SIMULATION OF CLIMATE CHANGE IMPACTS ON SELECTED CROP YIELDS IN SOUTHERN ALBERTA

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ABSTRACT

AquaCrop is a crop water productivity model that simulates crop yield response to water in various geographical locations. Parameterizing the crop model to specific local conditions can be difficult without detailed crop parameters. On the Canadian prairies there are many different varieties of barley, canola and wheat with measured crop parameters, grown in both irrigated and rainfed agriculture. The objectives of this study were to calibrate selected crop parameters for historical observed yields in southern Alberta using a grid search calibration method for both irrigated and rainfed conditions, and simulate future crop yields using five regional climate model (RCM) projections. The grid search calibration method was successful in parameterizing AquaCrop for barley, canola, and wheat yields for two areas in southern Alberta, thus a realistic assessment of climate change impacts could be performed. All five RCMs indicated increases in crop yields coupled with a strong simulated CO_2 fertilization effect.

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List of Abbreviations

AAFRD	Alberta Agriculture, Food and Rural Development
AAFS	Agriculture and Agri-Food Systems
ACRU	Agriculture Catchments Research Unit
AFSC	Agriculture Financial Services Corporation
AgMIP	Agricultural Model Intercomparison and Improvement Project
AGRASID	Agricultural Region of Alberta Soil Inventory Database
B	Biomass
BBCH	Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie
CAN$	Canadian Dollars
Canadian Prairies	Alberta, Saskatchewan, and Manitoba
canesm2	Canadian Earth System Model Version 2
cgcm3	Coupled Global Circulation Model Version 3
CN	Curve Number
CO_2	Carbon Dioxide
DDSAT	Decision Support System for Agrotechnology Transfer
E	Soil Evaporation
ET_a	Actual Evapotranspiration
ETo	Reference Evapotranspiration
ET_x	Maximum Evapotranspiration
FACE	Free-Air CO_2 Enrichment
FAO	Food and Agriculture Organization of the United Nations
FC	Field Capacity
GCM	Global Climate Model
GDD	Growing Degree Day
gfdl	Geophysical Fluid Dynamics Laboratory
GIS	Geographic Information Systems
gs	Stomatal conductance
HI	Harvest Index
I	Irrigation
IPCC	Intergovernmental Panel on Climate Change
IRM	Irrigation Requirements Model
Ksat	Saturated Hydraulic Conductivity
K_y	Factor between relative yield loss and relative reduction in evapotranspiration
MAE	Mean Absolute Error
ppm	Parts per million
PPT	Precipitation
PWP	Permanent Wilting Point
RAW	Readily Available Water
RCM	Regional Climate Model
RCP	Representative Concentration Pathways

RMSE	Root Mean Square Error
Sat	Soil Water Content at Saturation
SDSM	Statistical Downscaling Model
SRES	Special Report Emission Scenarios
Tbase	Base Temperature where crop growth ceases
TGICA	Task Group on Data and Scenario Support for Impact and Climate Analysis
Tmax/Tx	Maximum Air Temperature
Tmin/Tn	Minimum Air Temperature
Tr	Crop Transpiration
Tr	Canopy Transpiration
USDA	United States Department of Agriculture
WP	Water Productivity
WUE	Water Use Efficiency
Y_a	Actual Yield
Y_x	Maximum Yield

Chapter 1
Thesis Introduction

1.1. Introduction

A major global challenge today is to meet growing food demand under rapidly changing climate conditions. Continued global population growth puts greater pressure on the agriculture sector to produce enough food to feed the world population. Some countries suffering from drastic food shortages rely on the help of other nations through trade agreements to export food to the less advantaged regions. Future levels of support could be threatened by uncertain climate change impacts on agricultural productivity.

Canada plays a prominent role in meeting global food demand. According to government estimates, half of the value of primary agriculture production in Canada is exported (AAFS, 2014). In 2012, the Canadian Agriculture and Agri-Food System (AAFS) generated $103.5 billion, accounting for 6.7% of Canada's total GDP. Most of the agriculture production lies in the Prairie Provinces: Alberta, Saskatchewan and Manitoba. According to a report by Statistics Canada, Alberta set a record high in 2013 for principal field crop production of 34.5 million tonnes (Matejovsky, 2014). Agriculture is a very important sector in Canada's economy.

The focus for this research is the Oldman watershed, an extensive area for crop production located in southern Alberta, Canada. In 2010, the southern region, mostly within the Oldman watershed, was the province's largest producer of durum wheat, fodder corn, potatoes, flaxseed, dry beans, sugar beets, and vegetables

("Census of Agriculture," 2011). In Alberta, the largest allocation of water use is for irrigation (Klein et al., 2012), and is predominantly used in southern Alberta within the 13 irrigation management districts (Bennett and Harms, 2011). To assist these irrigation districts in better water resource management, a regionalized irrigation model known as the Irrigation Requirements Module (IRM) has been developed by the Irrigation Branch of Alberta Agriculture, Food and Rural Development (AAFRD) (Association and Committee, 2002). Close monitoring of crop yields is crucial given the vital contribution to the regional economy.

There are natural risks that constantly threaten the agriculture economy. Agriculture production is extremely dependent on climate and the environment, especially natural drought occurrences, the timing of rainfall and weather extremes. A report by Wheaton et al. (2008) concluded that consecutive drought years of 2001 and 2002 devastated the agriculture economy, resulting in an estimated loss of $3.6 billion dollars. Alberta and Saskatchewan were affected the most by the resulting water deficit, accounting for 90% of the total loss. Droughts can cause severe impact on the agriculture sector, at times costing billions of dollars in lost revenue.

Yet, projections for a warmer climate exist in southern Alberta also suggests more frequent and more intense occurrences of heavy precipitation (PaiMazumder et al., 2013; Gizaw and Gan, 2015). Such events can increase the risks of heat stresses for crops and potential hazards from severe rainstorms, although new opportunities for the agriculture industry might arise as atmospheric CO_2 concentrations increase (Kulshreshtha, 2011).

Future prospects for the agriculture industry remain highly uncertain, especially in southern Alberta, due to continued gaps in understanding the impacts of climate change on agriculture production, To help address these limitations, Regional Climate Models (RCMs) are downscaled from Global Climate Models (GCMs) and used for estimating future climate change impacts involving multiple climate variables (Teutschbein and Seibert, 2012). RCMs have been widely used for assessing future crop development (Moriondo and Bindi, 2006; Wang et al., 2011; Asseng et al., 2013; Vanuytrecht et al., 2015). These RCMs provide higher spatial resolutions compared to GCMs, allowing for the study of climate change effects on agricultural production at higher scales of resolution. RCM projections for southern Alberta have indicated potential increases in droughts in both severity and duration compared to the 20th century (Sauchyn and Bonsal, 2012; PaiMazumder et al., 2013). These projections are very concerning for planning future agricultural development. Crops can respond positively to increases of atmospheric CO_2 concentrations (Justin and David, 2013). This CO_2 fertilization effect is known to be complex and variable with different climates and crops (Ainsworth and Long, 2005).

This research aims to aid the agricultural industry in Alberta in making better decisions towards increased production in spite of climate change, by examining the impacts of climate change and CO_2 fertilization on crop yields. The crop water productivity model called AquaCrop, developed by the Land and Water Division of the Food and Agriculture Organization of the United Nations (FAO), will be used in this study for simulating crop yields. This model is particularly focused on water stress as the limiting factor in crop production (Steduto et al., 2009).

AquaCrop has been widely used with many different crops and varying locations under rainfed and irrigated conditions (Karunaratne et al., 2011; Salemi et al., 2011; Stricevic et al., 2011; Zinyengere et al., 2011; Abedinpour et al., 2012; Abrha et al., 2012; García-Vila and Fereres, 2012; Mkhabela and Bullock, 2012; Bwalya, 2013; Lorite et al., 2013; Abedinpour et al., 2014; Iqbal et al., 2014; Kumar et al., 2014; Vanuytrecht et al., 2014a). CO_2 fertilization effects are included in AquaCrop, but better understanding is still required in terms of interpreting influence on future agriculture production, including possible over-simulation of yields (Vanuytrecht et al., 2011). The AquaCrop model is quite new to Canada. Currently only Mkhabela and Bullock (2012) have carried out a study on simulating wheat production in Saskatchewan and Manitoba. AquaCrop has yet to be parameterized in southern Alberta and assessed for simulating crops under rainfed and irrigated conditions.

By combining the results of the AquaCrop model with future production estimates from RCMs and assessing the default irrigated settings with a local irrigation model, certain conclusions can be established from these theoretical research questions: Can AquaCrop be a valid tool for simulating wheat, barley and canola in southern Alberta? How will the future RCMs define crop yields? What uncertainties exist with regards to climate change and CO_2 fertilization effecting future crop growth? How do the default irrigated settings used with AquaCrop compare to a local irrigation model?

1.2. Objectives

Understanding the connection between water-driven stress on crop yields and impacts of future climate change is essential for making proper management decisions for crop production. The primary objectives of the research are listed below.

1. Calibrate the AquaCrop model to effectively simulate historical crop yields for three crops and two locations within the Oldman watershed.
2. Simulate future predictive crop yields using different regional climate models (RCMs) to understand the climate change impacts on crop yield.
3. Evaluate the differences between irrigated crop outputs between Irrigation Requirements Module (IRM) and the default settings from AquaCrop.

1.3. Thesis Structure

The structure of this thesis is divided into five chapters. The first chapter provides a brief introduction to the thesis topic and lists the main objectives. The second chapter contains a literature review of key topics relating to agriculture, crop modelling, and the impacts of climate change. It begins with a review on crops and the importance of crop production for Canada, followed by a review of crop modelling and the FAO's AquaCrop model. Chapter 2 continues with a summary of climate change and the description of Regional Climate Models, and ending with a review of crop modelling with impacts of climate change. The next two chapters (3 & 4) contain stand-alone journal paper formats, therefore some repetition exists

between individual chapters. Chapter 3 introduces and explains the methods of using a grid search algorithm for determining optimal wheat crop parameters for AquaCrop in a test location in the County of Taber, and concludes with an analysis of predicting wheat yields based on five RCMs. Chapter 4, expands on the procedures and methods from Chapter 3, but incorporates crop yield simulations for barley and canola, as well as new distinct region, the County Pincher Creek. Also, a comparison is made between a local irrigation model, Irrigation Requirements Model (IRM) and the default irrigation settings of AquaCrop. The final Chapter 5 provides a brief summary of the entire thesis, key discussion points found throughout the thesis, and concludes with considerations for future research on this topic.

Chapter 2
Literature Review

2.1 Introduction

This literature review will present a discussion of the literature based on crop modelling with a focus on the FAO's AquaCrop model and the impacts of climate change on crop production. A review of previous validations of the AquaCrop model will conclude that the model is proficient for this research. In addition, a summary of the importance of the impacts of climate change will be provided, as well the challenges of known uncertainties in predicting future yields.

The first topic will cover literature that introduces crops and the importance of agriculture in Alberta. The second topic proves that crop modelling is feasible and provides a review of the core dynamics of the AquaCrop model. Previous studies using AquaCrop for simulating crop yields will be summarized, as well as an additional review on the external capabilities that the model is lacking. The third topic focuses on climate change and using climate models (GCMs and RCMs) for scientific research. GCMs and RCMs have been used for predicting crop yields and an assessment of recommendations will be analyzed. The concluding remarks from various authors, include topics of uncertainties in predicting future yields from the effect of a CO_2 fertilization and yield variability produced from crop models, which will be highlighted, concluding how this research will attempt to fill some of the existing knowledge gaps.

2.2 Crops

"Crops are plant species grown for human or animal consumption or for special purposes" (Morrison, 2012, para. 1). Agriculture involves the processes, management and research in cultivating crops and animals for products used in industry or human consumption. The following section will review important processes of crop physiology that contribute to final yields that are quantified in crop models.

2.2.1 Photosynthesis and Calvin Cycle

Photosynthesis is the process by which plants convert solar energy to chemical energy that directly relates to crop yield (Sheaffer and Moncada, 2008). Photosynthesis requires water, CO_2 and sunlight to create its final product, glucose, a sugar used as energy for the crop's growth. Photosynthesis has been one of the main processes quantified in the development of crop modelling (Loomis et al., 1979). Simple coupling of light distribution and leaf photosynthesis can simulate canopy production, or with a radiation penetration model coupling movement of CO_2 into the leaf. Determining the final crop yield from photosynthesis depends on the crop's ability to effectively capture light, and convert the intercepted light into biomass (Long et al., 2006). More recently, simulated canopy growth is dependent on the canopy size for photosynthesis and has a constant relative growth rate under unstressed conditions (Steduto et al., 2009). A theoretical study done by Long et al. (2006) hypothesized on improving the photosynthesis of crops through genetic breeding, concluding it is very difficult to the complexity of crop growth. Other

research on improving crop yields with elevated CO_2 concentrations has been a practical focus (Drake et al., 1997; Zhu et al., 2008; Leakey, 2009; Raines, 2011).

The Calvin cycle is the process by which the chemical reaction of photosynthetic CO_2 converts into energy used for crop growth (Raines, 2011). Three different categories exist on describing a crop's Calvin cycle: C_3, C_4, and CAM. The majority of crops are C_3 (wheat, barley, canola, rice, alfalfa, cotton) which prefer a photosynthesis temperature range between 10 and 25°C. C_4 crops (corn and sorghum) are more water efficient, making them more suitable for places with occurring drought stresses (Leakey, 2009). CAM crops (cacti and pineapple) are adapted to hot temperatures and use a combination of both Calvin cycles, C_3 during the day and C_4 during the night (Sheaffer and Moncada, 2008). Differences exist in modelling C_3 and C_4 crops. The crops' efficiency to use water to produce biomass, referred to as water productivity (WP) (Steduto et al., 2007), is proportional to CO_2 concentrations with C_3 and C_4 crops. Research has shown that C_3 crop will benefit more than C_4 crops with elevated CO_2 (Drake et al., 1997; Kimball et al., 2002; Ainsworth and Long, 2005; Raines, 2011). Leakey (2009) states that there is uncertainty in C_4 crops benefiting from elevated CO_2. Ainsworth and Long (2005) reviewed several C_4 experiments which presented no benefits of increased CO_2, but Leakey (2009) states that the benefits are shown by making crops more tolerant under conditions of increased water stresses. Both authors concluded that more research is required for analysing the benefits of crops under elevated CO_2 concentrations. Regardless of how much benefit the crop species will gain,

increasing CO_2 concentrations from climate should aid crops in dealing with potential extremes of water stress and temperature variations.

