aggregated to the provincial level. Definition of acronyms in the legend: Prov_Avg: Entire agricultural area (both rainfed & irrigated); Prov_Avg_South: Both rainfed & Irrigated, only for sub-basins those are located in the irrigated districts; Prov_Avg_North: Excluding the Irrigated districts;

Prov_Avg_Rainfed: Purely rainfed for entire agricultural area; Prov_Avg_Irrigated: Purely irrigated (irrigated districts).

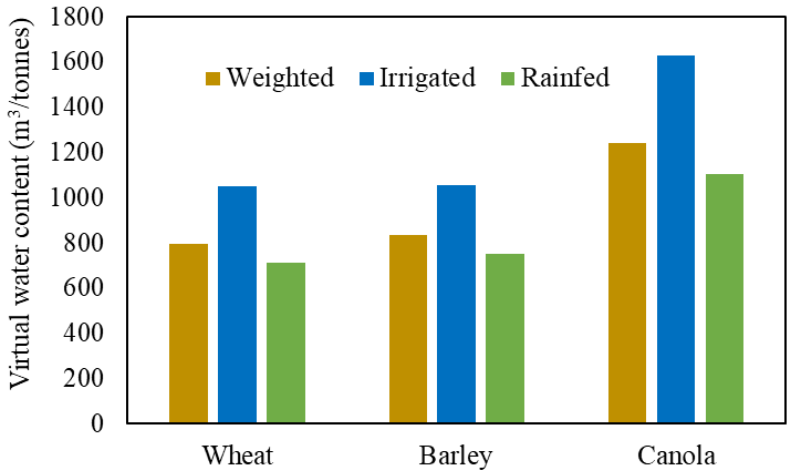

Fig. 6. Long-term average (1996-2005) modeled virtual water content (VWC) of cereal crops at the provincial level.

3.4 Provincial status of virtual water trade (VWT)

Based on the available data on the volume of the three cereal crops imported and exported during the 1996-2005 period, we calculated the status of VWT of the province (Fig. 7). Among these crops, wheat accounts for on average 65% of virtual water export followed by canola and barley that accounted for 25% and 10%, respectively (Fig. 7a). There was a decline in the export during 2000-2003 as the province experienced a significant drought (Masud et al., 2017a). The average annual VW export was 3.76, 0.57 and 1.44 billion m^3 for wheat, barley, and canola, respectively with a total of 5.77 billion m^3 per year. Overall, the results show that total virtual water import to the province was marginal with only about 0.05 billion m^3 annually (Fig. 7b). However, an increased amount of VW of barley was imported during the drought years, since Alberta is among the largest beef producing jurisdictions around the world and barley is used as the main feed crop. Out of total average annual net virtual water exports of 5.71 billion m^3, about 66%, 9%, and 25% were traded through wheat, barley and canola in the form of grain crops (Fig. 7c). Other processed or consumed crops (e.g., beef, cattle, calve, poultry, and beverage) in our VWF calculations will further increase the volumes (see section 3.5). As the VWT analyses depend on the existing import-export data, we projected future VWF rather than the VWT in the following section.

