Review

Climate change and the water footprint of wheat production in Zimbabwe

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ABSTRACT

Reductions in the water footprint (WF) of crop production, that is, increasing crop water productivity (CWP), is touted as a universal panacea to meet future food demands in the context of global water scarcity. However, efforts to reduce the WF of crop production may be curtailed by the effects of climate change. This study reviewed the impacts of climate change on the WF of wheat production in Zimbabwe with the aim of identifying research gaps. Results of the review revealed limited local studies on the impacts of climate change on the WF of wheat production within Zimbabwe. Despite this, relevant global and regional studies suggest that climate change will likely result in a higher WF in Zimbabwe as well as at the global and regional level. These impacts will be due to reductions in wheat yields and increases in crop water requirements due to high temperatures, despite the CO_2 fertilization effect. The implications of a higher WF of wheat production under future climate change scenarios in Zimbabwe may not be sustainable given the semi-arid status of the country. The study reviewed crop-level climate change adaptation strategies that might be implemented to lower the WF of wheat production in Zimbabwe.

Keywords: water footprints, climate change, wheat, yield, crop water requirements

INTRODUCTION

Agro-ecosystems are the largest users of water accounting for 70% of global withdrawals and 90% of the global water consumption (Shiklomanov and Rodda, 2003; Haddeland et al., 2011). Accelerated population growth, change in diets and demand for green fuels means that global freshwater demand in agro-systems will increase to cater for the rising need for food, fibre and biofuels (Falkenmark et al., 2008; Gleick, 2003). However, most countries of the world are located in already water-scarce basins with 2–3 billion people living in highly water-stressed areas (Oki and Kanae 2006; Kummu 2014). A possible solution to close the gap between agricultural water demand and availability might be to increase the crop water productivity (CWP), that is reduce the water footprint (WF) of crop production in agro-ecosystems (Hoestra and Mekonnen, 2012).

Efforts to decrease the WF in crop production of agro-ecosystems may be hampered by the possible implications of climate change and variability. In the last century global surface temperatures have risen by an average of 0.07°C whilst the global atmospheric CO_2 concentration is rising at an annual rate of 2 ppm (NASA, 2016). Since crop yields and evapotranspiration, and thus WF, are determined to a large extent by climatic conditions, future changes in climate are likely to affect the WF of crop production. The various non-linear ways in which climatic factors can affect crop production via geographic and crop-specific factors mean that the precise impact of climate change on the WF of crop production for many countries is not known. There is therefore a need for the assessment of the impacts of climate change on crop production WF at the national level (Sun et al., 2012).

Zimbabwe is already experiencing climate change and variability (GoZ, 2015). Climate change is anticipated to affect the production of staple crops such as wheat (Chawarika, 2016; Manyeruke, 2013). An initial process in the assessment of climate change impacts is a comprehensive review of past studies to ascertain the current state of knowledge. To the researchers' knowledge, there is no comprehensive review of studies assessing impacts of climate change and variability on the WF of wheat production in Zimbabwe.

This paper provides a literature review on the potential of climate change and variability to impact the WF of wheat production in Zimbabwe with the broad aim of identifying research gaps and needs. It firstly provides a background to wheat production and climate change in Zimbabwe and then critically assesses the results, methods and models of local research on the effect of climate change and variability on crop water consumption of wheat production. Search results from local studies were then compared with regional and global results. In response to the results of the literature review, adaptation strategies to help combat the impact of climate change on the local WF of wheat production in Zimbabwe are suggested.

DATA AND METHODS

Theoretical framework

In agro-systems the classical method used to measure a crop's capacity to convert water into marketable yield is the crop water productivity (CWP). For cereals the CWP can be defined as the ratio of the harvested grain yield to the volume or depth of water applied in irrigation or lost in evapotranspiration (Morisson et al., 2008; Tambussi et al., 2007). It is measured empirically by the formula:

$$CWP = Y_a/Et_a \quad (kg/m^3) \quad (1)$$

where Y_a is the actual marketable crop yield (kg/ha) and Et_a is the actual seasonal crop water consumption by evapotranspiration (m^3/ha).

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Another relatively new and innovative way of measuring a crop's capacity to convert water into marketable yield is the WF. The WF of crop production is defined as the freshwater volume (in cubic meters per ton of crop) required for crop growth and dilution of pollutants during the production process of crops (Hoekstra et al., 2009). Analogous to the ecological footprint and carbon footprint the WF is becoming increasingly popular in research and policy because of its universal application to non-agricultural sectors such as manufacturing as well as its critical linkages to human activities such as pollution and trade (Zhang et al., 2014). In some research circles the WF is also referred to as the virtual water content (VWC).

The WF has 3 components: green, blue and grey. The blue water footprint is the volume of freshwater that evaporated from blue water resources (surface water and ground water) to produce the crop. The green water footprint is the volume of water evaporated from green water resources (rainwater stored in the soil as soil moisture). The grey water footprint is the volume of polluted water that is associated with the production of the crop.

The blue WF can be calculated numerically as:

$$\mathrm{WF} = \mathrm{Et_a}/Y_\mathrm{a} \qquad (\mathrm{m^3/kg}) \qquad (2)$$

This can also be written as:

$$\mathrm{WF} = 1/(Y_\mathrm{a}/\mathrm{Et_a}) = 1/(\mathrm{CWP}) \qquad (\mathrm{m^3/kg}) \qquad (3)$$

Thus the blue WF is the reciprocal of the WP (Amarasinghe and Smakhtin, 2014).

The two dependent components of the WF of crop production are crop yield and crop evapotranspiration, both of which are affected by the main climatic parameters which are temperature, rainfall and atmospheric CO_2 levels. Climate change and variability is thus a significant issue that can potentially affect WF in crop production. The overall effect of climate change on yields and evapotranspiration can either be positive or negative depending on geography, the particular crop and the degree of climate change. High temperatures in mid- and low-altitudes are anticipated to elevate crop evapotranspiration and reduce crop yields for C4 crops (e.g. maize). whilst in high latitudes they may increase C3 crop (e.g. wheat) yields resulting in lower WFs of production (Gornall et al., 2010; Adams et al., 1999). However, for C3 crops like wheat, increases in atmospheric CO_2 levels can increase crop yields, the so called CO_2 fertilization effect, whilst simultaneously reducing crop transpiration resulting in a net reduction in the WF of crop production (Cartwright, 2013; Degener, 2017).