2.2.2 Water Use Efficiency

Water use efficiency (WUE) is a very important crop parameter for crop simulations that has multiple definitions (Steduto and Albrizio, 2005). Some confusion arises in determining the difference between efficient water use (EWU) and WUE. Steduto (1996) states that EWU is focused only on water transport of the crop and is the ratio between water outputted from transpiration and water imported by rain or irrigation. WUE differs by being calculated by the ratio of carbon gained through photosynthesis and water lost by transpiration. Increasing EWU is important for irrigated agriculture when less water is wasted on the crops through conservation or improved technologies (Efetha et al., 2009; Bennett and Harms, 2011; Klein et al., 2012). WUE can be defined in different ways. For crop modelling purposes, assessments of a yield-WUE is often used (Todorovic et al., 2009) for assessing the ratio between yield and cumulative crop evapotranspiration. For the purposes of the research focus being crop modelling, WUE, or sometimes called water productivity (WP), is defined as the crop yield, or biomass, produced per unit of water use, which has been used in various studies (Stöckle et al., 2003; Passioura, 2006; Efetha et al., 2009; Qian et al., 2009; Steduto et al., 2009; Todorovic et al., 2009; Vanuytrecht et al., 2014b).

2.2.3 Soil-Crop-Atmosphere continuum

Early crop models were concerned with the best way to simulate the development of crops at different stages in a variable environment (Loomis et al., 1979; De Wit and Van Keulen, 1987). For simulation purposes, it is an advantage that annual crops go through their life cycle from seeding to harvest in one year. These repeatable systems allow for simulations to undergo multiple validations of estimating the developmental stages of crops (De Wit and Van Keulen, 1987). De Wit and Van Keulen (1987) emphasized the importance of geographical location, as local climates and soils are important for determining crop development. The location determines the soil-crop-atmosphere continuum, which is the basis used in many crop models, such as WOFOST (Diepen et al., 1989), DSSAT (Jones et al., 2003), and AquaCrop (Steduto et al., 2009). Water transport throughout the soil-crop-atmosphere continuum is an essential process of this integrated system, where any change in one part of the system will have a dynamic effect on the whole system that determines the crop development and yield (Bwalya, 2013).

2.2.3.1 Soil Water Balance

The soil water balance is important for determining the inputs and outputs of soil water. The simple soil water equation (McGowan and Williams, 1980) without any surface runoff is commonly recognised as:

$$\Delta S = (P + I) - (ET + U) \quad \text{[Eq. 1]}$$

where ΔS is the change in soil water storage, the water inputs are P (precipitation) and I (Irrigated amount), and the outputs are ET (evapotranspiration from the crop and soil evaporation) and U (drainage and seepage from the soil).

Different soil types contain different hydraulic behaviors that affects the soil water balance. These factors need to be taken into consideration for crop modelling. A common method for expressing physical properties of soils is based on the USDA soil triangle (Figure 2-1). The USDA soil triangle derives percentages of sand, silt, and clay content for classifying hydraulic parameters (Cosby et al., 1984). Different types will have differences in their responses to water. Field capacity (FC), permanent wilting point (PWP) and soil moisture at saturation (SAT) are important soil characteristics that depend on soil textures and enable the quantification of plant available water (Dingman, 2002).

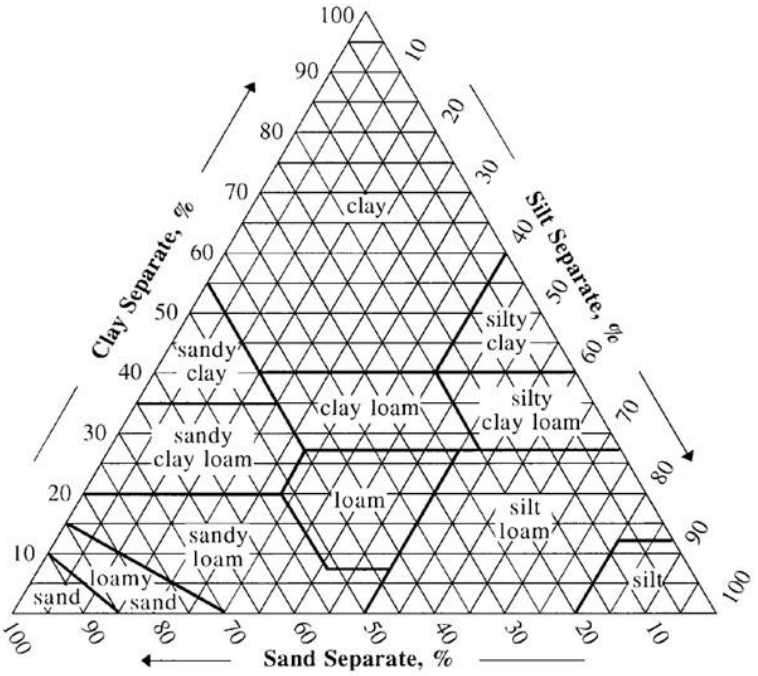

Figure 2-1 United States Department of Agriculture (USDA) soil texture triangle

2.2.3.2 Crop Development Stages (phenology)

While the crop cycle will always go through the same development stages, the timing of a crop cycle is dependent on the geographical location. Efforts in

developing a standard scale to describe certain stages of crop development begun with the Feekes scale (Large, 1954). Zadoks et al. (1974) were pioneers of creating an internationally accepted two-digit decimal scale for describing the growth stages of cereals. Adopted from Zadoks et al. (1974), a universal scale known as the BBCH (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie) providing a general framework for most crops and weeds (Lancashite et al., 1991). Other code scales, such as the Haun scale, have been used for only certain cereal crop types, like wheat, and led to software development for converting between scales (West et al., 1991). Newer models, such as AquaCrop (Steduto et al., 2009), DSSAT (Jones et al., 2003), and CropSyst (Stöckle et al., 2003), which will be reviewed later, use a simplified approach, where only the main development stages are simulated (Figure 2-2). AquaCrop considers the key developmental stages to be seeding to emergence, start of flowering (anthesis) or root/tuber initiation, maximum rooting depth, start of canopy senescence, and physiological maturity. The timing to reach these stages are dependent on the surrounding environment (atmosphere and soil) of the crop, while occurrences of water and temperature stresses can have negative impacts on the canopy development leading to lower yields (Steduto et al., 2012).

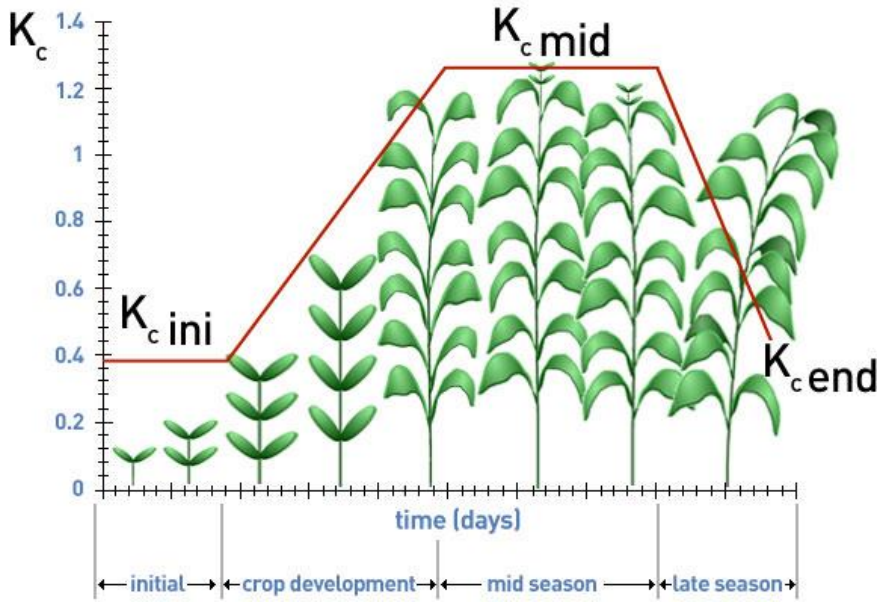

Figure 2-2 Graph showing the general crop stages of wheat for one annual growing season, where K_c is a crop coefficient relating the to the maximum evapotranspiration to the reference evapotranspiration (FAO, 2012).

2.2.3.3 Response to Temperature

Temperature is very significant in determining the behaviour of crop growth (Yan and Hunt, 1999; Wheeler et al., 2000; Wang and Frei, 2011). Most crop models use temperature as a means to simulate the development status of a crop (Jones et al., 2003; Stöckle et al., 2003; Steduto et al., 2009). The models will differ in crop scales and procedures resulting in difficulty of making comparisons between the simulated crop phenology (Touré et al., 1995; Wang and Engel, 1998). Determining the temperature response of a crop is critical. Regardless of different modelling methods, a crop will require a basic need for a moderate temperature during the entire crop life cycle (Luo, 2011). Extreme high and low temperatures can have harmful effects on crop development that lower yield or cease production (Porter and Gawith, 1999). Knowledge of determining the minimum, optimum and

maximum temperature for different crops is incomplete (Porter and Gawith, 1999), but many recent studies have determined the critical temperatures for certain crops (Wheeler et al., 2000; Luo, 2011; Robertson et al., 2013). At critical temperatures crop yields will decline, especially during the flowering stage. The challenge is to determine the optimal temperature at specific growth stages and when the crop is at vulnerable stages to the abiotic environment. In addition, crop cultivars are different depending on the geographical location. For instance, barley can have minimum and maximum temperatures of 5°C and 28°C in the Canadian prairies (Robertson et al., 2013), compared to 0°C and 15°C for a cooler area in Ethiopia (Raes et al., 2012).

One widely used method for determining the crop development stages in response to temperature is using Growing Degree Days (GDD). The equation is as follows:

$$GDD = \left[\frac{(T_{max}+T_{min})}{2}\right] - T_{base} \; or \; (T_{avg} - T_{base}) \quad \text{[Eq. 2]}$$

where T_{max} is the daily maximum air temperature, T_{min} is the daily minimum temperature, and T_{base} is the temperature above which a crop will grow.

The GDD is only considering positive values. McMaster and Wilhelm (1997) stated the importance of how this equation will be interpreted because of different the different methods used. Method 1 is described as follows: if $T_{avg} < T_{base}$, then the resulting GDD $= 0$ for that day, if $T_{avg} >$ the upper crop temperature threshold (T_{upper}), the GDD is at its maximum so GDD $= T_{upper}$ for that day. Method 2 adjusts

the T_{avg} calculation as follows: if $T_{max} >$ than T_{upper}, then $T_{max} = T_{upper}$, or if $T_{max} < T_{base}$, then it will be $T_{max} = T_{base}$, and if $T_{min} > T_{upper}$ then, $T_{min} = T_{upper}$, or if $T_{min} < T_{base}$, then $T_{min} = T_{base}$. McMaster and Wilhelm (1997) reported that Method 1 is mostly used with small grain cereals such as wheat and barley, whereas Method 2 is commonly used for calculating the GDD of corn. The FAO AquaCrop model added a third method that is similar to Method 2, but only the T_{max} temperature is adjusted (Raes et al., 2012).

2.3 Agriculture in Alberta

In Canada, crops are categorized based on the trade markets and are separated into cereals (e.g. wheat, barley, oats, corn), oilseeds (e.g. canola, flax, sunflower), orchards (e.g. apples, peaches, pears), berries (e.g. strawberries, grapes, blueberries), vegetables (e.g. carrots, onions, tomatoes), forages (e.g. timothy, clover, alfalfa), and special crops (e.g. tobacco and buckwheat) (Morrison, 2012). Most of the cereal and oilseed crops in Canada are grown in the prairie provinces of Alberta, Saskatchewan and Manitoba. This research will focus on wheat, barley and canola crops grown in southern Alberta.

Alberta's major grown crops are spring wheat, barley, canola and alfalfa (Shen et al., 2005; Bennett and Harms, 2011; AgCanada, 2015). Crop production in Alberta contributes a significant amount of seeded crop land with 25 million acres in 2011, while Canada totaled 87 million acres (Statistics Canada, 2011). Table 2-1 provides a comparison in the amount of the seeding land of spring wheat, barley, and canola in the Prairie Provinces and Canada. Canadian crops are dominantly

produced in the Prairie Provinces. This area is susceptible to many future vulnerabilities of climate change. Even in the past, John Palliser, an explorer from the mid-1880s, deemed the area unsuitable for crop production due to the extremely dry conditions. The region became known as the Palliser Triangle, mostly consisting of the southern portion of Alberta and Saskatchewan (Marchildon et al., 2009). The region is still at risk for reoccurring prolonged droughts (Marchildon et al., 2008) and already has been seen with droughts from 2001 and 2002 greatly impacting the Canadian economy due to agricultural losses ($3 Billion) (Wheaton et al., 2008). Irrigation systems can be used to mitigate droughts, and 97% of irrigated land in Alberta lies within the 13 different irrigation districts in southern Alberta (Bennett and Harms, 2011). However, irrigation puts pressure on available water from streamflow which creates other water use challenges (Byrne et al., 2006), so increasing irrigated land is difficult.