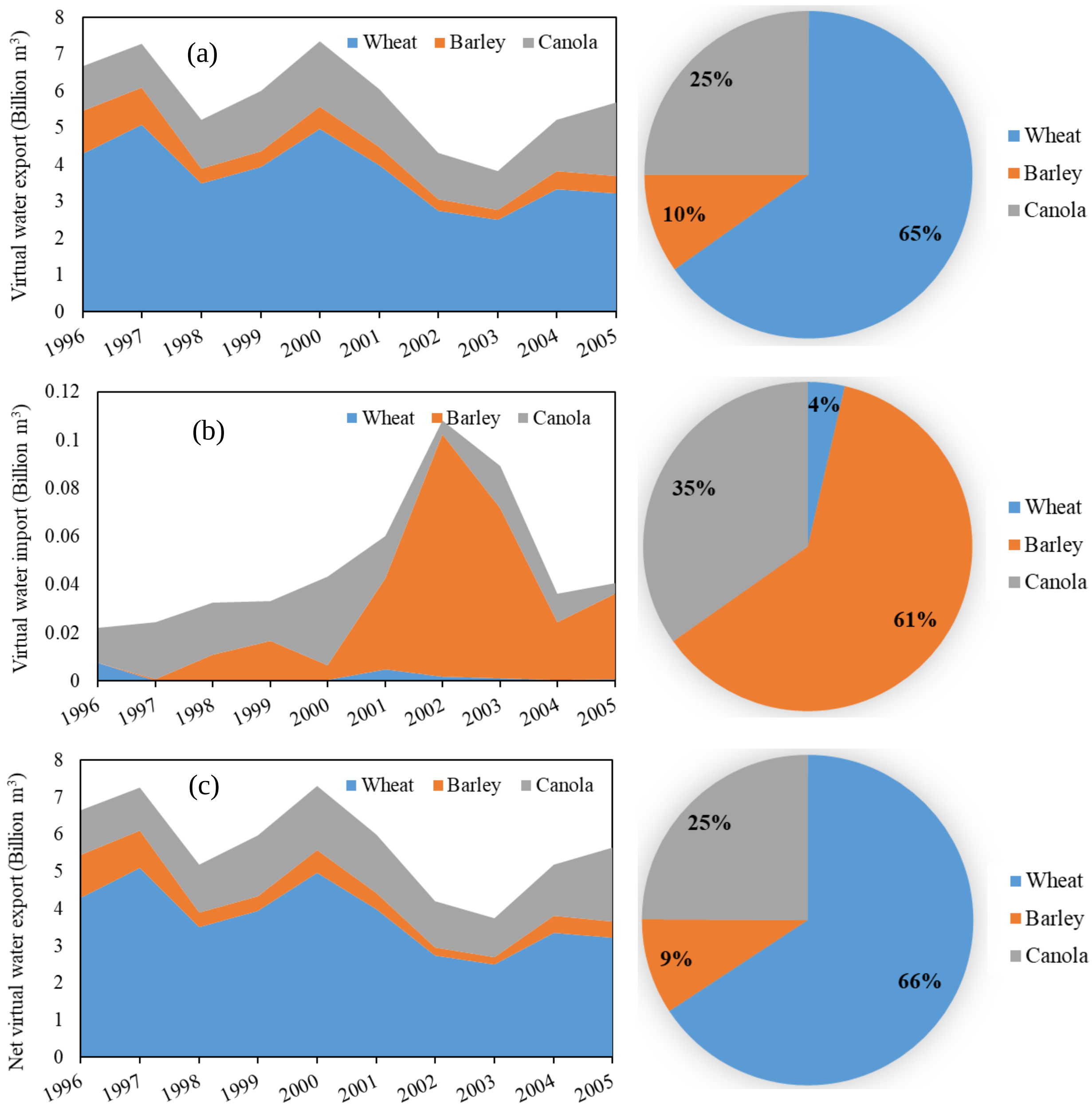

Fig. 7. Modeled annual virtual water export (a), import (b), and the net virtual water export (c) from Alberta. Pie charts show their corresponding shares.