Database search

The literature review was conducted by carrying out a literature search of peer-reviewed articles and grey literature published from 1985 to 20 February 2018. Many climate change studies on crops have focused on either crop yield or crop evapotranspiration, separately. For this reason, this study de-segregated its analysis of climate change impacts on WF by focusing separately on wheat yields, crop evapotranspiration and the actual WF. For peer-reviewed articles the databases EBSCO, PubMed, Web of Science, BioOne and Scopus were used. Grey literature searches were conducted using Eldis, Google Scholar and AGRIS (the Food and Agriculture Organization of the United Nations and the International Food Policy Research Institute) and UNESDOC (the UNESCO database). Since most climate impact studies present crop water use as either crop evapotranspiration, crop water requirements, irrigation requirements or their variants, these terms were included in the literature review. The search terms used in the search were 'Zimbabwe', 'Africa' or 'global' and 'climate change' and 'wheat', 'temperate cereals 'or 'cereals' followed by 'yields,' 'water footprints', 'virtual water contents', 'water productivity,' 'water use efficiency', 'irrigation requirements' or 'crop evapotranspiration'.

Only studies written in English were used due to limitations on resources. To be included, a study had to meet the following criteria:

- Any original peer-reviewed research, review paper or white/grey document that contained results on climate change impacts pertaining to Zimbabwe, Southern Africa or Africa
- The results of climate change impacts had to be specific to wheat, temperate cereals (barley and rye) or cereals in general
- Assess the effects of increasing CO_2 and temperature on the water footprints, virtual water contents, water productivity, water use efficiency, irrigation requirements, crop evapotranspiration or water use of wheat, temperate cereals (barley and rye) or cereals in general
- Provided quantitative or qualitative data on changes in yields of wheat, temperate cereals or cereals due to the effects of climate change

A schematic representation of the screening process is given in Fig. 1. The initial search produced 840 papers which were then subjected to filtering. The first filtering was based on the source title; a second filter was then applied based on the source abstract. Full documents (peer review articles, industry reports) were only reviewed after satisfying all inclusion criteria. Ultimately 34 articles were selected and analysed to provide 50 'observations' on wheat yield, water use and water footprints in Zimbabwe and the region.

Study area

Zimbabwe is a semi-arid country located in Southern Africa between latitudes 15° and 23°S, and longitudes 25° and 34°E. Zimbabwe has a tropical climate which is moderated in many places by the effect of local topography. As a result, wheat, a temperate crop, in Zimbabwe is mainly grown in the midveld and highveld areas (altitude above 600 m) were the cool winter season (0–20 °C) has proved ideal for wheat production (Havazvidi, 2006).

Significant wheat production also occurs in the lowveld (altitude below 600 m) in areas under government parastatals such as the Chisumbanje and Save-Valley estates.

These combined areas coincide with agro-ecological regions IIA, IIB and III which account for 75–80% of the area planted to crops in Zimbabwe (FAO, 2000). Wheat is the second-most strategic food security crop in Zimbabwe after maize, accounting for more than 50% of daily caloric intake in the country (Kapuya, 2010).

Wheat is mainly used to make flour and bran. Flour is used to make bread, which has become a staple food in the country, while bran is processed into a stock feed (Mutambara et al., 2013). Since there is very little or no rainfall during the winter months (May to August), irrigation is required to achieve a good wheat crop. Wheat is therefore a fully-irrigated winter crop in Zimbabwe. The irrigation requirements for wheat and its associated energy and water development costs mean that wheat production in Zimbabwe is mainly a commercial enterprise. The heavy reliance of wheat production