Table 2-1 Hectares of spring wheat, barley and canola grown in Canada and the prairies

Crop	Geographical Location	Seeded Area Per Quinquennial Census (1000 Hectares)				
		1991	1996	2001	2006	2011
Spring Wheat	Canada	11,900	10,000	8,300	7,600	6,800
	Manitoba	2,100	1,600	1,500	1,200	1,000
	Saskatchewan	7,000	5,600	4,300	3,900	3,200
	Alberta	2,800	2,600	2,400	2,300	2,400
Barley	Canada	4,500	5,200	4,700	3,700	2,800
	Manitoba	500	600	500	300	200
	Saskatchewan	1,300	1,900	1,900	1,400	900
	Alberta	2,200	2,300	2,000	1,700	1,500
Canola	Canada	3,100	3,500	3,800	5,000	7,800
	Manitoba	500	600	800	900	1,300
	Saskatchewan	1,400	1,600	1,900	2,400	4,000
	Alberta	1,200	1,300	1,100	1,600	2,500

Source: Statistics Canada. Table 004-0003 - Census of Agriculture, selected crop data, Canada and provinces, every 5 years (accessed: September 17, 2015)

2.3.1 Wheat

Wheat (*Triticum aestivum L.*) is an essential crop grown on the Canadian prairies. Wheat has been economically important for Canada since the 1920s and have been aiding the prairies in developing their financial and cultural agriculture industry (McCallum and DePauw, 2008). Alberta has been consistent with around 2.5 million hectares of seeded wheat since 1991 (Table 2-1). However, yields per hectares are most likely to have been increasing from advancements in Canadian breeding efforts in developing new cultivars with traits of increased disease and drought resistance, earlier crop maturity dates, and producing a greater number of kernels (McCaig and DePauw, 1995; McCallum and DePauw, 2008). Wheat yields in mid- to high-latitude areas (such as Canada) could increase from higher temperatures due to global warming (Porter et al., 2014).

2.3.2 Barley

Barley is mostly grown in the prairie provinces in Canada. Alberta has the highest barley production out of the three prairie provinces (Table 2-1). About 80% of barley production is used for livestock and the rest is mostly used for malt production and human food (Juskiw et al., 2001). Weather conditions in southern Alberta have been said to be unfavourable for barley, but with proper agronomic practices acceptable yields can be achieved (McKenzie et al., 2005).

2.3.3 Canola

Canola was the most dominant oil crop in Canada, but more recently became the most grown crop in Canada (Table 2-1) (Johnston et al., 2002). Canola has been transformed from the previous species known as *rapeseed* that was undesirable for commercial use. The new cultivars of canola became much more favorable (Bell, 1982). The main canola products are oil for human consumptions and meal for livestock feed and a potential use for biodiesel fuel (Canola Council of "Canola growers manual," 2003). Canola is one of Canada's most valuable crops, which in 2013 had contributed $19.3 billion to the Canadian economy (Cardillo et al., 2015).

2.4 Southern Alberta Climate

Southern Alberta is situated in the rain shadow of the Rocky Mountains, resulting in a semi-arid climate. The region has relatively long winters and relatively short and cool summers which limits the crop growing season (Xu et al., 2012). The Rocky Mountains act as a main water supply for domestic and irrigated agriculture use in southern Alberta by having the highest precipitation and runoff ratios of the region (Mahat and Anderson, 2013). This water supply is under pressure from climate change by snowfall changing to rain with projected warmer climate affecting the timing and magnitude of streamflow (Kienzle et al., 2012). The increase of surface air temperature made central and southern Alberta vulnerable to the impact of drought toward the end of the last century (Shen et al., 2005). The continuation of a warmer climate will only cause further risks of drought within the area (Sauchyn and Bonsal, 2012). Some beneficial changes of climate to crop producers is that the

frost free period has increased by over 30 days in northern and central Alberta over the last century (Shen et al., 2005). This warming trend in southern Alberta effects crop management decisions such as earlier seeding dates, which can provide potential increases to crop yields (McKenzie et al., 2011). Potential future increases of both frequency and durations of droughts still remain a challenge (Xu et al., 2012; Gobena and Gan, 2013; PaiMazumder et al., 2013).

2.5 Crop Modelling

Models can be defined as a simple or abstract representation of a real system (Loomis et al., 1979). Model simulations typically go through a calibration phase, where the modeller is tuning the model by making comparisons with observed data. Biological systems such as crops are very complex systems, making them a challenge to model. However, because crops such as annuals go through their complete life cycle in one year or a growing season, they belong to a repetitive biological system. The repeatable and reoccurring real systems can be validated independently making it possible to develop models and continue to build on them year after year (Loomis et al., 1979). The development of crop growth models began in the 1960s and have advanced and become more refined since (El-Sharkawy, 2011). Crop models can be useful for agronomic research tools that predict the growth, development and yield of a crop in response to a surrounding environment (Steduto et al., 2009). There are many existing crop models that are used around the world. All of the models have different structures, methods, inputs and algorithms for simulating crop growth (Todorovic et al., 2009). The next section will provide a review of the AquaCrop model used in this study.

2.5.1 AquaCrop

The AquaCrop model is defined by Steduto et al. (2009) as "canopy-level and engineering type of model, mainly focusing on simulating the attainable crop biomass and harvestable yield in response to the water available" (p. 427). The model was developed for the purpose of using fewer parameters in a balance of simplicity, accuracy, and robustness. Water is used as the main driver in AquaCrop for simulating yield production. Water is very important for crop production and was proven early on to be one of the major limiting factors in crop growth (De Wit and Van Keulen, 1987). Crops use water to carry minerals, sucrose and hormones through the plant. Water is also critical factor in the chemical reaction of photosynthesis (Sheaffer and Moncada, 2008). Water-limiting conditions will result in lower yields at the end of the season, so it is an important factor for crop modelling.

The main concepts of connecting the soil-crop-atmosphere continuum in AquaCrop are illustrated in Figure 2-3. The soil component of the continuum is focused on the water balance within the soil, the plant represents the growth, development and yield processes, and the atmosphere represented by air temperature, rainfall, evaporative demand, carbon dioxide concentrations and irrigation (Steduto et al., 2009). Figure 2-3 shows the interaction of different variables that AquaCrop combines for simulating yield output. The model uses separate input components of climate data, crop parameters, management (irrigation and field), soil (soil characteristics and groundwater) and simulation period for simulating crop yield.

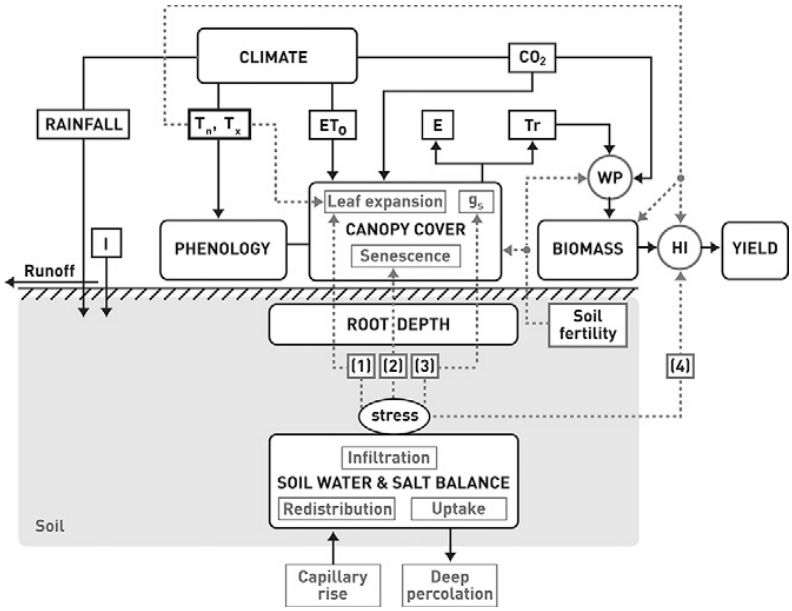

Figure 2-3 Chart of AquaCrop indicating the main components of the soil–plant–atmosphere continuum and the parameters driving phenology, canopy cover, transpiration, biomass production, and final yield [I, irrigation; Tn, minimum air temperature; Tx, Max air temperature; ETo, reference evapotranspiration; E, soil evaporation; Tr, canopy transpiration; gs, stomatal conductance; WP, water productivity; HI, harvest index (Steduto et al., 2009).

The AquaCrop model uses the yield response to water equation (Eq. 3) as a starting point for the model. Doorenbos and Kassam (1979) developed this equation, which has been widely used to estimate yield response to water by planners, economists and engineers (Vaux and Pruitt, 1983; Howell et al., 1990). AquaCrop evolves from this approach (Eq. 3) by separating the evapotranspiration into crop transpiration and soil evaporation to develop a final yield as a function of the final biomass of the crop (Eq. 4). This separation allows for distinguishing the effects on the non-productive consumptive use of water, soil evaporation, to better simulate crop growth. The water productivity (WP, biomass produced per unit of

cumulative transpiration) is a conservative parameter and is considered to be constant for given climatic conditions (Steduto et al., 2009).

$$\frac{(Y_x - Y_a)}{Y_x} = K_y \left(\frac{(ET_x - ET_a)}{ET_x}\right) \quad \text{[Eq. 3]}$$

where Y_x and Y_a are maximum and actual yield, ET_x and ET_a are maximum and actual evapotranspiration and K_y is the proportionality factor between relative yield loss and relative reduction in evapotranspiration.

$$B = WP * \sum Tr \quad \text{[Eq. 4]}$$

where B is the final biomass, WP is the water productivity (biomass per unit of cumulative transpiration), and Tr is the crop transpiration.

The WP parameter is based on the atmospheric evaporative demand and the atmospheric CO_2 concentration for the purpose of being applicable to diverse locations and simulating future climate scenarios. Equation 5 shows the procedure for calculating the normalized WP based on adjustments to annual CO_2 concentrations. This approach has a tendency to over-simulate future crop yields caused by CO_2 fertilization when compared to free air CO_2 enrichment (FACE) experiments (Vanuytrecht et al., 2011). This lead to the introduction of a crop sink strength parameter to address the response of WP, resulting in higher yields (Vanuytrecht et al., 2011), but there are still many uncertainties and more research is needed for a better understanding of crop behavior with increased CO_2 concentrations.

$$WP = \left(\frac{B}{\sum\left(\frac{Tr}{ET_o}\right)}\right)_{CO_2} \quad \text{[Eq. 5]}$$

where CO_2 is the mean annual CO_2 concentration and ET_o is the atmospheric evaporative demand. The CO_2 outside the bracket is the normalization concentration for a given year.

Once the final biomass is calculated at harvest, the final yield output is the function of the final biomass (B) and the Harvest Index (HI). HI is the ratio between the harvested product and the total above ground biomass (Unkovich et al., 2010). AquaCrop simulates the build-up of HI starting from the flowering stage to reach the reference HI, a crop parameter set by the user. The build-up of HI increases linearly with time, but adjustments of HI are made depending on crop stresses during simulations, resulting in lower yields or even zero yields under conditions of pollination failure caused by severe stress (Steduto et al., 2009).

Vanuytrecht et al. (2014a) performed a global sensitivity analysis of AquaCrop in an attempt to create guidelines for model simplification and efficient calibration. The parameters that were determined to be a priority for AquaCrop are parameters describing the crop phenology, a crop response to extreme temperatures, water productivity, root development, and soil water characteristics. These parameters require the most attention for model calibration for accurately simulating final yields.

2.5.2 Automating AquaCrop

AquaCrop is effective for modelling yields under a limited number of site locations. The current version of AquaCrop (4.0) struggles with the ability to run multiple simulations under different conditions and locations. This issue has been assessed by the creation of two external utility programs called AquaData and AquaGIS (Lorite et al., 2013). The flow chart (Figure 2-4) describes the process of using AquaCrop with the two utility programs AquaData and AquaGIS. This allows a spatial visualization of crop yields over a greater area enabling the capability to

perform a spatial analysis (Lorite et al., 2013). AquaData acts as a database that contains all data necessary for creating input files used in AquaCrop. FAO have developed an AquaCrop plug-in program that will run AquaCrop without a user interface, which allows an application like AquaData to automatically run multiple crop simulations much more efficiently (Raes et al., 2013). The AquaCrop plug-in program can be used for iterative runs for calibration purposes or for inputting into a Geographical Information System (GIS) for subsequent spatial analysis. Using similar methods, AquaCrop can be used for calibrating and analyzing long-term climate change impacts on crop yields in southern Alberta.

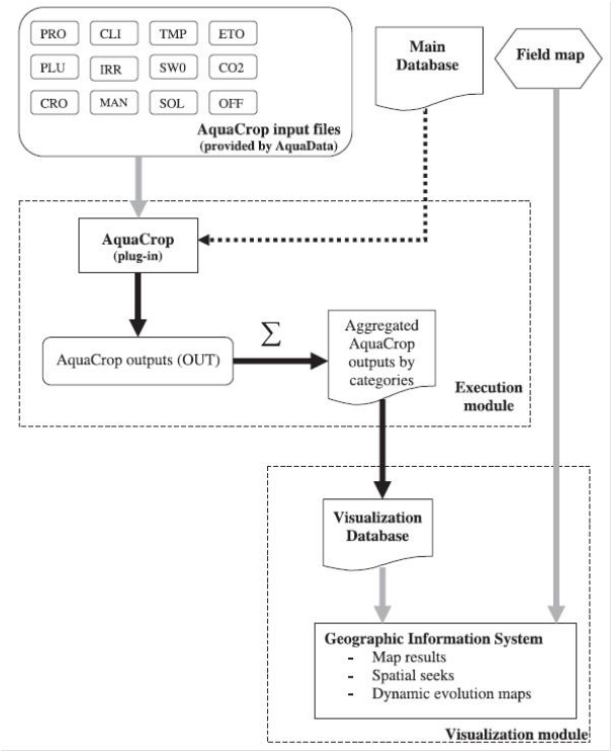

Figure 2-4: Diagram of two utility programs AquaData and AquaGIS, used with AquaCrop to provide a visual database and spatial analysis capabilities with GIS (Lorite et al., 2013).