3.5 Future potential of virtual water flow (VWF)

Figure 8 shows the future export potential of wheat, barley, and canola regarding production and associated VWF. Here we calculated the export potential for each year and then averaged for the entire simulation period. The future potential of exporting these cereal crops have been determined after meeting local demands based on the cropping area, Y, and per capita consumption and population. We used the simplified assumption by considering the local demands only from the demographic sector, while there are other sectors including beef-cattle, poultry and beverage industries, where cereal crops are consumed in their production processes. Since the majority of these commodities are exported, we assumed that they are exported in the form of crops rather than consumed crops. Future alterations in demand from these sectors are not considered, which requires a comprehensive assessment of future local consumption and production patterns based on socio-economic and demographic changes. Figure 8a demonstrates that Alberta has a great potential to export wheat and barley followed by canola. Overall, Alberta is projected to export 70, 60, 52 million tonnes of wheat, barley, and canola, respectively. Results also revealed that Alberta is projected to export a large volume of virtual water by exporting canola followed by wheat and barley, as the VWC of canola is the largest among all three crops. A larger difference between RCP 2.6 and RCP 8.5 in potential VWT of canola is due to a higher Y and lower crop water use in RCP 8.5 than RCP 2.6 that resulted smaller VWC in RCP 8.5 (Fig. 4). Overall, average annual trade of wheat, barley, and canola is projected to lead the export potential of 44, 32 and 62 billion m^3 of virtual water, respectively that amounts to a total of 138 billion m^3. Earlier studies (Faramarzi et al., 2017, 2015) found a provincial level long-term average annual precipitation, water yield (surface water availability), and actual ET of 289.62, 66.14, and 224.36 billion m^3 for the historic period (1983-2007), respectively. Our projected total VWF through the export of wheat, canola and barley, in the form of both crop and processed foods, would outweigh the total historical water yield and will account for about 47% of total precipitation and 61% of total ET due to ET from all vegetation and crop types. This imbalance between total provincial water yield and projected VWF has implications for long term sustainable VWT (see section 4).