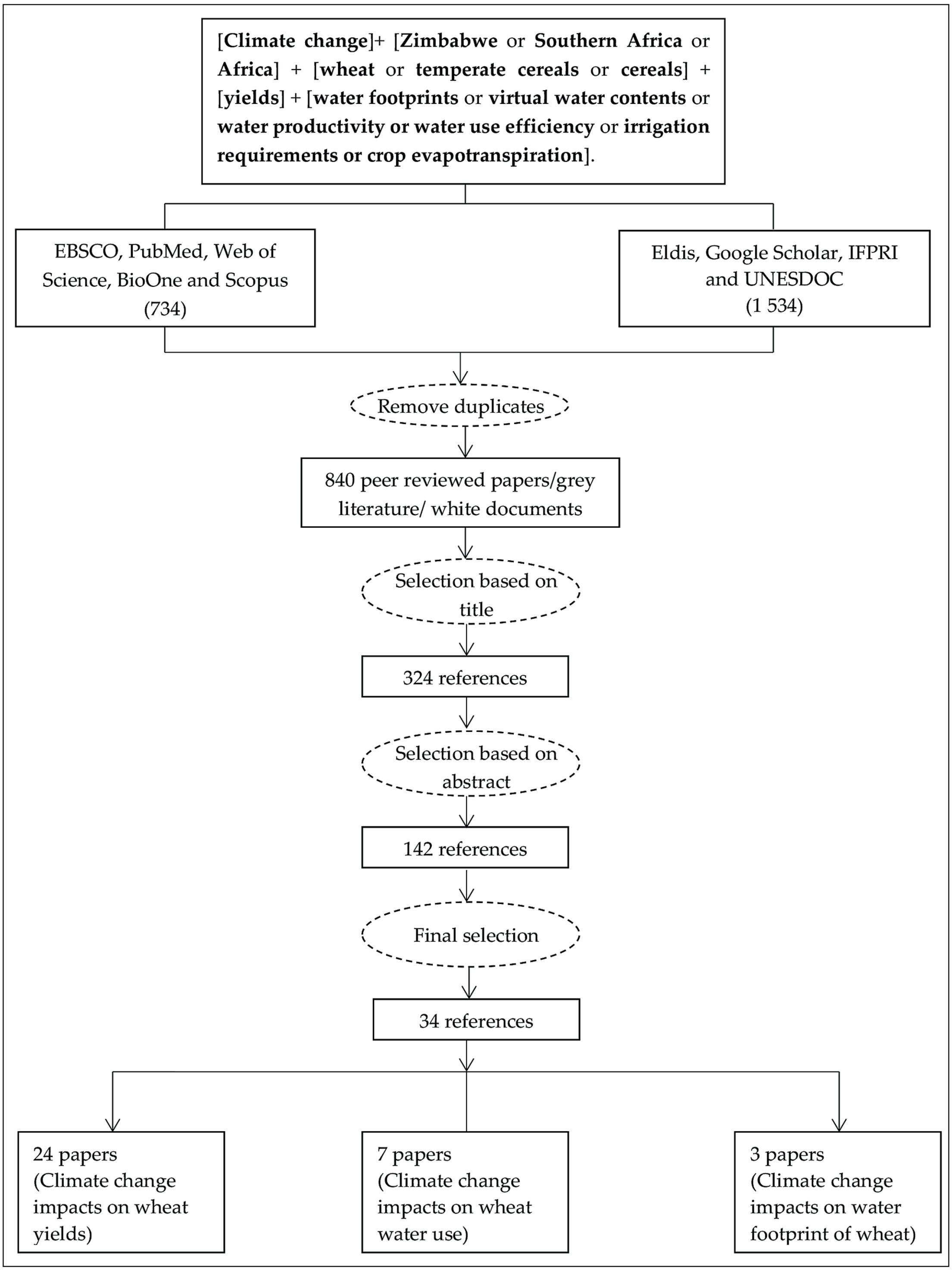

Figure 1. Schematic representation of the review process

on irrigation in the predominantly semi-arid climate of Zimbabwe, which is experiencing the effects of climate change, implies that the efficient utilization of water resources is a key issue. Zimbabwe adopted the concept of integrated water resources management (IWRM) at the 2nd World Water Forum, held in The Hague in March 2000 (Swatuk, 2005). One of the key Dublin policy principles that enshrine IWRM stipulates that water resources must be used in an efficient manner in all human endevours.

RESULTS AND DISCUSSION

Climate change and variability in Zimbabwe

Compelling evidence exists which shows that climate change is already occurring in Zimbabwe. During the 20th century the annual mean temperatures over Zimbabwe have significantly increased. Unganai (1996) reports the mean centurial rise in temperature at 0.8°C. Rekacewicz (2005)

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posits a conservative increase of 0.4°C but notes that there has been an increase in both the minimum and maximum temperatures over Zimbabwe represented by a decrease in the number of days with a minimum temperature of 12°C and a maximum of 30°C. Brown et al. (2012) estimate the overall rise in the daily minimum and maximum temperatures to be 2.6°C and 2°C, respectively.

Most researchers concur that the annual mean rainfall over Zimbabwe has declined (Makarau, 1995; Unganai, 1996; Rekacewicz, 2005; Chamaille-Jammes et al., 2007). Unganai (1996) used linear regression and noted a 10% decline in annual mean rainfall over the country in the past century. Makarau (1995) used quadratic and exponential analysis and noted a reduction of approximately 100 mm in the mean annual rainfall from 1901 to 1994. Rekacewicz (2005) concluded that the mean annual rainfall received during a rainy season has decreased by about 5% since 1900 and rainfall patterns have shifted; more rainfall is occurring at the beginning of the season, in October, and less rain is being received between January and March. Mazvimavi (2010), however, used the Mann-Kendal test and concluded that due to the high rainfall inter-annual variability over Zimbabwe it is meaningless at the moment to associate any rainfall change with global warming.

With regards to climate projections, the annual mean temperature over Zimbabwe is anticipated to increase by about 3°C for the 2050s, compared to the 1961–1990 normal, using various global circulation models (GCMs) (Hulme et al., 2001; Christensen et al., 2007). Similar results were obtained at a catchment level when Mujere and Mazvimavi (2012) projected a 3°C maximum temperature increase for Mazoe catchment for the 2050s. Seasons will likely change with hotter dry seasons and colder winters. Simulations using GCMs anticipate 5–18% less mean annual rainfall by the year 2080 compared to the 1961–1990 normal (Hulme et al., 2001; Christensen et al., 2007). The traditional onset and cessation of rainfall seasons will shift with fears of shorter and more erratic rainfall seasons. The reduction in precipitation means that in the long term yields from reservoirs will be reduced and there will be less water available for allocation across all sectors. Climate change is anticipated to cause a streamflow decline of up to 50% for the Gwayi, Odzi and Sebakwe catchments in Zimbabwe (Mazvimavi, 1998).

Growing research is showing that climate change at decadal timescales is closely linked with the increased frequency of the El Niño-Southern Oscillation (ENSO) phenomenon (Fedorov and Philander, 20000; Zhang et al., 2008; Cob et al., 2013; Cai, 2015; Wang et al., 2017). The frequency and strength of El Niño have been more variable during the 20th century than the preceding 7 000 years (Cob et al., 2013). In Zimbabwe 62% of El Niño occurrences are associated with below normal rains and droughts which result in reduced water availability in surface and groundwater sources (Gopo and Nangombe, 2016).

Zimbabwe is one of the many sub-Saharan African nations which are extremely vulnerable to climate change due to a combination of factors that include endemic poverty and constrained coping mechanisms (Chagutah, 2010; Madzwamuse, 2010). Agriculture is the mainstay of the economy, contributing an average of 16.76% (7.41–22.89%) of GDP and providing employment to 60–70% of the population (Malaba, 2013). Cross-national poverty profiles show that poverty is endemic in the country, with more than 70% of the population classified as poor and 84% of these living in rural areas (Sakuhuni et al., 2012; Malaba, 2013; Manjengwa et al., 2012). Without adaptation strategies the impacts of climate change may be potentially severe for the country due to its heavy dependence on agriculture and lack of financial resources for mitigation and adaptation to climate change. Climate change adaptation strategies, especially in the agricultural sector, are therefore a principal development challenge in Zimbabwe.

Climate change impacts on wheat productivity

There is a general consensus among several studies, using different models and approaches, that projected climate change will negatively affect wheat yields for Africa and the world at large (Liu et al., 2008; Ringer et al., 2010; Nelson et al., 2009; Zhao et al., 2017; Challinor et al., 2014; Wheeler et al., 2012; Asseng et al., 2014, Matiu et al., 2017). This review found 24 regional and global studies that predicted declines in wheat yields due to climate change and variability (Table 1). Of the 24 studies reviewed no local studies were found suggesting that very little research has been carried out in Zimbabwe on climate impacts on wheat yield. Most local climate change impact studies have focused on maize due to its importance as the prime staple of the country (Makadho, 1996; Mano and Nhemachena, 2007; Muchena, 1994; Ciarns et al., 2016; Rurinda et al., 2015; Lebel et al., 2015; Makuvaro, 2014).

Nonetheless it was still possible to isolate climate change impacts on Zimbabwean wheat yields from global and regional studies.

Parry et al. (2004) estimated the future global wheat yields at a national level using yield transfer functions and concluded that wheat yields in Africa may decrease up to 30% in the 2080s. For Zimbabwe the study determined wheat reductions of from 10–30% for the 2080s under A1FI, A2, B1and B2 scenarios, but using only one GCM, the HadCM3 model.