2.5.3 Other Crop Models

The Decision Support System for Agrotechnology Transfer (DSSAT) has been used extensively around the world by researchers (Jones et al., 2003). The software package contains a group of sixteen different crops and associated data management and analysis tools. The model has been validated and used widely around the world but is developing at a relatively slow pace in the absence of funding support (Bwalya, 2013). Another well-known model is CropSyst (Stöckle et al., 2003), which is one of the few crop models that incorporate pest damages to the crops. CropSyst has been used widely around the world and it is planned to continue the improvement of the model and integrate better communication and exchange of information from modellers to advance the progress of cropping systems (Stöckle et al., 2003). WOFOST (Diepen et al., 1989) is a model that provides analysis on crop growth that is explained by a hierarchy of water and nutrient limiting production. All of the models have similarities and differences. AquaCrop, CropSyst and WOFOST all differ in levels of complexity that simulates crop growth differently and with require different amounts of input parameters (Bwalya, 2013).

2.5.4 Evaluation of AquaCrop

Studies have shown that the AquaCrop model provided reasonable results for simulating crop yields in a wide range of geographical locations around the world (Araya et al., 2010; Andarzian et al., 2011; Karunaratne et al., 2011; Salemi et al., 2011; Stricevic et al., 2011; Vanuytrecht et al., 2011; Zinyengere et al., 2011; Abedinpour et al., 2012; Abrha et al., 2012; Mkhabela and Bullock, 2012; Iqbal et al., 2014). AquaCrop has provided very accurate results for simulating crop yields

under full irrigation conditions in India (Abedinpour et al., 2012) and in Serbia (Stricevic et al., 2011). However, both studies have concluded that AquaCrop has its greatest error in simulating rain fed crops, especially in a wet year. Mkhabela and Bullock (2012) used AquaCrop to simulate wheat yield and soil water content on the Canadian Prairies (Saskatchewan and Manitoba) from experimental sites from 2003 through 2006. They concluded that AquaCrop can be a valuable tool for simulating both wheat grain yield and soil water content on the Canadian Prairies. The performance concern of Gobena and Gan (2013) was that AquaCrop needs to be evaluated and fine-tuned over a wider range of conditions and greater area. An assessment of AquaCrop, CropSyst and WOFOST was done by Todorovic et al. (2009), comparing the results of all three models. In their study, Aquacrop out-performed CropSyst, but WOFOST model simulated biomass growth during the crop time course better than the other two models. However, the paper argues that WOFOST requires a detail list of input parameters that makes it a limiting factor of the model.

2.6 Climate Change

2.6.1 Global Climate Change

Climate is defined as the average weather or weather variability, over a period of time that can range from months to millions of years (IPCC, 2013). Weather describes the current conditions of the atmosphere in parameters of temperature, air pressure, humidity, wind and other meteorological elements at a given location and time. The state of the climate, which can be the cause by natural phenomena or human activity, can be analysed by using various statistical methods

(such as frequency, magnitude, trend analysis, etc.) (IPCC, 2013). Scientific advancement and continuous data collection of weather data has enabled a better understanding of the Earth's variable climate and the responses to human and natural influences (Moss et al., 2010). The predictability of future climate remains a challenge with many uncertainties. For a more comprehensive understanding of future climate, multiple future scenarios are often explored for providing a wider set of consequences for investigating the challenges of the future. Global Climate Models (GCMs) represent a physical model of the different geographical feedbacks that describe the climate (Barrow and Yu, 2005). GCMs are used for simulating the past, present and future climates at coarse scales, usually grid cells of several 100km in size (Xu, 1999; Barrow and Yu, 2005; Vanuytrecht et al., 2015). Pierce et al. (2009) demonstrated that combining multiple GCMs using a multi-model ensemble technique, was superior to any individual GCM for studying regional changes in the hydrological cycle of the western United States. Using multiple GCMs help distinguish the variability between models and the uncertainties of future climate (Semenov and Stratonovitch, 2010).

The Intergovernmental Panel on Climate Change (IPCC) have reported a continuation of surface warming with increases of atmospheric CO_2 concentrations projected by many GCMs. Previously, global average surface air temperatures increased 0.6°C during the 20th century, and GCMs are projecting increases between 1.4°C and 5.8°C by 2100 (Barrow and Yu, 2005), however, increases of a minimum of 2.0°C by 2100 is now more likely (IPCC, 2013). This global increase of temperature creates challenges for crop production around the world by having an

effect of crop management adaptability with changes in sowing dates, crop and variety switching, expansion of irrigation, extreme weather events (Gourdji et al., 2013).

2.6.2 Regional Climate Models

Most GCMs have coarse spatial scales between 250 and 600 km (Barrow and Yu, 2005). They can be useful for simulating the large-scale atmospheric state at a global or continent level (von Storch et al., 1993). However, GCMs were not designed for climate change impacts in hydrology, therefore are not well suited for regional hydrologic variability (Xu, 1999) and regional impact studies because of their coarse spatial scales (Wilby et al., 2002; Barrow and Yu, 2005). The same issue applies for regional crop modelling that are heavily dependent on water as an influence on agricultural production (Steduto et al., 2009). Luo et al. (2005) used downscaled RCMs with a wheat model for determining the potential impact of climate change on wheat yield in South Australia. For assessing impacts of climate change at regional scales, downscaling GCMs into Regional Climate Models (RCMs) can improve simulations. Downscaled RCMs are a valuable method of studying the impact of climate change at regional scales (Erda et al., 2005; Wang et al., 2011). White et al. (2011) reviewed 221 peer-reviewed papers on impacts of climate change on agricultural systems and a significant portion that have used RCMs in their methodologies.

Several different downscaling techniques have been used for studying regional impacts of climate change. Some of the most used methods are statistical

downscaling (Boé et al., 2007) and the delta change method (Mahat and Anderson, 2013). Other methods have additions to these methods for improving or simplifying downscaling techniques. An application called Statistical Downscaling Model (SDSM) developed by Wilby et al. (2002) is a decision support tool for assessing climate change, using robust statistical downscaling techniques for single-site scenarios (Toronto, Canada). Moriondo and Bindi (2006) state that RCMs can result in an over-estimation of extreme climatic events impacting specific crop phenological stages, where an artificial neural network may provide better results. These potential biases from RCMs can be corrected to better simulations with observed values from simple scaling to more sophisticated approaches which were reviewed by Teutschbein and Seibert (2012).

2.7 Crop modelling with climate change

2.7.1 CO2 fertilization

Since the beginning of the Industrial Era, elevated atmospheric CO_2 has been caused from many different anthropogenic sources. As of 2015, CO_2 concentration reached 400 ppm (ESRL, 2015), but without mitigation strategies are expected to reach 670 ppm with extremes of 936 ppm by 2100 (Meinshausen et al., 2011; IPCC, 2013). While rising atmospheric CO_2 concentrations is a serious concern for global warming and climate change, there can be a potential benefit to crop production. Elevated atmospheric CO_2 is said to reduce crop stomatal conductance and transpiration which will improve WUE (Drake et al., 1997). This has led to many free-air CO_2 enrichment (FACE) experiments (Kimball et al., 2002; Ainsworth and Long, 2005; Vanuytrecht et al., 2011). FACE experiments are conducted for

researching the effects of elevated CO_2 on plants and ecosystems under normal environmental conditions (Ainsworth and Long, 2005). CO_2 increases have shown increases of photosynthesis and biomass and yield production with C_3 species and smaller increases with C_4 species (Kimball et al., 2002; Ainsworth and Long, 2005). Nevertheless, both types of species have shown improved WUE (Kimball et al., 2002), indicating potential benefits for crop production in the future.

2.7.2 Modelling future crop variability

Predicting future yields are heavily dependent on the coupling of meteorological information and crop models. The relationship between the two can be convoluted because of a mixed relationship of linear and non-linear responses (Semenov and Porter, 1995). Detailed climate data are required because the daily variability of temperature can greatly influence crop yields. Extreme high and low temperatures decrease the rate of dry matter at production and can even cease production. The future of crop yields are likely to become more variable if climate follows the same pattern (Semenov and Porter, 1995; Isik and Devadoss, 2006). Different crops will have different response to climate variability. For example, Isik and Devadoss (2006) have done an analysis on the variance of future crop yields, where the future variance of barley and wheat yields will decline but potato and sugar beet yields will increase (Idaho, USA). Also, variability exists within crops models. Li et al. (2015) used 13 different rice crop models, resulting in 5% to 60% differences between predicted and measured yields. They concluded that no single model could consistently predict yields over the 30-year study period.

Crop yields are dependent on the equipment, methods, and land used by farmers. These factors contribute to a potentially large yield variability between modelled potential yields, demo farms, maximum farmer yields, and average farmer yields, and are referred to as the yield gap (Lobell et al., 2009). Yield gaps between modelled crop yields determining the potential yields are higher than the maximum farmer yields. Most irrigated crops of wheat, rice, and corn only reach 80% of the potential (Lobell et al., 2009). These results suggest that room for improvement for increasing farmer yields with newer technologies such as sensor-based methods for determining optimal nutrient and water management. However, a farmer's access to improved technologies varies per farmer and location, causing yield variability (Grassini et al., 2015). Global warming will demand new adaptive measures, such as changes in sowing dates, crop and variety switching, expansion of irrigation, agricultural expansion into relatively cooler areas (Gourdji et al., 2013). It is viable for farmers to adapt to new strategies and methods for climate change to lower the variability between potential yields and farmer yields.

2.8 Conclusion

Crops are very complicated systems that provide challenges for a crop model's ability to simulate yields. Crop production is critical to southern Alberta's economy and world food production, which requires a fundamental understanding of the factors influencing crop production, because droughts and future climate change can have devastating impacts on crop yields. Based on the review of the FAO model AquaCrop, the simplicity of the model will benefit this study because of the

high number of simulations required in this analysis and the use of the robust methods of using a lower amount of input parameters for simulating crop yields.

The impacts of climate change on future crop yields requires many processes for determining useful results. GCMs will be required to be downscaled to RCMs for providing more regionalized climate data for AquaCrop. Many uncertainties are present in simulating future crop yields. The effect of CO_2 fertilization remains uncertain to what degree crop yields will increase and the variability between climate and farming techniques causes yield gaps between potential modelled yields and farmer yields.

Chapter 3

Parameterization of the AquaCrop Model using a Grid Search Calibration Method to simulate Wheat and assess Climate Change Impacts on Yield in Southern Alberta, Canada

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3.1 Introduction:

Assessment of impacts and adaptability to climate change at the local scale necessitate parameterization of models to incorporate local conditions and management practices. Crop modeling started in the late 60s with the aim of evaluating regional agriculture production. Since then, many different crop models such as WOFOST (Diepen et al., 1989), EPIC (Williams, 1989), DSSAT (Jones et al., 2003) and CropSyst (Stöckle et al., 2003) have been validated and compared (Touré et al., 1995; Todorovic et al., 2009). Although all models allow for a better understanding of crop responses to climate and management scenarios (Fraisse et al., 2006; Resop et al., 2012), each model has its own strengths and weaknesses. For this study, a crop water productivity model developed by the United Nations Food and Agriculture Organization (FAO), called AquaCrop, was parameterized for an area in southern Alberta, Canada. AquaCrop is a water driven model that attempts to achieve an optimal balance of accuracy, simplicity and robustness, making it a valuable model for decision makers or researchers world-wide (Steduto et al., 2009; FAO, 2012). The model has been evaluated and calibrated in different climates and used with various crops around the world, such as maize, sunflower and sugar beet

(Stricevic et al., 2011), barley (Abrha et al., 2012), and winter wheat (Iqbal et al., 2014). Although the model is fairly new to the Canadian prairies, Mkhabela and Bullock (2012) have demonstrated that AquaCrop can be a valuable tool for simulating wheat yield.

Wheat (*Triticum aestivum L.*) is an essential crop grown on the Canadian prairies, which consist of the southern parts of the provinces of Alberta, Saskatchewan and Manitoba. Spring wheat occupies almost 6 million acres in Alberta with an irrigation potential of over 1.2 million acres (Statistics Canada, 2011). A major goal of wheat breeding programs is to increase grain yield by increasing the kernel number and kernel weight (McCaig and DePauw, 1995). This is a challenge when droughts can have devastating impacts on Canadian agriculture. The droughts of 2001 and 2002 caused an estimated loss in agriculture production of CAN$3.6 billion (Wheaton et al., 2008). The agriculture sector of the Canadian prairies faces a great challenge for the future, as water availability at the right time and in the right place is becoming increasingly uncertain (Schindler and Donahue, 2006; Sauchyn and Kulshreshtha, 2007). It is important to better understand how crop yields are being affected on the Canadian prairies subject to fluctuating climate conditions and water stresses.

AquaCrop requires more localized cultivar-specific parameters that describe the crop development stages in order to achieve reasonable crop simulations. The shorter growing season of the Canadian prairies requires updated wheat crop values from the given default values. With proper calibration, AquaCrop

can now be used for better predicting future yields. Since understanding future yields will require a future climate dataset, Regional Climate Models (RCMs) are used. These RCMs define a scenario of a plausible future climatic state of a particular region (Barrow and Yu, 2005). Isik and Devadoss (2006) have stated that it is important to learn from the impacts of future climate change on agriculture in order to properly prepare for future crop yields and crop variability. AquaCrop has been used as a tool for studying the impacts of future climate change on crop yields (Lorite et al., 2013; Abedinpour et al., 2014). It is known that there is a significant rise in the atmospheric carbon dioxide concentration (CO_2). Elevated CO_2 conditions can improve crop water use efficiency (Drake et al., 1997). Ainsworth and Long (2005) stated that increased yields of wheat have been shown where elevated CO_2 exists. The semiarid prairies, with a potentially warmer climate and CO_2 increase, could create more future agricultural opportunities. However, there is much uncertainty, and some indication of AquaCrop over-simulating crops from the effect of a CO_2 fertilization (Vanuytrecht et al., 2011).

The objectives of this study were: (1) Build an AquaCrop input parameter database and design an automated grid search calibration program using MySQL and the C# scripting language; (2) Select an arbitrary location in southern Alberta as a test case and run simulations of wheat using the grid search calibration program; and (3) Assess the impacts of climate change on wheat yields with the calibrated wheat file for five different RCMs.