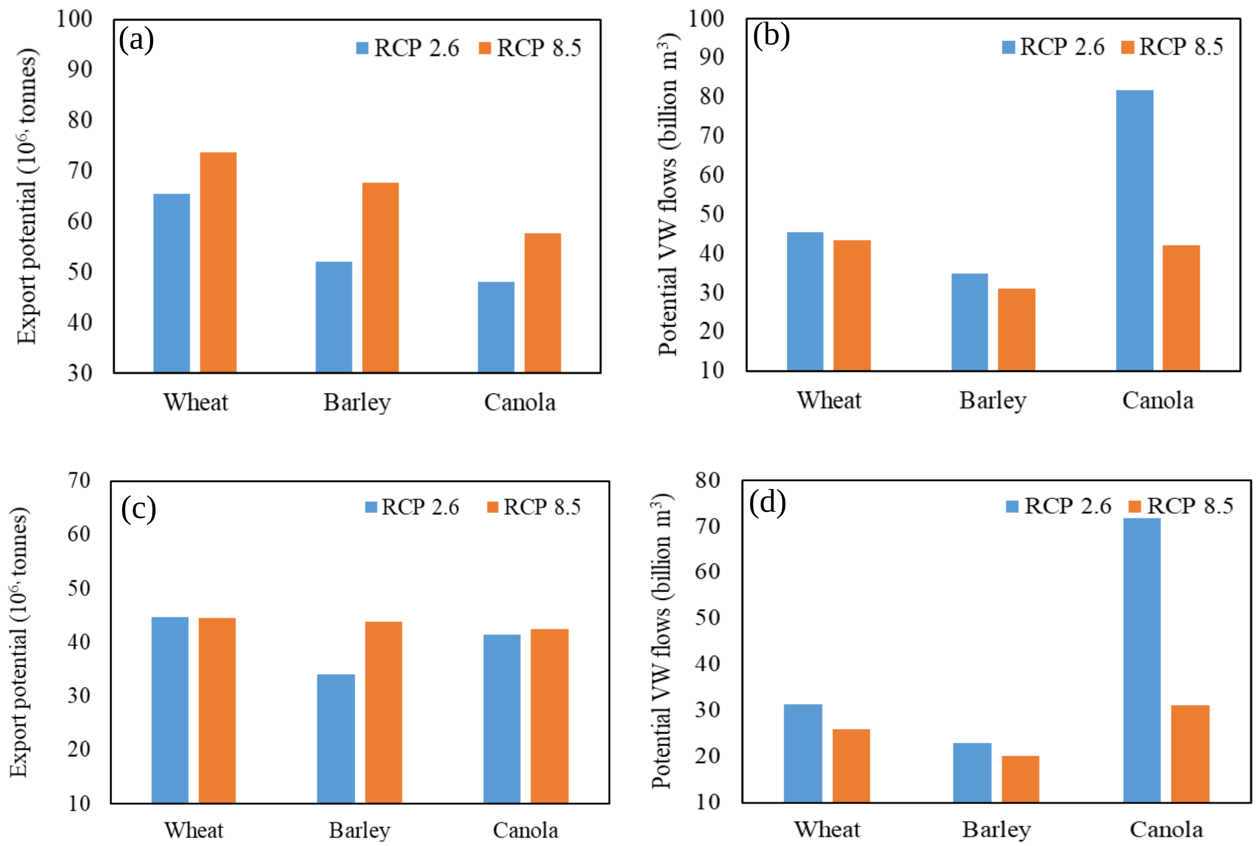

Fig. 8. Projected annual export potential of cereal crops (a), and their corresponding virtual water flows (b) for the 2040-2064 period. (c) and (d) show the same results for the scenario, where only the top 90% of density values in the crop density maps were considered for future cropping areas.

It is worth mentioning that we assumed future cropping area remains the same as the historical acreage. Here, we also evaluated the potential crop export, and their corresponding VWF based on the assumption that only grid-cells with >10% crop density values will be considered for cropping areas. Therefore, the area under cultivation for each sub-basin was decreased with the highest reduction obtained for barley crop (Fig. A1). As a result, the volume of export potential and VWF were reduced for all cereal crops. Overall, the projected annual export potential for wheat, barley, and canola are 45, 39, and 42 million tonnes (Fig. 8c). The corresponding annual

VWF are 29, 21, and 51 billion m^3 for wheat, barley, and canola, respectively (Fig. 8d). The reduction in area coverage of cereal crops resulted in a total of 101 billion m^3 VWF and indicated a reduction of about 27% as compared to the use of full area coverage based on the crop density map of Fig. A1.

4. Discussion

4.1 Comparison with previous studies

Historical regional studies on the VWF demonstrate substantial variation in VWC of a given crop in a geographic location. In this study, our simulated VWC of rainfed and irrigated crops fall below the range reported in other large-scale studies. In a global study by Hoekstra and Hung (2002), the long-term average (1995-1999) VWC of wheat and barley for Canada were reported to be 1441 and 1098 m^3/tonne, respectively. Similarly, other global scale studies reported a wide range from 1057 to 2209 m^3/tonne for VWC of wheat in Canada (Chapagain et al., 2006; Aldaya et al., 2009; Hanasaki et al., 2010; Mekonnen and Hoekstra, 2014; Tuninetti et al., 2015). While global studies ignore important information at a local scale and often simplify the representation of the key processes, our predicted VWC based on a locally adapted large-scale SWAT model was 797 m^3/tonnes for Alberta. Inadequate consideration of local climate and soil conditions, and inaccurate reflection of local management practices, as well as poor calibration and validation of the models, may be attributed to the uncertainty in estimating VWC in earlier regional and global studies (Mekonnen and Hoekstra, 2014). Variations also existed among studies for the estimation of VWC for barley and canola. For barley, the ranges found in the literature (546-1029 m^3/tonne) (Mekonnen and Hoekstra, 2014) overlap well with the overall average value (835 m^3/tonne) found in this study. However, results from our study indicated large variations in the VWC estimation in different sub-basins within Alberta (Fig. 4). This suggests that the estimation of VWC is sensitive to time, crop parameters, input data, and geographic location in the modeling framework (Hanasaki et al., 2010). Sun et al. (2013) found the local agricultural management practices as the most influential factor in calculating the VWC, followed by the regional climate and its variation. Similar discrepancies have been found by Shtull-Trauring and Bernstein (2018) who compared global and local scale datasets in calculating VWC and suggested the use of local datasets. Higher resolution and accurate data are essential for the development of appropriate local, regional and national agricultural policy.

According to our analysis, Alberta has enormous potential to export virtual water through grain export to the rest of the world (Fig. 8). Previous studies supported our results by estimating the historical trade record of Canada, which is one of the top five countries with net virtual water export (Hoekstra and Hung, 2005; Hanasaki et al., 2010). However, local water renewals and demands of other water use sectors and environment should be taken into account for a comprehensive understanding of the future risks and opportunities for food production. Therefore, developing a locally adapted modeling framework for simulation and projection of both VWF potentials and local water renewals, similar to this study, is necessary for both regional and global water-food policy and planning in support of sustainable agriculture.