Konar et al. (2016) used climate outputs from 14 GCMs run under the high carbon emission SRES A2 scenario to force a process-based crop model, Global Hydrology Model (H08). Their global model predicted a decline in wheat yields in Zimbabwe of 26–63% for the 2030s. In another global study, Deryng et al. (2014) used the global crop yield model PEGASUS, driven by projected climate data from the MAGICC 6 GCM forced under all four RCPs emission scenarios. For Zimbabwe the study by Deryng et al. (2014) determined a 50% reduction in wheat yields.

With respect to climate variability studies, Zampieri et al. (2017), Iizumi and Ramankutty (2016) and Ray et al. (2015) concluded that year-to-year variability in climate has resulted in significant variations in wheat yields. At a global level as much as 75% of the wheat yield variability can be explained by climate variability whilst for Zimbabwe it was between 30 and 45%. Using statistical analysis the researchers correlate global historical wheat yields with historical climate data to detect patterns in yield changes. An advantage of statistical analysis is that it is based on observational historical data from individual farms or regions which implicitly takes into account farmer management behaviour as opposed to field experiments.

A statistical description of the results of the reviewed studies showed that there is wide variation in wheat yield reduction depending on spatial extent and time period (Fig. 2). However, there is general agreement that, regardless of spatial extent and time period, wheat yields will be negatively affected by climate change. The anticipated declines in wheat yields suggest that negative climate change impacts, like heat

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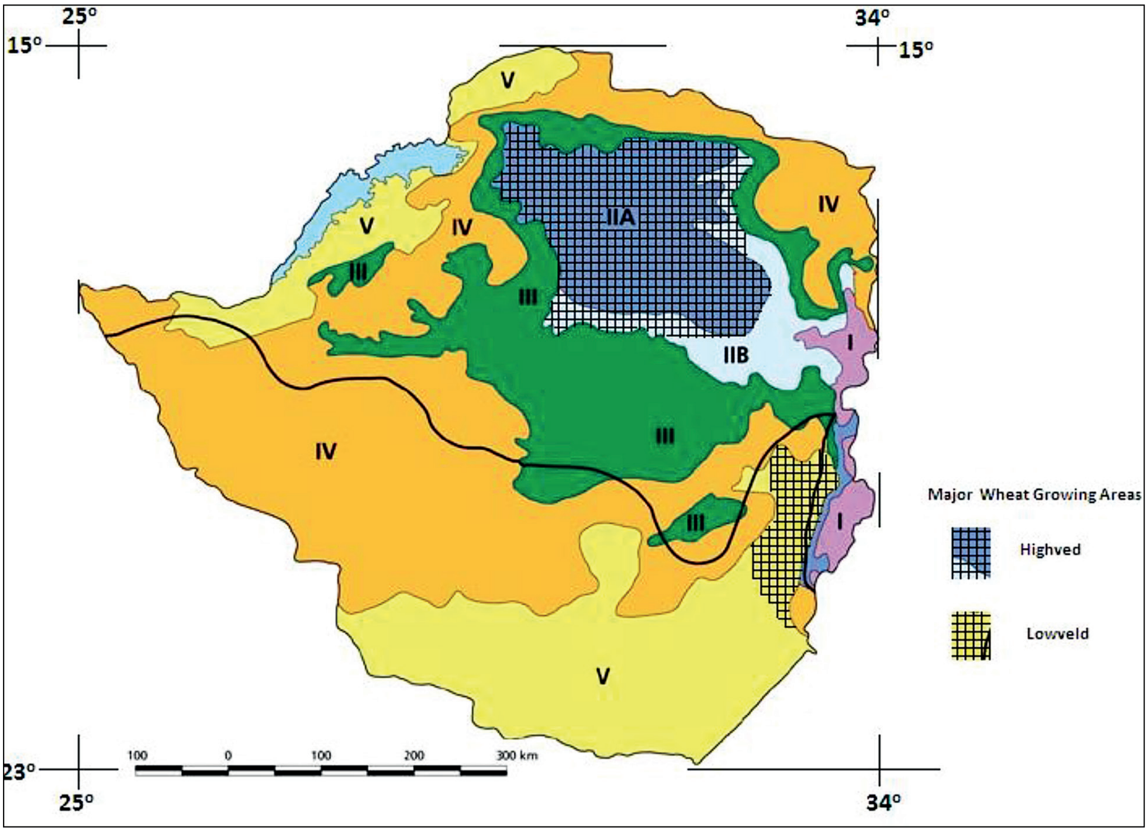

Figure 2. Agro-ecological zones and the major wheat-growing areas in Zimbabwe: After Morris (1988)

stress due to temperature rise, counter the beneficial effects of CO_2 fertilization (Siebert and Ewert, 2014; Matiu et al., 2017, Zampieri et al., 2017). For instance, in a meta-analysis Challinor et al. (2014) found that yield decline for a unit increase in temperature (°C) was 4.90% whilst yield increment for a unit increase in atmospheric CO_2 (ppm) was 0.06%, suggesting that at a global level heat stress overrides the CO_2 fertilization effect. The review shows that anticipated impacts of climate change might be higher at smaller spatial scales (national level) but lower at larger spatial scales (global and continental level). The average decline in wheat yields per time period in 46%, 22% and 8% for Zimbabwe, Africa and the world, respectively.

The implications of the decline in wheat yields are significant for Zimbabwe. Traditionally, Zimbabwe has had some of the highest national average wheat yields, of between 5–6 t/ha compared to the current global average of 2.5–3 t/ha (Bhasera and Soko, 2017). This has partly been due to the impact of wheat breeding research in Zimbabwe over the period 1969 to 1991 as well as introduction of agronomic practices which have resulted in a potential maximum wheat yield of 10 t/ha (Mashiringwani and Mutisi, 1994). Wheat yield reductions of 46% would shift the national average wheat yields to 3.15–3.78 t/ha. Economic analysis using the current gazetted wheat prices for Zimbabwe in 2017 shows that the break-even yield that results in a gross profit of zero is 4 t/ha (Bhasera and Soko, 2017).

The literature review revealed that climate impact studies use a diverse variety of GCMs, emission scenarios and crop models. For this reason a time-series plot of wheat yield shocks produced no meaningful trend since diverse emission scenarios and GCMs can be used by various studies for the same time-slice, resulting in varying results (Fig. 3). Earlier studies used a limited number of GCMs in their simulations (e.g. Parry et al., 2004 used only the HaDCM3 GCM); however, more recent studies are incorporating GCM ensembles in their analysis (e.g. Deryng et al., 2014).