3.2 Methods:

3.2.1 Study site

The county of Taber is mostly situated within the Oldman River Watershed in southern Alberta (Figure 3-1). The Oldman River Watershed is one of four watersheds within the major South Saskatchewan River Basin, and one of the three southern basins closed to any new surface water allocations. Water availability has become an increasing concern in the Oldman River Watershed, especially since roughly 90% of the stream output is already used (Byrne et al., 2006). Therefore, irrigated areas can only be expanded with difficulty, and rainfed farming of wheat still dominates. As of 2014 in Alberta, there was a total of 4.7 million acres of dryland wheat compared to almost 0.25 million acres of irrigated wheat (AgCanada, 2015). Therefore, only rainfed conditions were considered in this study. As of 2011, the most common field crops in the Taber County are wheat (224,642 acres) and canola (105,556 acres) (Statistics Canada, 2011).

The Canadian prairies have soils that are mostly composed of the Canadian Chernozemic soils group, which have a Mollic epipedon (Pennock et al., 2011). Climate is one of the main characteristics in shaping the soils (Fuller, 2010). Southern Alberta is a semi-arid region that has a landscape of undulating hummocky till plain that has been strongly shaped by the Wisconsinan glaciation (Beaty and Young, 1975). These factors contribute to the area resulting in the Brown Chernozem soil group of the Canadian system of soil classification (Figure 3-1) (Canadian Agricultural Services Coordinating Committee, 1998). Brown Chernozems are considered to have the lowest water availability out of the all

chernozemic groups and are well-drained soils. An Alberta soil survey reports that the Taber region has a diverse textural composition with surface textures ranging from sandy loam to silt loam (McNeil et al., 1994).

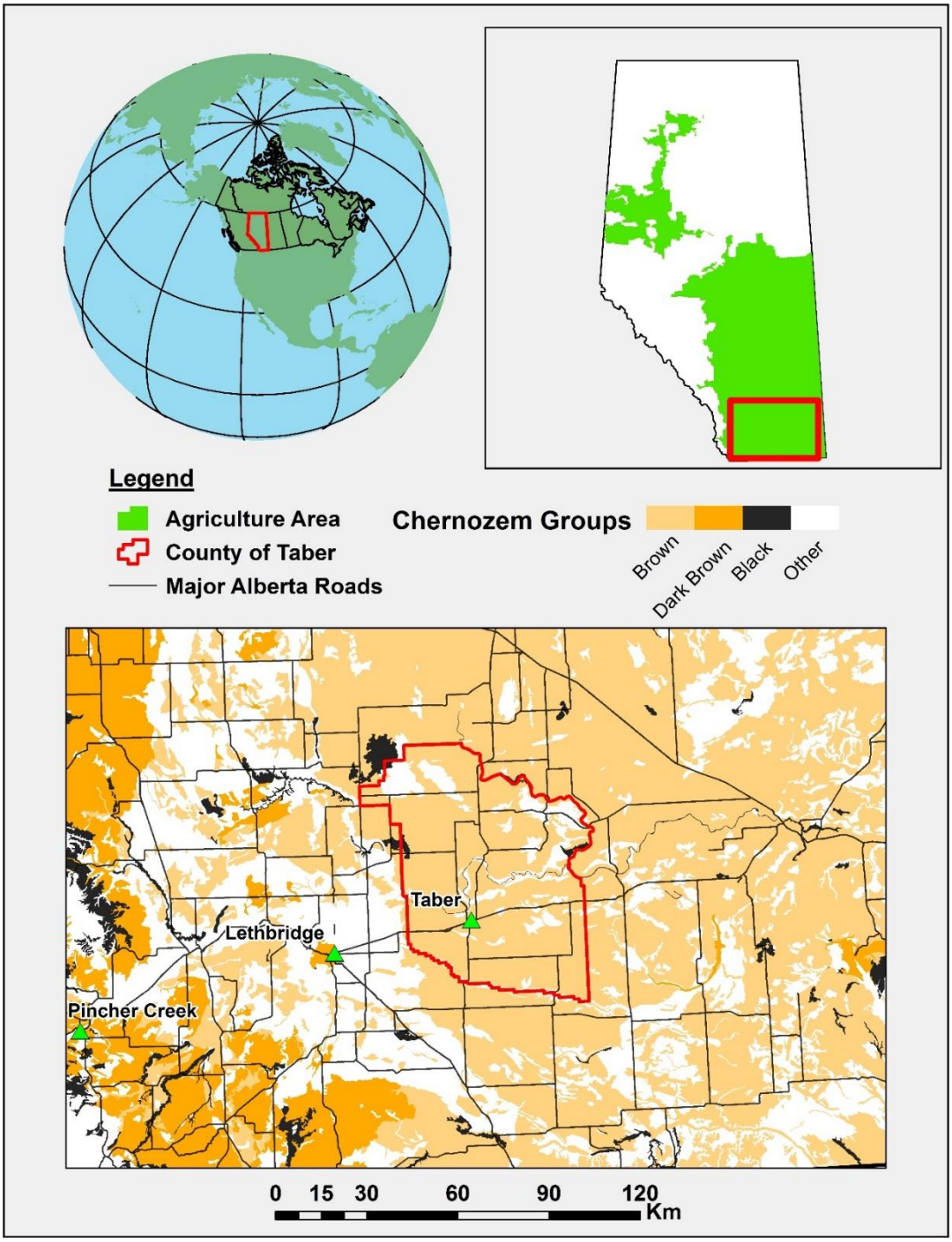


Figure 3-1 Chernozemic Soils map of the Southern Alberta Plains

3.2.2 AquaCrop Description

The model focuses on water as the main driver for agricultural production. Water is connected throughout the soil-crop-atmosphere continuum that AquaCrop

is built around. This requires certain input data to run crop simulations. According to Steduto et al. (2009), the aim of AquaCrop is to provide a functional crop simulation model of yield response to water that can be used for agricultural sectors world-wide. AquaCrop provides default values and robust methods for handling missing inputs that are further explained in Raes et al. (2009). However, Steduto et al. (2009) indicated that it is imperative for AquaCrop to be calibrated and validated extensively for crops, before it can be used as a planning or decision making tool.

The default values do not always fit the climate conditions in some regions of the world. The short growing season of the Canadian prairies limits wheat varieties to a shorter length of crop cycle (McCaig and DePauw, 1995). The default wheat crop file used in AquaCrop will result in a failure in the Canadian prairies due to the crop being unable to reach maturity because of the limitation of the seasonal growing degree days (GDD). Currently, AquaCrop's default wheat file is calibrated for Valenzano, Italy with a total requirement of 2400 GDD to reach plant maturity. The default wheat file will sometimes require two years before the crop will reach maturity, which is unrealistic in the county of Taber. Mkhabela and Bullock (2012) have parameterized AquaCrop for certain study sites in Saskatchewan and Manitoba with plant maturity GDD ranging from 975 to 1141. In AquaCrop, the key crop development stages are: emergence, start of flowering, maximum rooting depth, start of senescence and physiological maturity (Steduto et al., 2009). These parameters vary among different wheat varieties and require calibration to accurately simulate localized yields.

AquaCrop requires fewer parameters and inputs to simulate yield compared to other crop models, but there is still the need to manually set up local parameters. In this study, an application similar in principle to that developed by Lorite et al. (2013) was used to automatically manage the inputs for AquaCrop. It addressed the time-consuming issues of manually creating the input files for AquaCrop. Lorite et al. (2013) developed two utility applications called AquaData and AquaGIS that have proven to save approximately 1000 hours of work when running the model for a high number of simulations. Similar techniques were used in this study to handle automated creation of input files with use of an open-source database, MySQL (MySQL, 2008).

3.2.3 AquaCrop Input Files

3.2.3.1 Climate

Agriculture and Agri-Food Canada (AAFC) have developed and thoroughly tested a Canada-wide interpolated spatial model of daily minimum and maximum temperature and precipitation (Hutchinson et al., 2009). The datasets cover all of Canada, except the far North, with spatial grids of 10 km^2. Each grid contains daily values for maximum and minimum temperature and precipitation. The original data ranged from 1961 to 2003, but has been extended to 1950-2010 with the added refinement of climate data using climate stations (Hopkinson et al., 2011). A randomly selected grid was chosen within the county of Taber as the training area. The selected grid has a calculated growing season, which begins at the start of five consecutive days of a mean temperature greater than 5°C, and ends following five consecutive days of a mean temperature lower than 5°C. The yearly GDD sum of

above 5°C ranges from roughly 1443 to just over 1987 GDD, between 1950 and 2010. Trend analysis reveals an increase from 1667 GDD in the 1950s to 1718 GDD in the 2000s, an increase of 5 GDD per decade. The average annual precipitation is 344 millimeters per year with a gradually decreasing trend line of 345 for the period 1950, and 317 in 2010.

AquaCrop requires four main climate parameters to run (Rainfall, Reference Evapotranspiration, Temperature, and Atmospheric CO_2). The AAFC 1950-2010 dataset was used to create the rainfall and temperature input files (.PLU and .TMP). Reference Evapotranspiration (ETo) values were calculated with the standardized Penman Monteith equation (.ETo). AquaCrop provides default global atmospheric CO_2 values recorded from the Mauna Loa observations (.CO2). Based on the four created parameter files, a climate file (.CLI) was created that will allow annual simulations of 61 years (1950-2010).

3.2.3.2 Crop

Crop input parameters were derived from AquaCrop's default *WheatGDD.CRO* file. The file was modified to local conditions based on data collected from various sources. Table 3-1 shows the conservative crop values that were reported to not change with geographical location (Mkhabela and Bullock, 2012). The other non-conservative parameters that describe the key stages of wheat phenology, such as GDD from seeding to emergence, start of flowering and maximum rooting depth, senescence, maturity and length of flowering, were added into a grid search calibration algorithm (see section: 2.6). The algorithm searched

for the optimal crop parameters based on observed yields for a specific geographical location. These parameters have been previously termed as genotype coefficients and have undergone similar calibration procedures with different crop models (Hunt et al., 1993).

Table 3-1 Conservative crop input parameters for rainfed wheat obtained from various sources

Non-Conservative Parameters	**Value**	**Units/(Symbol)**
Base temperature below which crop development does not progress (3,5)	5.0	°C
Upper temperature above which crop development no longer increases with an increase in temperature (3,5)	35.0	°C
Maximum Rooting Depth (1,2)	1.2	m
Number of plants per hectare (4)	2,700,000	plants/ha
Harvest Index (default)	48	%
Conservative Parameters		
Water Productivity normalized for ETo and CO2 (WP*) (5)	14	gram/m^2
Minimum air temperature below which pollination starts to fail (cold stress) (5)	8	°C
Maximum air temperature above which pollination starts to fail (heat stress) (5)	40	°C
Excess of potential fruits (5)	50	%
Canopy growth coefficient: Increase in canopy cover (fraction soil cover per day) (5)	0.011072	unitless
Maximum canopy cover in fraction soil cover (5)	0.95	unitless
Canopy decline coefficient: Decrease in canopy cover (in fraction per day) (5)	0.009067	unitless
Soil surface covered by an individual seedling at 90 % emergence (5)	5.0	cm^2
Crop coefficient when canopy is complete but prior to senescence (5)	1.1	unitless
Maximum root water extraction in top quarter of root zone (5)	0.020	m^3(water) m^{-3}(soil) day^{-1}
Maximum root water extraction in bottom quarter of root zone (5)	0.005	m^3(water) m^{-3}(soil) day^{-1}
Effect of canopy cover in reducing soil evaporation in late season stage (5)	60	unitless
Soil water depletion factor for pollination - Upper threshold (5)	0.80	unitless
Soil water depletion fraction for stomatal control - Upper threshold (5)	0.55	unitless

Shape factor for water stress coefficient for canopy expansion [5]	4	unitless

Source: (1) Entz et al. (1992); (2) Touré et al. (1995); (3) Bennett and Harms (2011); (4) McKenzie et al. (2011); (5) Mkhabela and Bullock (2012)

3.2.3.3 Soil

The Agricultural Region of Alberta Soil Inventory Database (AGRASID) version 4.0 provides the latest digital and spatial representation of soil information of the agricultural area in Alberta (AGRASID, 2013). This soil database contains soil landscape polygons as a shapefile with attribute data compiled to a map at scale 1:100,000. Soil surveys began in Alberta in 1920, enabling development of AGRASID to compile all soil information into a digital standard for users.

AGRASID 4.0 can be downloaded for free in a geodatabase file format (http://www1.agric.gov.ab.ca/$Department/deptdocs.nsf/All/sag14652). It contains a *SoilLandscapePolygons* shapefile with a polygon ID (POLY_ID) that has a relationship to a series of attribute tables (Figure 3-2). Each polygon can contain up to a maximum of 6 different *PolygonComponents* which requires querying through a series of relationship tables to a soil layers table (called *SoilLayers*) that includes all the necessary information for input into AquaCrop. The exact location of where the soil samples were taken is not provided in the database. Instead, a percentage of the total area of a particular soil type is provided for each polygon.