4.2 Global and regional policy implications of VWT

The net VW export from Alberta, due to the trade of grain wheat, to other countries is presented in Fig. 9. Alberta has exported wheat to more than a hundred countries in the world (Table A7). According to our results, the largest virtual water importers from Alberta are Japan, China, USA, Indonesia, Mexico, Italy, Colombia, Peru, Nigeria, and Bangladesh (Fig. 9); and altogether these countries import more than 50% of the total virtual water. We also calculated the magnitude of virtual water requirements if the importing countries would have produced grain wheat on their own soil. VWC of the importing countries was obtained from Hoekstra and Chapagain, (2006) and Mekonnen and Hoekstra (2011), and the global average VWC was used for Indonesia as there is no data available for this country. The results showed that during 1996-2005, Japan, China and USA have annually imported 0.342, 0.303 and 0.293 billion m^3 of virtual water by importing grain wheat from Alberta. This revealed a VW saving of 0.516, 0.616 and 0.512 billion m^3, respectively (Fig. 9). Overall, we found the global water savings due to the export of grain wheat from Alberta to other countries was 4.897 billion m^3. This supports the fact that regional and global WUE can be increased if countries use their comparative advantages and disadvantage regarding water availability and water use (Chapagain et al., 2006).

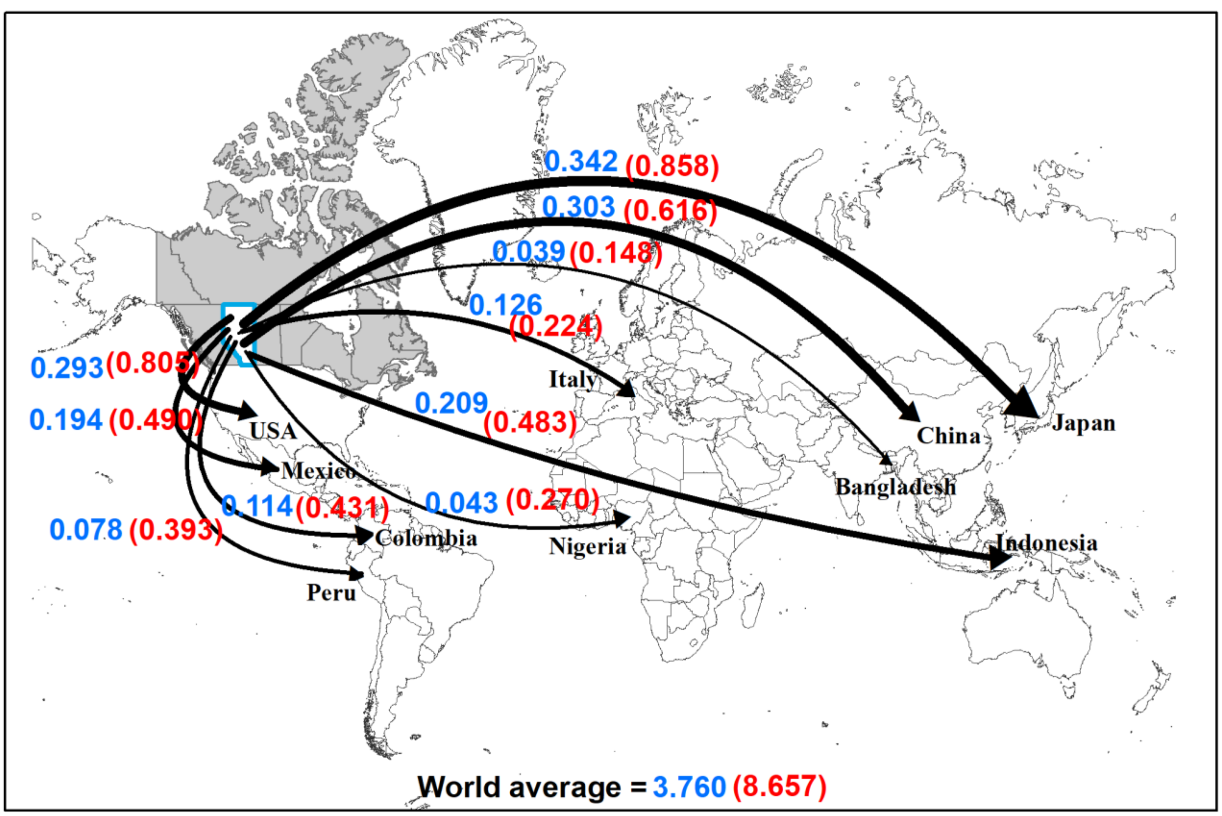

Fig. 9. Global water saving (billion m^3/yr) related to the wheat export from Alberta to selected countries during 1996-2005 (all countries listed in SI). Values in the parentheses indicate the amount of virtual water required if the importing countries produced those imports on their own soil.

It is important to note that irrigation in Alberta is unquestionably a significant part of the agricultural industry contributing to more than 19% of the gross provincial production and covering 6% of the total cultivated lands in southern part of the province (Alberta Agriculture and Forestry, 2018b). Although importing countries have benefited by importing wheat grain from Alberta, the local water resources in Alberta and their low renewal rates in southern parts of the province may become a barrier to long-term production and trade opportunities. This is evident from our earlier studies (Faramarzi et al., 2015, 2017), where a large historical water scarcity was found for agricultural crop growing months in irrigated districts of southern sub-basins. This also indicated by Goswami and Nishad (2015) that the net virtual water export alone can lead to loss of water sustainability of a nation (e.g., India) by less than 300 years. Canada has the highest negative balances of water, mainly due to wheat exports and the associated water consumption that is more than 50% of total water consumption to produce export goods (Fader et al., 2011). Therefore, local water security challenges need to be considered in future VWF calculations to ensure a sustainable trade pattern in the future.