The majority of the studies used process-based crop growth simulation models for assessing the impacts of climate change on wheat productivity. Common models used in the studies include the Decision Support System for Agro-technology Transfer (DSSAT), APSIM (Agricultural Production System Simulator), the GIS coupled Erosion Productivity Impact Calculator (GEPIC), the Agro-Ecological Zone (AEZ) model, WOFOST (WOrld FOod STudies) and the FAO's Cropwat model. Process-based crop models are based on crop physiological responses to environmental factors which is a key strength if external validation of the model to the environment is done (Roberts et al., 2017). A down-side of the models is that validation is based on experimental field plots but not on real farmer-managed fields where pest, weed and disease control strategies, fertilizer applications and other management practices significantly vary, depending on farmer behavior. Perhaps more importantly, process-based models were developed for finer spatial scales with homogeneous environmental conditions and their use over large spatial scales with multiple heterogeneities in environmental conditions might lead to errors (Abraha and Savage, 2006; Schulze and Walker, 2006).

In an effort to increase precision in modeling approaches a significant number of researchers are adopting a multimethod approach (Asseng et al., 2014; Zhao et al., 2017). A multimethod approach incorporates process-based crop models, statistical modeling as well as Free-Air

Table 1. Reviewed literature on climate change impacts on wheat yields

Sources	Methods	Region	Emission scenario	CO_2 effect	Time period	Percentage per +1°C	Change per period
Asseng et al., 2014	Multimethod ensemble	Global	–	Included	2020s, 2050s	−6%	
Zhao et al., 2017	Multimethod ensemble	Global	RCP2.6, RCP4.5, RCP6, RCP8		1961–1990 2071–2100		−13.6%
IPCC, 2014	Meta-analysis	Global	–	–	1960–2013		−8%
Challinor et al., 2014	Meta-analysis	Global	–	–	-	−4.90%	
Moore et al., 2017	Meta-analysis	Global	–	Included	1995–2005	−5%	
Knox et al., 2012	Meta-analysis	Africa	–	–	-		−17%
Lobell et al., 2008	Process-based	Southern Africa	A2, B1, A1b	Not included	2020–2040		−15%
Liu et al., 2013	Process-based	Africa Zimbabwe	A1FI, A2, B1, B2	Included	2020–2040		−17% −50–75%
Fischer et al., 2005	Process-based	Zimbabwe Africa		Included	2020s, 2050s, 2080s		−25–50% −12%
Wiebe et al., 2015	Process- based	Africa	RCP4.5, RCP6 RCP8	Included	2050		−10%
Muller et al., 2010	Process- based	Zimbabwe		Included	2046–2055		0–5%
Konar et al., 2016	Process-based	Global Zimbabwe			2000–2030		−6.5% −26–63%
Parry et al., 2004	Process-based	Global Zimbabwe	A1FI, A2, B1, B2	Included	2020s, 2050s, 2080s		−5% −30–10%
Tatsumi et al., 2011	Process- based	Southern Africa Global	A1B	Included	2090		−36.83 +7%
Rosenzweig and Parry, 1994	Process- based	Zimbabwe	550 ppm CO_2	Included	2060		−10–30%
Nelson et al., 2014	Process- based	Global		Included	2050s		−2.3–25%
Ringler et al., 2010	Process- based	Africa		Included	2000–2050		−22%
Nelson et al., 2009	Process- based	Africa		Included	2050		−28%
Deryng et al., 2014		Global Zimbabwe	RCP 2.6 /8.5	Included	2050-2080		+sp −50%
Iizumi and Ramankutty, 2016	Statistical	Global	–	–	1981–2010		±19%–33%
Lobell et al., 2011	Statistical	Global	–	Indirectly included	1980–2008		−5.5%
Ray et al., 2015	Statistical	Global Zimbabwe	–		1961–2000		±75 ±30–45%
Matiu et al., 2017	Statistical	Global	–	–	1961–2014		−9.2%
Zampieri et al., 2017	Statistical	Global			1980–2010		±40%

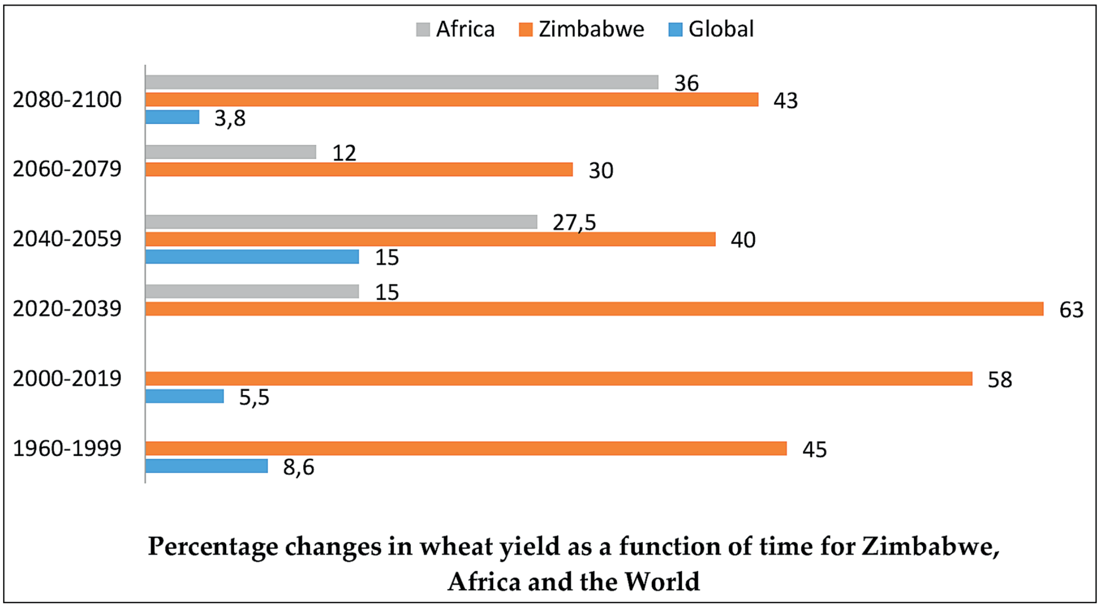

Figure 3. Wheat yield reductions per period from reviewed studies

Carbon-dioxide Enrichment (FACE) experiments where crops are grown in CO_2-rich environments to mimic the effect of climate change. However multimethod approaches may simply result in great precision in climate studies but not accuracy if the delimitations for each separate method are not resolved. For instance, Jones et al. (2014) have shown that though FACE experiments provide precise information about crop physiological and phenological responses to enriched CO_2, most of the experiments are spatially biased since they have been carried out in the temperate regions of Europe and America. Extrapolation of experimental results from these regions to the tropical Asian and African regions might result in inaccuracy since tropical areas have different biomes and environmental conditions.