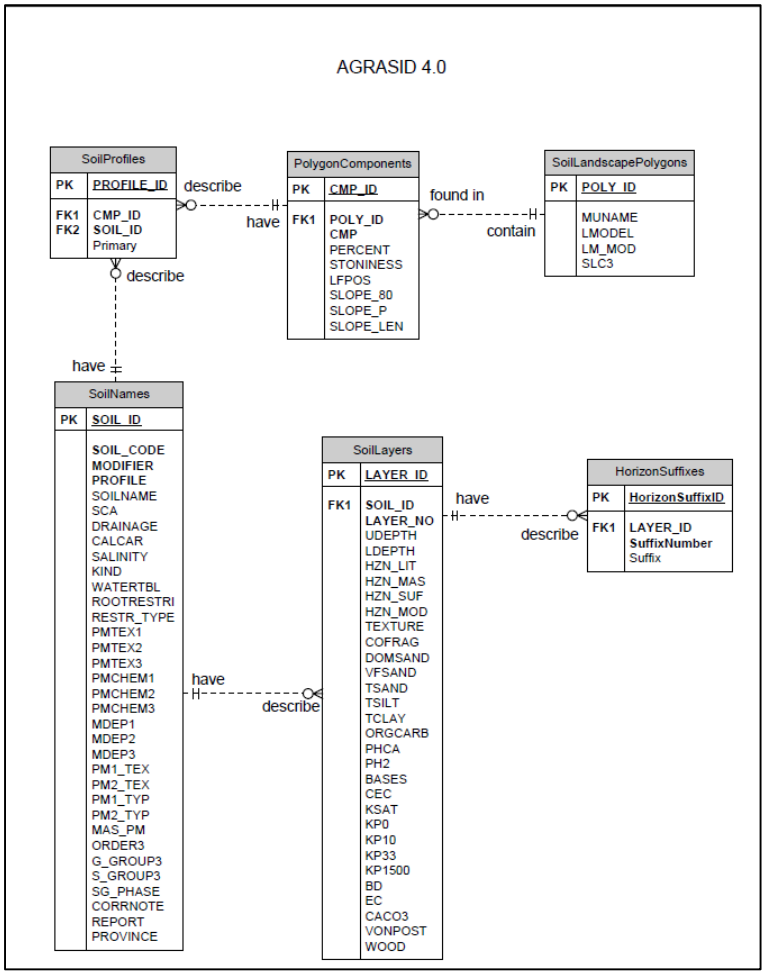


Figure 3-2 Relationship table of AGRASID 4.0 (AGRASID, 2013).

The entire AGRASID 4.0 geodatabase file was converted into a MySQL database, allowing for the creation of all necessary table relationships. Consequently, queries can be easily processed to extract all the required soil data to create the soil information input file required by AquaCrop (text file with the extension .SOL). AquaCrop allows for the input of up to five different soil horizons into the .SOL file (Raes et al., 2009). Each horizon requires the following soil data: soil water content at saturation (Sat), field capacity (FC), permanent wilting point (PWP), and depth. The total depth for each horizon is calculated by taking the

difference between the upper and lower depth of the soil layer. The AGRASID field names KP0, KP33 and KP1500 are associated with the porosity, field capacity and permanent wilting point. The values 0, 33, and 1500 represent the soil matrix potential (bars) describing the soil-water status as a function of pressure (Dingman, 2002). The saturated hydraulic conductivity (Ksat) values were based on the soil type from a look-up table provided by AquaCrop's default soil physical characteristics found in the Soils.DIR file. The Curve Number (CN) was obtained from Table 2.13b in the AquaCrop's Users Guide (Chapter 2) that looks at the top horizon's Ksat value to determine the CN input value (Raes et al., 2012). In cases where AGRASID 4.0 has more than five soil horizons, the extra layers over five were aggregated into the fifth layer. The total soil depth and the averages of Sat, FC, PWP were calculated. By following this procedure, the maximum rooting depth is not limited by only the first five horizons, which can limit crop growth in simulations. The AquaCrop version was set to 3.0 for the soil file because 4.0 includes capillary rise coefficients, which are excluded in this study, as they are considered to be negligible for this particular region.

The soil profile having produced the highest yields is identified as *CHN (Table 3-2)* and represents approximately 65% of the climate grid. It is, therefore, considered to be the most representative soil for crop yield simulation purposes. The idea is to focus on reaching the potential maximum yield in the simulations as a best case scenario given the location and climate.

Table 3-2 CHN soil information added into the .SOL AquaCrop template file

Horizon	Thickness (m)	SAT (vol %)	FC (vol %)	WP (vol %)	Ksat (mm/day)	Description
1	0.12	52.8	28.9	15.8	250	Loam
2	0.08	47.2	29.2	16.5	250	Loam
3	0.36	47.2	33.3	17.8	150	Silt Loam
4	0.25	49.1	40.6	22.3	15	Silty Clay
5	0.79	49.1	39.2	21.7	15	Silty Clay

3.2.3.4 Simulation Period

The seeding date is determined by searching the annual temperature time series for five consecutive days with an average temperature above 5 °C. After the five days are found, the following day is set as the seeding date. The searching process begins on April 1st, because regularly occurring warm winter chinooks (foehn winds) could otherwise falsely implement a seeding date in winter. The search method proves to be quite accurate in determining seeding dates that fall within the optimal seeding dates from mid-April to beginning of May (McKenzie et al., 2011). Harvest dates are linked to the growing cycle and end the simulation on the day that the crop reaches maturity. Once the plant reaches maturity the Harvest Index (HI) will stop increasing (Steduto et al., 2009), hence simulated yield will not further increase after maturity.

3.2.4 Observed Yields

Annual Observed Yields from 1991-2004 were recorded by the crop insurance agency AFSC (Agriculture Financial Services Corporation). Observed yields are recorded as the average yield per quarter section (64.7497 ha). These quarter sections are part of the Canada's Dominion Land Survey system which is

commonly used in the agriculture sector (McKercher et al., 1986). Yield measurement errors are unknown. Multiple observed rainfed yields may exist within a climate grid for a single year. If this was the case, only the maximum yield was considered, because the AquaCrop simulations are based on optimum growing conditions in relation to the soil profile and climate.

3.2.5 Database Development

The climate and soil data need to be assembled in a form that allows easy data extraction when performing a large number of simulations (Lorite et al., 2013). MySQL Workbench version 6.0 was used to establish the database for AquaCrop, which is an open-source visual database design application created for easily creating tables and managing a database (MySQL, 2008). MySQL has a Visual Studio integration for developers that allows MySQL to connect to the C# programming language (Williams, 2002). C# was used to create customized functions for MySQL, such as creating a workflow for connecting to multiple tables and creating AquaCrop input text files.

All data were added into tables in MySQL, in which the climate *Grid-ID* acted as an associate primary key that links the daily climate data grids, soil data, and observed yields together. As the database was established for southern Alberta, the required data volume is large. Its climate data file contains 6,929,080 rows, the AGRASID soil information contains 10,592 rows, and four different observed crop yields per quarter section contain 1,092,329 rows. All the data contains an associate polygon shapefile. The shapefiles were spatially overlain in Esri's ArcMap version

10.2 (ESRI, 2013), so that each resulting polygon contained *Grid-ID* as the foreign key (Figure 3-3). Functions were implemented to automatically query the requested data by the user from the *Grid-ID,* thus allowing the automatic generation of input files required by AquaCrop.

Figure 3-3 Example of the spatial overlay of data used for AquaCrop

3.2.6 Grid Search Algorithm

In Southern Alberta, many different varieties of wheat are grown (AgCanada, 2015). Each different cultivar will react slightly differently to climate, especially their phenology development stages (McCaig and DePauw, 1995;

Mkhabela and Bullock, 2012). This makes it difficult to obtain detailed crop parameters for AquaCrop.

To address this issue, a grid search algorithm was used to find the best crop parameters based on observed annual yield data. The root mean square error (RMSE) was used to identify the set of crop parameters, which simulated yields with the smallest differences with observed yields. RMSE is frequently used to measure the difference between simulation and observed values based on squared difference of values. The objective was to find a combination of crop parameter values to minimize the RMSE between the crop yield predicted by AquaCrop and the observed data. It is not possible to examine the infinite number of combinations of possible parameter values. Instead, the grid search algorithm is a straightforward way to find approximates to the optimal parameter values.

The grid search algorithm starts by partitioning the possible values of each parameter into a regular grid, with a fixed increment between some minimum and maximum values (Figure 3-4). Each grid point represents a particular combination of parameter values. The parameter values at each grid point are fed into an AquaCrop simulation to predict crop yield, and the resulting RMSE from the observed data can be calculated. The grid point corresponding to the lowest RMSE is an approximation of the optimal parameter values.

The accuracy of the approximation can be improved using a finer grid, but there is a trade-off between better accuracy and computational time. For example, halving the increments for each parameter will result in a factor of 2^d more grid

points where d is the number of parameters. Using a fine grid uniformly can be computationally intensive (Hsu et al., 2003). Instead, a coarser grid was first used to find a candidate grid point. The grid search algorithm was then applied again on the region surrounding the candidate grid point with a finer grid to obtain a better approximation. The candidate point can be refined iteratively, until the objective does not improve significantly. The iterative refinement approach gives a more accurate approximation without a significant computational cost.

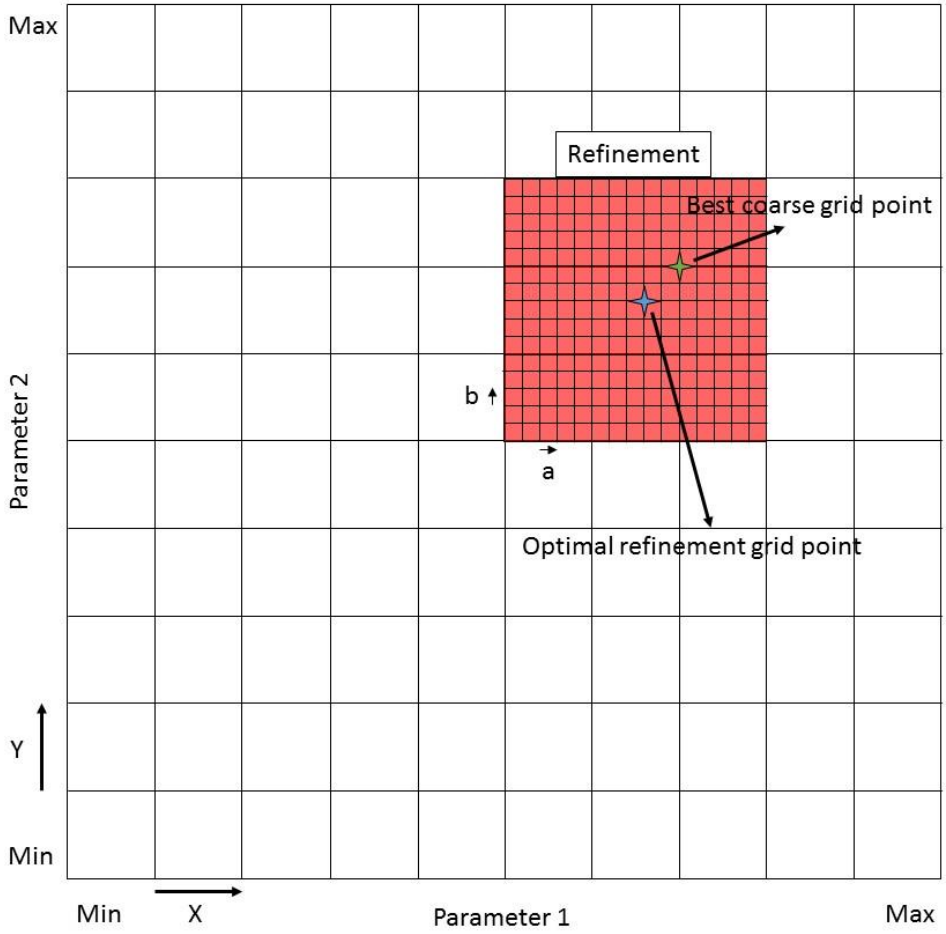


Figure 3-4 Two dimensional example of a grid search algorithm. Green area is the result of the coarse grid search; Red area is the area of the finer grid search; X, Y are the constant incremented values; a, b are the incremented values for the refinement.

To find the optimal crop parameter values for AquaCrop, the grid search algorithm is applied to the five parameters. The first four parameters are the number of GDD from the seeding day to emergence, maximum rooting depth, start senescence, maturity (length of crop cycle). The last parameter is the length of the flowering stage. A five-dimensional grid is used in the search, and the setup of the coarse grid is outlined in Table 3-3. The values for maximum rooting depth and the beginning of the flowering stage were combined in one dimension. This simplification can be applied because once wheat begins to flower, the wheat's root growth will slow down and eventually stop (Watt et al., 2013). In addition, the parameter describing the GDD of the building up of the HI is adjusted to finish 100 GDD before maturity, similar to the parameters used in Mkhabela and Bullock (2012). This is based on the recommendation that the building up of the HI should reach its values at, or shortly before, crop maturity (Raes et al., 2012).

Table 3-3 Five dimensional grid search used for the crop phenology parameters

Parameter (GDD) GDD from Sowing to:	**Minimum Value**	**Maximum Value**	**Increment**
Emergence	20	80	10
Maximum Rooting Depth/ Flowering	600	700	20
Start Senescence	800	1100	50
Length of Flowering Stage	100	150	10
Crop Maturity	1100	1300	40
		Total Iterations	10,584

Based on the number of increments of the five variables listed in Table 3-3, the AquaCrop program ran 10,584 times. To handle the large number of runs, FAO has developed an AquaCrop plug-in program that can run multiple simulations without using the graphical interface (Raes et al., 2013). An application in C# was implemented to automatically create Project Files based on individual conditions: start year, finish year, selected crop, selected climate *Grid-ID*, management (irrigated or rainfed), and a file directory where all input data are found. The grid search procedure selects data from the database and creates a series of project files along with all the other text files required for series of simulations. For successive years, the Project File is populated and iterated for as many years as required.

3.2.7 Grid Search Calibration

The annual observed yields obtained from the AFSC from the years 1991 to 2004 were used to validate the simulated wheat yields. The calculation of RMSE was performed for all 10,584 crop iterations to establish the least amount of error between simulation and observed results. The entire procedure was automated (Figure 3-5), such that each crop file name begins at 1 and is incremented by 1 until 10,584 crop iterations are reached. The best crop parameter set was # *9330* resulting in a RMSE of 0.4451 (Table 3-4).

As recommended by Hsu et al. (2003), it is worth to iteratively run the grid search again but on a finer scale to optimize the parameter set. The parameters of crop file 9330 were selected as the middle point of the grid. The increment values from Table 3-3 were all halved and a smaller incremental value was selected. The

refinement process produced 3,125 additional crop files with one identical to crop file 9330. The result of the refinement process was crop file 2556, which increased the crop emergence value by 5, lowered the start of senescence by 50 and reduced the length of flowering by 10 (Table 3-4). The fine-tuning process lowered the RMSE from 0.4451 to 0.4320. The differences in the RMSE in the refinement were very low. Any additional refinements would be insignificant.