On the contrary, Aldaya et al. (2009) reported that precipitation and rainfed agriculture is by far the largest share of VWC in wheat export from Canada. Given the low opportunity cost of rainfed agriculture as compared to irrigated, Alberta might be in a relatively good future condition regarding VWF due to the projected increases in precipitation (Masud et al., 2017b), larger Y, and higher production as shown in this study. However, the long-term environmental impacts (e.g., on soil and water quality), and the imbalance between local water yields and water consumption (e.g., if the future VWF potentials exceed local water yields), may require landuse change and a proper water-food, and land management. All these important factors need to be taken into account for a sustainable and an environmentally informed VWT strategy. These are subjects of our future studies.

4.3 Limitations

In this framework, some limitations are worthy of further improvements. A crop consumption component in the production and export processes of other commodities than grain crops (e.g., beef, poultry, and beverages) would enhance the VWF accounting. The VWT can be influenced by socioeconomic factors like food prices which play a significant role in the consumption pattern and quantity of crops. The international trade efficiency of crops is also highly dependent on other factors than water alone, including land scarcity, cost of labor, comparative advantages, domestic and international subsidies and taxes (Chapagain et al., 2006). Moreover, the bilateral political relationship between countries may considerably influence the trade pattern and overall efficiency.

5. Conclusions

This study developed a framework to project future VWF related to cereal crops and corresponding water savings under different climate change scenarios. Our results for the historical 1985-2009 and future 2040-2064 periods revealed that:

- Future climate change leads to an increase in cereal crop yields and a decrease in VWC.
- The VWC varied substantially in time and space and for different production conditions (rainfed and irrigated).
- The area-based weighted average VWC of both rainfed and irrigated crops at provincial level revealed that the VWF of wheat grain from Alberta to more than a hundred countries in the world has led to a global annual water saving of 4.897 billion m^3 during 1996-2005.
- Future climate change may provide opportunities for increases in the export of virtual water through export of cereal crops. However, it may exceed some hydrologic water balance

components and be affected by local water resources availability and low renewal rates. Our results indicated that total VWF through the export of cereal crops, in the form of both grain and processed foods, would outweigh the total historical water yield and will account for about 47% of total precipitation and 61% of total ET due to ET from all vegetation and crop types.

- For a sustainable VWT strategy, future water renewals, as well as environmental impacts, should be predicted using locally adapted modeling tools.

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