Climate change impact on wheat water use

A literature search on the impact of climate change on water requirements of wheat in Zimbabwe yielded little or no local results. The search did, however, result in 7 global and regional studies that have attempted to quantify climate impacts on wheat water use. Of the 7 studies, 2 studies had results for Zimbabwe., and 2 of the 7 studies specifically focused on wheat whilst the remaining 5 collectively focused on cereals, temperate cereals or all crops (wheat included). Compared to the 24 papers reviewed under wheat productivity the relatively small number of papers on wheat water use may signal that food security issues have a higher research priority than water security issues. However, water security and food issues are intricately connected (Brazilian et al., 2011).

Global studies suggest that high temperatures lead to an increased irrigation water demand by increasing the overall crop transpiration rate. Using two GCMs (Hadley and CSIRO) under A2r scenarios Fischer et al. (2007) projected a 20% increase in net irrigation requirements for the world by 2080. They noted that about 65% of the global net irrigation requirement increases would emanate from higher crop water demands under the changed climate, and the remaining 35% from extended crop calendars. For Africa net irrigation requirements for crops were expected to increase by 14%. The significantly lowered CO_2 concentrations may contribute to lower crop water demand.

Doll and Siebert (2002) used the GIM (Global Irrigation Model) to determine how irrigation requirements might change under the climatic conditions of the 2020s and the 2070s using two climate models, ECHAM4 and HADCM3. Their simulation gave contradictory results for southern Africa based on the climate models. The ECHAM4 model showed a consistent decline in irrigation requirements across the region for the 2020s and the 2070s whilst HADCM3 showed increments for both scenarios. The study shows that climate change impact predictions vary significantly, depending on the crop models used, climate change scenario and the number and types of global circulation model (GCM) used.

Pan et al. (2015) determined that global crop lands would experience an increase of about 38.9% and 14.5%, respectively, under both the A2 and B1 scenarios between the 2090s and the 2000s. Their analysis suggested that climate variability accounted for 91.3% of the inter-annual variation in evapotranspiration. Whilst the study pointed to increased evapotranspiration rates, it also showed that strength of the CO_2 fertilization effect would determine the magnitude of global terrestrial evapotranspiration during the 21st century. The CO_2 fertilization can result in reduced evapotranspiration through reduction in stomata conductance in plants.

Two global studies noted a decline in global irrigation requirements. Liu et al. (2013) noted that globally the net irrigation requirements for cereal crops (wheat, maize and rice) would decrease in the 2030s and 2090s. However net irrigation requirements would increase in southern Africa. For Zimbabwe, the study determined that crop water use would both increase (12.5% to 11.4%) and decrease (−45.7%–25.8%) for the 2030s and 2090s, respectively.

Zhang and Cai (2013) used 5 GCMs and noted that global irrigation requirements for major crops might decline slightly despite the anticipated rise in temperature. In their analysis wheat irrigation requirements for Zimbabwe and Africa as a whole decreased. This counter-intuitive effect noted by Zhang

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Table 2. Percentage change in crop water use from reviewed papers and publications

Sources	Region	Crop	Methods	Emission scenario	CO_2 effect	Time period	Water use percentage	Changes depth
Fischer et al., 2007	Global Africa	All crops	Process-based	o, A2r	Included	1990–2080	20% 14%	
Doll and Siebert, 2002	Global Africa	All excluding rice	Process-based	IS92a	Included	2020s, 2070s	5.4% −1.4%	
Pan et al., 2013	Global	General	Process-based	A2 and B1	Included	2090s	38.9–14.5 %	
Liu et al., 2013	Zimbabwe	Wheat, rice, maize	Process-based	A1FI and B2	Included	2030s, 2090s	−9.95–11.95%	
Zhang and Cai, 2013	Zimbabwe Global	Wheat	Process-based	A1B-SAM	Included	2099		0–99mm
Elliott et al., 2014	Global	All	Process-based	-	Included	2090s	−15%	
Fant et al., 2013	Zimbabwe	Wheat	Process-based	-	Included	2050	5.8%	

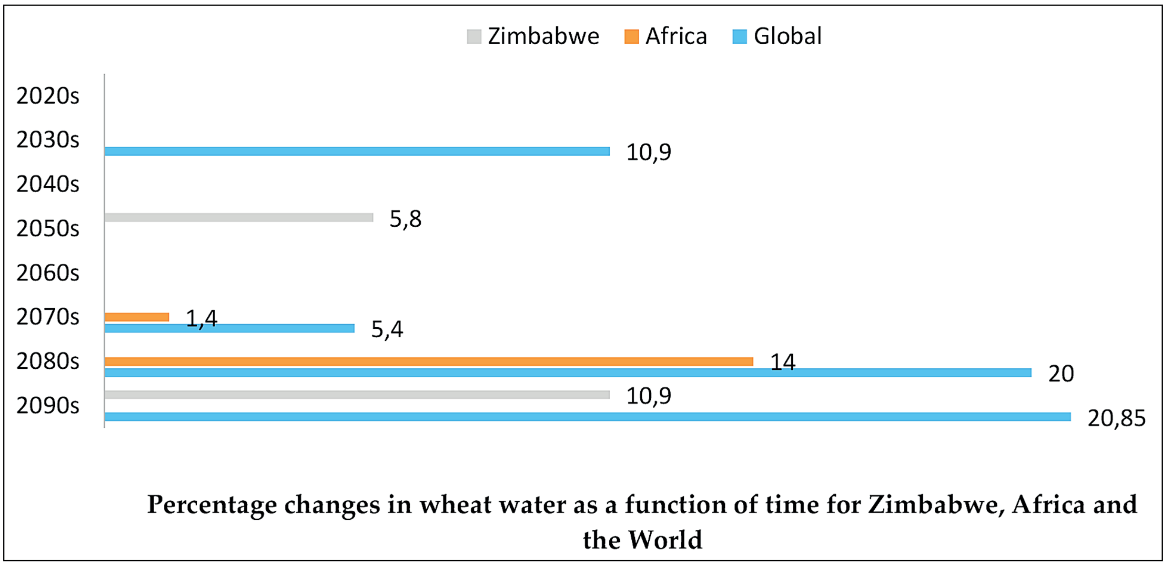

Figure 4. Irrigation demand changes per region from reviewed studies

and Cai (2013) and Liu et al. (2013) of reduction in irrigation requirements despite increments in temperature can be explained by the diurnal temperature range (DTR; difference between daily maximum temperature and daily minimum temperature). Zhang and Cai (2013) note that increments in temperature may not cause higher evapotranspiration in cases where there is a decline in the DRT.