Table 3-4 Results of the best crop parameters based on the lowest RMSE for the initial and refinement runs.

Parameter **GDD from Sowing to:**	**Initial** (Crop:9330)	**Refinement** (Crop:2556)
Emergence	80	85
Maximum Rooting Depth/ Flowering	620	620
Start Senescence	800	750
Length of flowering stage	150	140
Crop Maturity	1100	1100
RMSE (ton/ha):	0.4451	0.4320

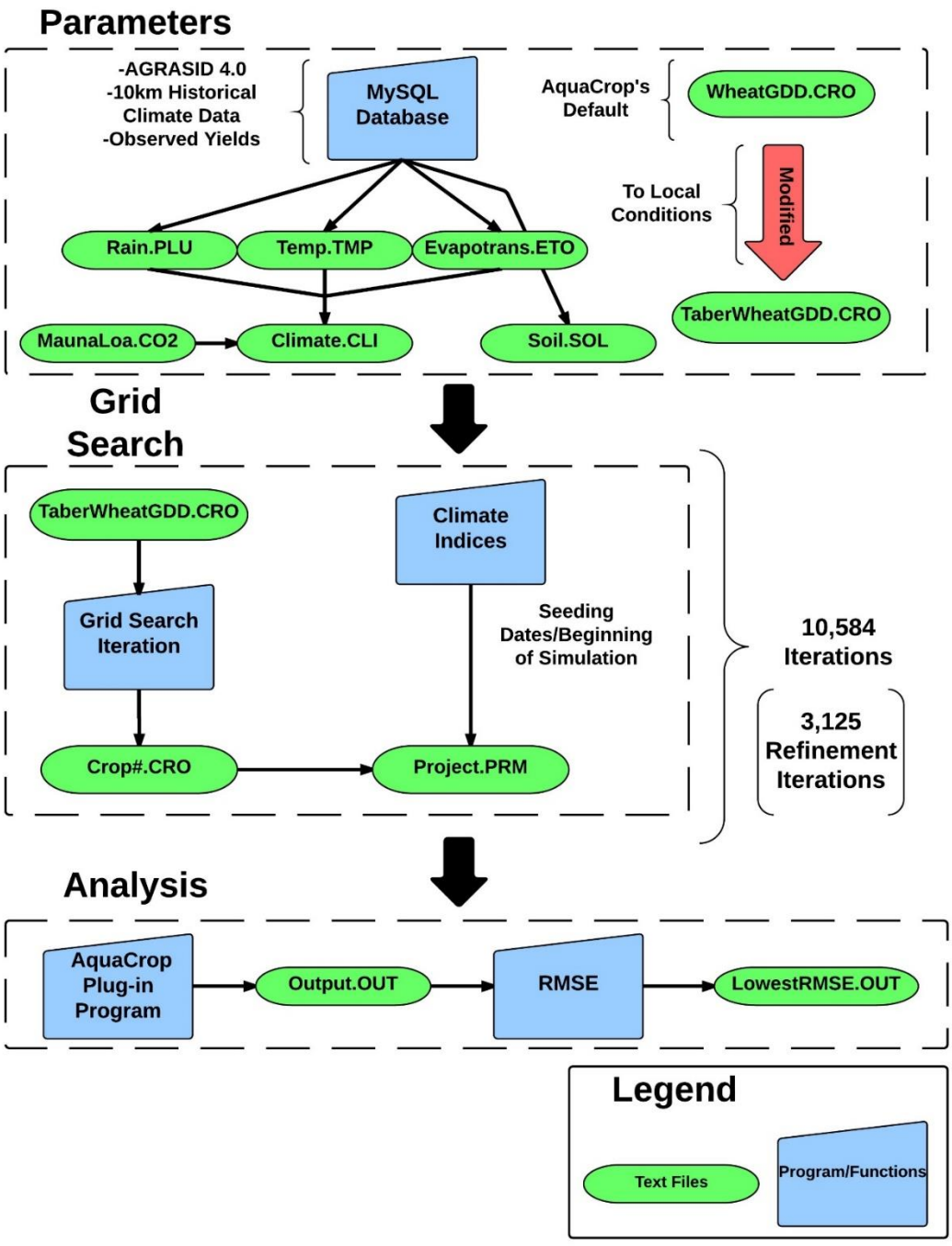


Figure 3-5 Diagram of total execution of the AquaCrop Calibration application. Beginning with the querying of input files from a MySQL database, iterative processing to create multiple crop files through a grid search algorithm, and calculating the RMSE

3.2.8 Regional Climate Models (RCMs)

Simulations explaining the impact of climate change on wheat yields were performed to give a better understanding of the future potential yield in the area. A main problem identified by Barrow and Yu (2005) is the selection of the number of scenarios to use for impact analysis. The Intergovernmental Panel on Climate Change (IPCC) *Task Group on Data and Scenario Support for Impact and Climate Analysis* (TGICA) currently recommends the selection of a range of scenarios that will help build a complete picture of the range of future climate variability of a region (Carter et al., 2007). Five scenarios were selected (Table 3-5) following Barrow and Yu (2005): four representing relatively extreme changes in either or both temperature and precipitation, and one representing median conditions. Three of the five RCMs are based on two Canadian Global Climate Models (GCMs), namely the Coupled Global Circulation Model Version 3 (cgcm3), and the Canadian Earth System Model Version 2 (Canesm2), both developed by the Canadian Centre for Climate Modelling and Analysis, a division of the Climate Research Branch of Environment Canada, housed at the University of Victoria. Two of the five RCMs are based on Geophysical Fluid Dynamics Laboratory (gfdl), a GCM developed by Princeton University, USA. All of these GCMs, or their earlier versions, have been applied by the IPCC. The general climate differences of each RCM projection are represented in Table 3-6.

Table 3-5 Regional Climate models and their climate description

RCM	Description
RCM3-gfdl	Cooler/drier
RCM3-cgcm3	Cooler/wetter
CRCM-cgcm3	Median
CRCM4_22-canesm2	Warmer/Wetter
HRM3-gfdl	Warmer/Drier

The RCMs with spatial resolutions of 22 to 44 km^2 were downscaled to match the 10 km^2 climate grids used in this study. Each RCM has two datasets: One historical period ranging from 1971-2000, and one future period ranging from 2041-2070. All future simulations used the AquaCrop's so-called A2-CO_2 file that is based on the IPCC special report emissions scenarios (A2.CO2). The A2 scenario ("business as usual") provides a steady increase of CO_2 concentration throughout the future years. The RCM time series representing the historical period were calibrated to match the observed gridded climate dataset, and the same calibration was applied to the future dataset. This method has been used widely when studying the impacts of climate change (Semenov and Porter, 1995; Barrow and Yu, 2005; Gobena and Gan, 2013; Lorite et al., 2013). As the RCMs cannot replicate or project climate for a specific day, the two entire climate periods were compared.

The reference evapotranspiration (ET_o) was calculated by using the RCM weather data of Tmax, Tmin and PPT. The Penman-Monteith method is the recommended formula to calculate ET_o for AquaCrop (Steduto et al., 2009). Historical climate averages of incoming radiation, relative humidity, sunshine hours, and wind speed were used in both time series for all RCMs. Therefore, the only climate differences between RCMs are Tmax, Tmin, and PPT. For the simulation of

future wheat yields, the soil characteristics and crop parameter file were the same files found by the grid search calibration procedure. The criterion for the seeding date used was the same dynamic method as described above.

Table 3-6 Climate conditions for historical (H, period 1971-2000) and Future (F, 2041-2070) of five regional climate models for the growing season (April – October)

Variable	RCM3-gfdl		RCM3-cgcm3		CRCM-cgcm3		CRCM4_22-canesm2		HRM3-gfdl	
Time Period	H	F	H	F	H	F	H	F	H	F
Rainfall (mm)	250.5	266.6	250.5	296.2	250.5	271.0	250.5	315.1	250.5	244.1
Rainfall % Difference		6.4		18.2		8.2		25.8		-2.6
Tmax (°C)	19.9	22.2	19.9	22.4	19.9	22.3	20.0	23.5	19.9	23.1
Tmax Difference (°C)		2.3		2.5		2.4		3.5		3.2
Tmin (°C)	5.2	7.0	5.2	7.5	5.2	7.7	5.2	8.5	5.2	7.8
Tmin Difference (°C)		1.8		2.3		2.5		3.3		2.6

3.3 Results and discussion:

3.3.1 Grid Search Results

The grid search algorithm produced a total of 10,584 different crop and project files and an additional 3,125 crop and project files after the refinement. The 10,584 iterations resulted in RMSE maximum of 0.987 (ton/ha), minimum of 0.445 (ton/ha), and a mean of 0.680 (ton/ha). Table 3-7 represents the outcome of the ten best results with the lowest RMSE. The top results represent a specific region in the grid. This means that the best set of parameters, based on a validation with observed yields, is narrowed to a certain combination. The repetition of the same parameters indicates a more confident combination of parameters, as opposed to a more random set in multiple different regions of the grid. The final result of crop

parameters represented in Table 3-4 provided realistic results compared to nearby experiments in Manitoba and Saskatchewan (Mkhabela and Bullock, 2012), which all overestimated wheat yield by 3%. After the refinement search on a finer grid, the RMSE was lowered by 0.0131 (ton/ha) and overestimated by 0.26% relative to the mean wheat yield. Figure 5 shows the wheat yields of simulated and observed values. The correlation between simulated and observed yields resulted in a moderate R^2 of 0.565 (Figure 3-6), with a slope of the regression line of 0.683. The average simulated and observed yields during the simulation period 1991-2004 had a difference of 0.006 in tons per hectare (Table 3-8).

Table 3-7 The lowest 10 RMSE (ton/ha) results of the 10,584 iterations of the grid search algorithm

Crop Iteration	Emergence	Max Rooting Depth/ Start of Flower	Senescence	Maturity	Length of flowering	RMSE (ton/ha)
9330	80	620	800	1100	150	0.445
9326	80	620	800	1100	110	0.446
9327	80	620	800	1100	120	0.447
9325	80	620	800	1100	100	0.447
9328	80	620	800	1100	130	0.448
9329	80	620	800	1100	140	0.448
7814	70	620	800	1100	110	0.456
9365	80	620	850	1100	140	0.457
7813	70	620	800	1100	100	0.457
7815	70	620	800	1100	120	0.457

It is important to emphasize that the use of fertilizer is not considered and that AquaCrop does not simulate pests and diseases (Steduto et al., 2009). As well, there is no knowledge of extreme weather events such as hail, extreme wind and field fires that could lower crop yields. These differences could explain some of the

over-simulated yields shown in Figure 6. For under-simulated results, the observed yields could contain the use of fertilizer or other farm management strategies that help produce higher yields.

Table 3-8 Statistical comparison between simulated and observed wheat grain yield for years 1991-2004

Variable	Avg Observed	Avg Simulated	RMSE (ton/ha)	R^2
Wheat Grain Yield (ton/ha)	2.258	2.264	0.4320	0.565

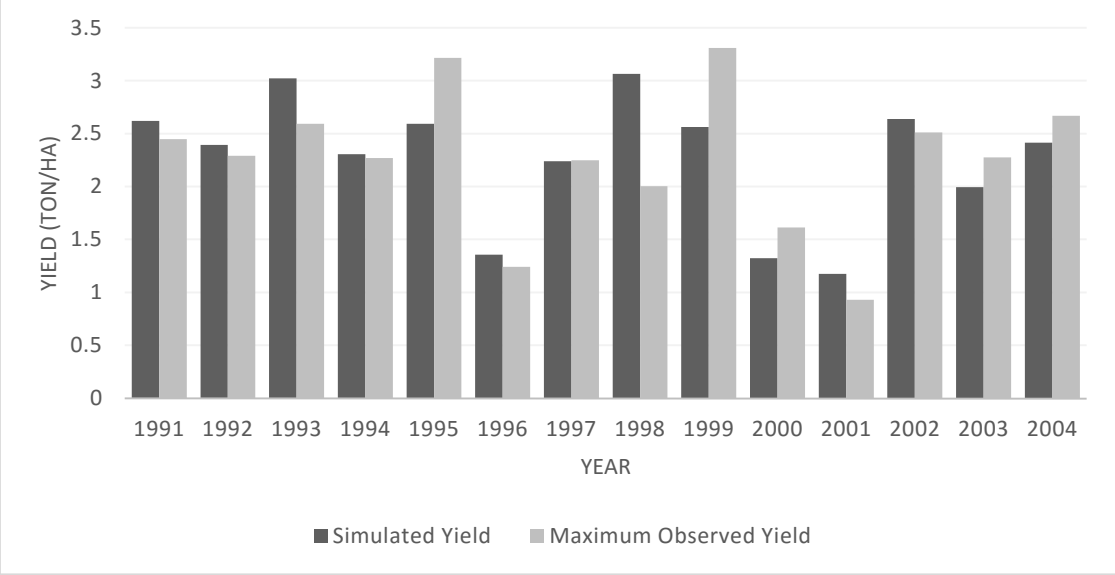


Figure 3-6 Comparison of grain wheat yields between the maximum reported yields within the 10km^2 climate grid and the lowest RMSE output from the grid search calibration algorithm