Fant et al. (2013) explored the impacts of climate change on irrigation requirements in the Zambezi basin which overlaps with the south-eastern part of Zimbabwe. Their robust analysis used a large pool of climate projection (6,800) based on the full set of the CMIP-3 GCMs for the 2050s time slice. Their analysis predicts a 6% increment in irrigation demand for cereals (excluding maize) for 4 countries in the basin, including Zimbabwe.

A statistical description of the results using a bar graph is shown in Fig. 3. It shows that across all time periods and emission scenarios crop water use at the global, regional and local scale will increase. There is, howeverk a lot of uncertainty in these estimations since most of the studies focused on a range of crops and not just wheat.

The implications of the increase in water requirements for wheat in Zimbabwe are significant. Recommended water requirement for wheat per season in the country ranges from 350 to 600 mm/ha depending on method of irrigation and geography (Bhasera et al., 2017). Rahman et al. (2015) determined that for the highveld areas of Harare and Domboshava the crop water requirements ranged from about 550 to 990 mm per season and varied significantly with irrigation methods used. In a survey of 41 commercial farms, Longmire et al. (1987) determined that the average total water actually applied in wheat farms was 570 mm (range 360 to 800 mm). These irrigation requirements in Zimbabwe where water availability has always been erratic and highly variable have made water resources the most limiting factor in the production of winter wheat. An increment in the irrigation requirements due to climate change and variability can compound the situation.

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Climate change impacts on the water footprint of wheat production

The literature search on the impact of climate change on the actual WF of wheat in production in Zimbabwe yielded limited or no local studies. At a global or regional level only 3 papers by Fader et al., 2011, Deryng et al., 2016 and Konar et al., 2016 have explored the possible climate change impacts on crop WFs.

Fader et al. (2011) modelled global VWC under climate change scenarios. Values of VWC are equal and comparable to values for WF. The global study showed that by the 2070s, under A2 emission scenarios of future climate change and increasing atmospheric CO_2 concentrations, the WF for temperate cereals like wheat and barley will decrease globally. However, for many arid regions, such as Australia, South Africa, Argentina and the Mediterranean, the WF would increase. Although Zimbabwe is classified as semi-arid it was not included in the study. In the arid regions it is expected that the negative effects of climate change exceed the positive effects of CO_2 fertilization. An interesting analysis by Fader et al.(2010) showed that yields are the main driver of WF, rather than evapotranspiration; decreases in WF by more than 1 m^3/kg were highly correlated to yield increases, and increases in WF by more than 1 m^3/kg^{-1} were highly correlated to yield decreases.

The critical role of yields in determining the WF was also noted by Konar et al. (2016) who analysed VWC under future climate change scenarios. Konar et al. (2016) based their assessment on projected yield shock scenarios (low, medium and high yield) predicted by Hertel et al. (2010). In their analysis global WF decreased under the medium- and high-yield scenarios for all crops but increased under low yield scenarios.

Perhaps the most intensive study on climate impacts on global WF of wheat production was carried out by Deryng et al. (2016). The researchers analysed climate change impacts on the CWP of wheat production at a global level. Since the CWP is the inverse of the WF their results are comparable to this study by taking the inverse of the CWP. Using a network of field experiments and an ensemble of process-based crop models and GCMs, Deryng et al. (2016) determined that CO_2 fertilization decreased global WF of cereals by 10–27% by the 2080s. In sharp contrast to the study by Fader et al. (2010), the study determined that the WF of crops grown in arid climates benefits the most from the effects of elevated CO_2 leading to additional significant reductions in consumptive crop water use by 2080. The contrast in results by Fader et al. (2010) and Deryng et al. (2016) highlights the fact that the impact of higher atmospheric CO_2 concentration is a major source of uncertainty in crop yield projections.

From the conflicting and few results of the three global studies on WF of wheat production there is a lot of uncertainty on how climate change will impact WF of wheat production for Zimbabwe. However, it is possible to extrapolate the results from the literature review on local yield and wheat water use. The literature review showed both a median decrease in wheat yields and increase in water consumption for Zimbabwe. Pooled together these results might indicate that climate change may result in increased WF for wheat production in the country. The possible increase in the local WF of wheat production may not be sustainable for the country which is classified as semi-arid with limited water resources.

The severity of the impact of climate change on the WF of wheat production depends on the actual increase in the WF and the current WF determined for the country at the present moment; a high WF would be further exacerbated by climate change whilst a low WF can absorb and significantly neutralize climate change impacts. Since no local research has been conducted, the actual increase in WF cannot be ascertained without a significant amount of error. Furthermore, information on the current WF of wheat production in Zimbabwe is not known. Notwithstanding, Fader et al. (2011) reported that WF differs significantly among regions with highest values > 2 m^3/kg common in large parts of Africa. There is thus a need for local research to determine the effect of climate change and variability on the WF of wheat production.

Possible climate change adaptation strategies

The foregoing discussion suggests that there may be a need for climate change adaptation strategies in Zimbabwe that decrease the WF of wheat production. Options for increasing wheat yields that have been documented in literature and may be categorized as crop-level adaptations (e.g. increasing yields and decreasing crop water use by breeding for higher yields, drought resistance or heat resistance (Deressa et al., 2009) and planned adaptations (e.g. expanding irrigation infrastructure or improvement in agricultural markets [Mendelsohn, 2001]). This study will primarily focus on crop-level adaptations partly because they fall under the study scope of the researchers and have been shown to be effective. Research shows that crop-level adaptations have the potential to boost yields by 7–15% more compared to similar scenarios that do not utilize adaptation (PCIC, 2014). A list of possible crop-level adaptations are listed in Table 3.

Crop breeding to develop new wheat varieties with higher yields, drought or heat resistance is touted as a possible solution to combat the negative effects of climate change on WF. High-yielding wheat varieties would result in more production with less or equal amounts of water applied compared to lower yielding varieties. This would reduce the WF of crop production.

There is, however, general disagreement over whether crop breeding for wheat would have any significant effect on yield. Compelling evidence suggests that in certain regions of the world wheat yields are plateauing and the rate of yield progress is falling to as low as 1.16% (Graybosch and Peterson, 2010; Cassman et al., 2010; Mackay et al., 2011). Hawkesford et al. (2013) notes that the main route in crop breeding for higher yielding cereals was increasing the harvest index (HI), which is currently at 60%, hinting that further increases above that value may not be physiologically possible. The highest wheat yield ever recorded is 16.791 t/ha (New Zealand) setting the current wheat yield barrier at 17 t/ha (Agrifac, 2017).

Zimbabwe has a lot of local high-yielding varieties that include SC Nduna (White) (11t/ha) and SC Sky (Red) (12 t/ha) (Seed Co, 2018). Considering that the highest national average wheat yields have been between 5 and 6 t/ha a significant yield gap still exists suggesting that higher yields can currently be attained by adopting good farm management practices rather than crop breeding. Some of these practices are highlighted in Table 3 and include good fertilizer management as well as timely sowing. The prospects of adapting to a higher WF of wheat production under climate change by decreasing crop water use can be done through a number of interventions. One possible strategy with a lot of potential is the adoption of irrigation scheduling techniques by local farmers. Historically studies have shown that there has been inefficient water use among wheat farmers in Zimbabwe with a tendency to over-apply irrigation water (Morris, 1988). Irrigation scheduling is the technique of determining the time, frequency and quantity

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Table 3. Possible climate change adaptation strategies to decrease WF of wheat production in Zimbabwe

Options	Strategies	Description
Increasing wheat yields	Crop breeding	Breeding for drought resistance and heat tolerance to higher temperatures
	Fertilizer management	More soil testing, variable rate application better matching rates to crop demand to improve efficiency of fertilizer use
	Timely sowing:	Timely sowing so that flowering and grain-filling occurs after the period of heightened frost risk, but before the effects of late season water limitation and high temperature can reduce yield
Reducing crop evapotranspiration	Irrigation scheduling	Farmers training on methods of scientific irrigation scheduling; more research carried out to demonstrate the benefits of improved water management
	Deficit irrigation	Higher yields per unit of irrigation water applied
	Irrigation technology	Phasing out the use of sprinklers in preference to centre pivot systems with high application efficiency and flexibility
	Partial root-zone drying	Irrigating approximately half of the root system of a crop; more research to be carried out
	Shift planting dates	Matching farm activities with changes in temperature
Tillage and residue management:	Crop mulching and stubble retention	Use of crop residues or synthetic material to curb soil evaporation
	Zero tillage	Soil surface management to minimize soil evaporation and maximize infiltration

of irrigation water applications to reduce overall crop water use by reducing crop evapotranspiration. Irrigation scheduling is particularly suitable for Zimbabwe because inefficient water use has been traced to farmers' ignorance on how to implement scientific scheduling and inadequate research carried out to demonstrate the benefits of improved water management. Tambo and Senzanje (1988) noted that most wheat farmers rarely practice irrigation scheduling.

Deficit (or regulated deficit) irrigation is another potential strategy that can be used to adapt to climate change in Zimbabwe and reduce the WF for higher yields per unit of irrigation water applied. Deficit irrigation is defined as the application of water below the crop water requirements exposing the wheat crop to a particular level of water stress for a specified period (Fereres, 2006). The assumption of deficit irrigation is that possible yield reductions due to water stress will be insignificant compared to the benefits derived by diverting water to other crops.

Research by Nyakatawa and Mugabe (1996) (see Table 4) showed that wheat yields of more than 4 t/ha can be expected when wheat is grown on deficit irrigation of at least 170 mm/season.

Good tillage and residue management on wheat farms can also help curb the effects of climate change on WF of wheat production by increasing yields and lowering crop evapotranspiration. Conventional tillage on wheat farms in Zimbabwe involves deep ploughing (ripping or chisel plough), followed by basal fertilizer application (option for liming), disking and then rolling (Basera and Soko, 2017). Conventional tillage practices have been linked to decreased water infiltration, increased soil evaporation and reductions in crop yield (Esser, 2017). Adopting conservation tillage practices together with the use of crop residues as mulching material can reduce soil evaporation, increase infiltration, and boost yields, resulting in a lower WF. Gwenzi et al. (2008) in the Save Valley demonstrated that minimum tillage and no-tillage in a irrigated wheat-cotton rotation was more sustainable than conventional tillage; they improve soil structural stability and carbon sequestration. No studies on mulching on wheat farms have been conducted locally. However, the potential exists. In a meta-analysis Nyamangara et al. (2013) showed that conservation tillage and residue management may increase maize yields.

The adoption of efficient irrigation systems at the farm level can assist in decreasing the WF of wheat production under climate change. The majority of wheat farmers in Zimbabwe use overhead sprinkler systems (Tembo, 1988; Gambara, 2016). Overhead sprinkler systems are composed of laterals that have many joints and have to be moved from one position to the other. They are thus associated with water losses and leakages which can increase the WF. Overhead sprinkler systems have an average application uniformity efficiency of 75%.

Centre pivot and drip irrigation systems have been replacing traditional flood irrigation and subsurface drip irrigation. Centre pivots and drip irrigation systems are highly efficient with up to 95% efficiency in terms of application uniformity. A study by Maisiri et al. (2005) in the semi-arid Insinza district of Matabeleland South province showed that drip irrigation systems on wheat farms use only 35% of the water used by the surface irrigation systems resulting in low WF of crop production.

CONCLUSIONS

This paper fills an important gap in climate impact studies by providing a review of the anticipated climate change impacts

Table 4. Experimental wheat yields in Zimbabwe under deficit irrigation

Irrigation level	Days to maturity		Number of ears/m^2		Grain yield	
Full	114.3	112.0	375	350	5 537	5 290
Three quarter	112.1	110.5	367	345	4 862	4 894
Half	109.7	108.5	358	318	4 431	4 223

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on wheat yields, crop water and WF of wheat production in Zimbabwe. From the study, and in relation to the objectives set, it can be concluded that there is a dearth of information on the possible impact of climate change on the WF of wheat production in Zimbabwe. No local studies have been carried out in the country to determine climate change impacts on wheat yields, crop water use and the WF of wheat production.

Despite the scarcity of information global and regional studies hint towards an increase in the WF of wheat production in Zimbabwe under future climate change scenarios. The increase in the WF stems from a decrease in local wheat yields and increase in crop water use.

A lot of uncertainty exists at on the global and regional level on the precise effect of climate change on the WF of wheat production. The uncertainty is partly due to the predominant use of process-based models which might not be suitable for large spatial scale with high heterogeneity with respect to environmental conditions.

There is therefore need for more local studies to be carried out within Zimbabwe to ascertain accurate impacts of climate change on the WF of wheat production.

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