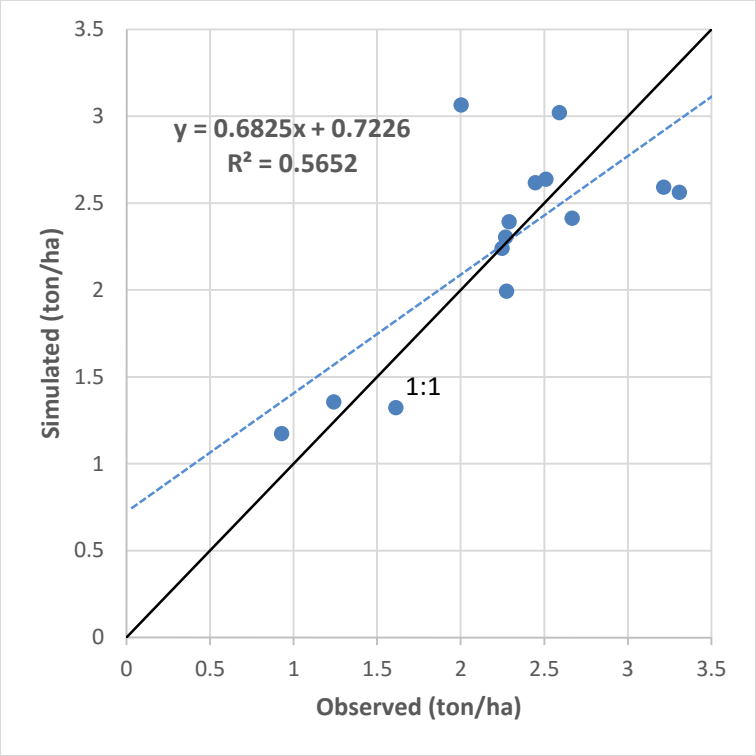


Figure 3-7 Relationship between simulated and observed wheat grain yield (ton/ha) for annual yields from 1991-2004

3.3.2 RCM Analysis

Figure 8 and Table 3-9 describe the differences of yield for the different RCM predictions. In all cases, the average yield for the whole 30-year period has increased substantially. The "warmer and wetter" scenario (CRCM4_22-canesm2) showed the largest yield increase of 88.0%. The "cooler and drier" scenario (RCM3-gfdl) resulted in the smallest yield increase, which was still an ample 42.6% increase. The "warmer and wetter" scenario was expected to result in the largest yield increase, because it is associated with more GDDs in the growing season, which the model used to determine the crop development and phenology (Raes et al., 2009). The addition of a wetter environment results in less water-limiting stress on the crop, which translates to higher yields. The "cooler and drier" scenario is

affected by the conditions previously mentioned, but with a shorter amount of GDDs and more water limitation. Although the yields are simulated to be higher in all cases, the variability between the maximum and minimum yields is higher in the future simulation period than in the historical one. In all five future scenarios, the minimum, median and maximum and inter-quartile yields simulated to be higher in the future, thus resulting in reduced risk of rainfed wheat production in the future.

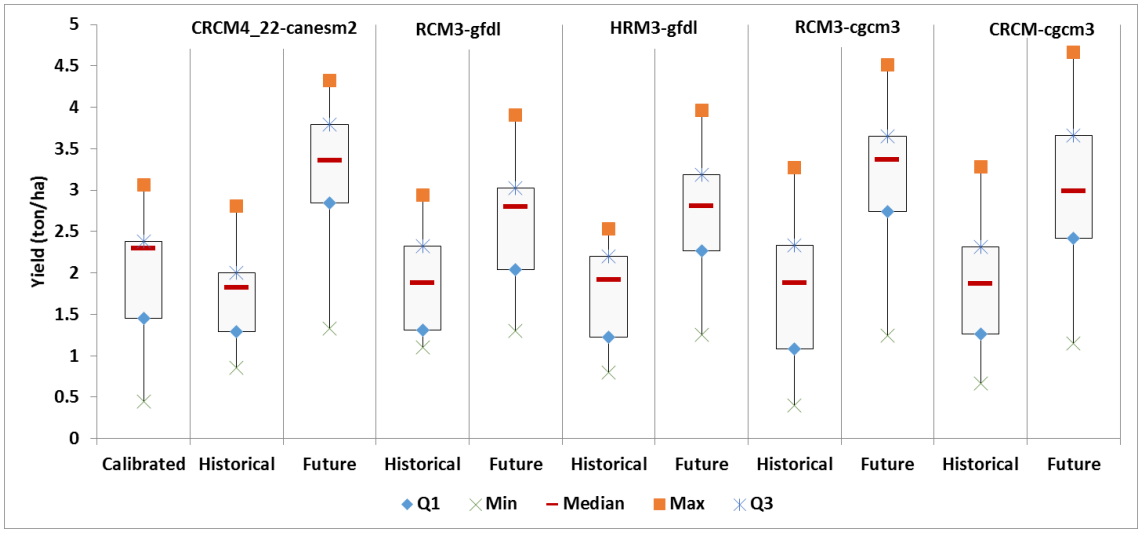


Figure 3-8 Yield (ton/ha) comparison between simulations of the calibrated dataset and the five RCMs of the historical and future time series. Q1 is the 25th percent quartile, Q3 is the 75th percent quartile that represent the distribution of wheat yield

It is predicted in the literature that above-ground biomass will increase with elevated CO_2 levels (Ainsworth and Long, 2005; Vanuytrecht et al., 2011). The high yields in all five RCMs can be explained by an effect of a CO_2 fertilization. The AquaCrop model is known to overestimate yields under conditions of elevated CO_2 (Vanuytrecht et al., 2011). The IPCC A2 future emissions scenario (2041-2070) has an average of 561 ppm CO_2 by volume with an increasing trend, compared to the historic (1971-2000) 347 ppm CO_2 by volume, or the current (2015) 400 ppm CO_2. The water productivity parameter in AquaCrop captures this effect, as it is based on

ETo and CO_2, which is used to calculate the crops' biomass (Steduto et al., 2009). An additional simulation was performed by matching the same CO_2 input for both historical and future time series (Table 3-9). Without the effect of a CO_2 fertilization the yields were still predicted to increase, except for the "cooler-drier" scenario showing a slight decrease over the entire 30 years of -4.4%. From these results, AquaCrop simulations of wheat yields are strongly impacted by the effect of a CO_2 fertilization causing yields to increase around 50% from elevated CO_2 in the 2041-2070 climate period.

Table 3-9 Simulated wheat comparison between the historic and future time series of all five different regional climate models

RCM	Rank	% Yield Increase	%Yield Increase (Historical CO_2)
Warmer-Wetter	1	88.0	30.1
Cooler-Wetter	2	74.6	19.4
Median	3	60.5	9.2
Warmer-Drier	4	55.5	5.0
Cooler-Drier	5	42.6	-4.4

3.4 Conclusion

External applications were created for handling large datasets and automating AquaCrop for parameterizing wheat for southern Alberta. Input data were added to a MySQL database and applications were written in the C# programming language to automatically create input files for AquaCrop. These applications enabled running a grid search calibration algorithm for determining optimal crop parameters based on observed yields. Over 13,000 simulations of AquaCrop were analyzed in determining the most optimal crop parameters. The final results (Table 3-8 and Figure 3-6) proved to be adequate with a yield RMSE of

0.432 (ton/ha), compared to results of yield RMSE of 0.743 (ton/ha) from Mkhabela and Bullock (2012). After the reasonable parameterization was achieved, an assessment on the impact of climate change on wheat yield was performed based on five RCMs.

The RCMs represent projected climate changes of cooler and drier (CD), cooler and wetter (CW), median (M), warmer and drier (WD), and warmer and wetter (WW) to the future climate period of 2041-2070. All RCMs were also available for the historical period 1971-2000, thus enabling the comparison between future and historical climate periods. Results are considered to be slightly high (Figure 3-8), with simulated potential increases of yield over the entire climate period ranging from 43% (CD) to 88% (WW). These increased wheat yields were caused by AquaCrop boosting the simulated crop yields with a CO_2 fertilization effect. By matching the historical CO_2 concentrations with the future climate projects, yields would lower around 50%. This could indicate an over-estimation in crop yields from elevated CO_2 concentrations.

All datasets cover the entire agricultural area in Alberta, making it possible to simulate different zones of entire watersheds or larger-scale areas. Using external utility applications similar to Lorite et al. (2013), it is possible to simulate yields for larger areas with a certain degree of accuracy. The grid search calibration algorithm may be improved with the addition of more observed yields. Although, with 14 years of observed yields, the grid search calibration algorithm provided a reasonable combination of crop parameters with the lowest RMSE when compared

to observed yields. Using similar techniques as Lorite et al. (2013) to automate the AquaCrop input file creation from a database made it easier to calibrate the model, with an initial 10,584 runs and a subsequent 3,125 additional runs. The resulting simulated yield provided a reasonably low RMSE for a random location selected within the county of Taber, Alberta.

The simulated wheat yields based on five different RCMs revealed that all produce increased yields in the future 2041-2070 period. However, based on the presented results, wheat yields are expected to increase within the study area with proper farm management, with the exception of extreme weather events such as hail storms, extreme wind, natural fires, etc., or even field variability with sudden topographic changes which would reduce yields. In addition, pests and diseases are not simulated in AquaCrop and observed soil salinity was excluded from this study.

Our automated method to parameterize AquaCrop to local Canadian Prairie conditions makes the program suitable for other regions, where it can be used as a decision making tool for predicting future wheat yields over large areas. Sufficient data, such as climate time series and soils data are available to run the simulation for the entire agricultural area of the province of Alberta. Results can be used to assess differences between the lower and high latitude areas, as well as different soil zones, and identify regions in Alberta with the highest potential wheat yields. In addition, a large range of other agricultural crops can be analyzed in a similar way, allowing a series of maps with crop yield potentials to be produced.

Chapter 4

Simulation of Impacts of Climate Change on Barley, Canola and Wheat yields in Southern Alberta

4.1 Introduction

Barley (*Hordeum vulgare* L.), canola (*Brassica napus* L.), and wheat (*Triticum aestivum L.*) are essential crops grown in Alberta, Canada (Shen et al., 2005; Bennett and Harms, 2011; AgCanada, 2015). According to the Yield Alberta report for 2014 (AgCanada, 2015), barley was produced on 1,979,000 dryland acres and 98,000 irrigated acres, canola was grown on 4,770,000 dryland acres and 105,000 irrigated acres, and wheat was planted on 4,683,000 dryland acres and 247,000 irrigated acres. This is a significant agriculture production that contributes to the prairie region (Alberta, Saskatchewan, and Manitoba) where agriculture is a major economic driver (Kulshreshtha, 2011). Southern Alberta is unique within in the prairie agriculture region as it contains around 97% of the entire irrigated land of Alberta (Bennett and Harms, 2011). In addition to dryland agriculture limitations, southern Alberta crop production is vulnerable to recurring drought (Xu et al., 2012) and climate variability (Gizaw and Gan, 2015). The droughts of 2001 and 2002 caused an estimated loss in agriculture production of CAN$3.6 billion, mostly in the provinces of Alberta and Saskatchewan (Wheaton et al., 2008). The agriculture sectors of southern Alberta and the rest of the Canadian prairies face a growing future threat, as water availability at the right time and in the right place is becoming increasingly uncertain (Schindler and Donahue, 2006; Sauchyn and Kulshreshtha, 2007). Kulshreshtha (2011) indicated that the agriculture industry could face both positive and negative impacts as a result of climate change, but

many unknowns still exist. The benefits of CO_2 fertilization on crops can increase yields (Drake et al., 1997; Raines, 2011), however, more research is required with major crops within major growing zones, due to the limited but optimistic chamber experiments (Ainsworth and Long, 2005) and regional effects of different environments (Justin and David, 2013). Regional studies over longer temporal periods are essential to anticipating future change. For example, Shen et al. (2005), concluded overall that the agriculture industry of Alberta has benefited from the last century's climate, but also indicated that growing agro-climatic vulnerabilities within the southern Alberta region could increase droughts if climate patterns and trends stay the same.

Crop models enable the estimation of crop growth and production under different spatial locations with diverse climates and soil conditions (De Wit and Van Keulen, 1987). In view of growing concern over climate change effects on agriculture production, crop models have been used extensively for determining potential impacts of climate change on crop yields (Semenov and Porter, 1995; Fraisse et al., 2006; Isik and Devadoss, 2006; White et al., 2011; Resop et al., 2012; Asseng et al., 2013; Bassu et al., 2014). Many different crop models exists such as WOFOST (Diepen et al., 1989), EPIC (Williams, 1989), DSSAT (Jones et al., 2003), CropSyst (Stöckle et al., 2003) and AquaCrop (Steduto et al., 2009). Although all models allow for a better understanding of crop responses to climate and different management scenarios (Fraisse et al., 2006; Resop et al., 2012), each model has its own strengths and weaknesses (Todorovic et al., 2009). This is why multi-model assessments are recommended (Rosenzweig et al., 2013). As a solution for handling

the complexity of the global agriculture production under climate change, the Agricultural Model Intercomparison and Improvement Project (AgMIP) was been created as a major international collaboration for linking climate, crop, and economic models with climate impact projects for the agriculture sector (Rosenzweig et al., 2013). The AgMIP analyzed 23 different crop models for simulating maize (corn) production globally, concluding that temperature increase had a strong negative influence on yield, and that increases of CO_2 concentrations would have a positive influence on yields (Bassu et al., 2014). However, the yield response of increased CO_2 concentrations suggested significant uncertainty between crop models. A similar AgMIP study also concluded that there is a need for crop models to improve on the reliability in predicting yield with reposes to increasing CO_2 concentrations and temperatures (Li et al., 2015).

For this study, a crop water productivity model developed by the United Nations Food and Agriculture Organization (FAO), called AquaCrop, was parameterized for an area in southern Alberta, Canada. AquaCrop is a water driven model that attempts to achieve an optimal balance of accuracy, simplicity and robustness; making it a valuable model for decision makers or researchers world-wide (Steduto et al., 2009; FAO, 2012). The model has been evaluated and calibrated in different climates and used with various crops around the world, such as maize, sunflower and sugar beet (Stricevic et al., 2011), barley (Abrha et al., 2012; Tavakoli et al., 2015), canola (Zeleke et al., 2011) and winter wheat (Xiangxiang et al., 2013; Iqbal et al., 2014). Although the model is fairly new to the Canadian prairies, Mkhabela and Bullock (2012) have demonstrated that AquaCrop can be a valuable

tool for simulating spring wheat yield. The AquaCrop model differs from other models, as it focuses on water-limiting condition (Iqbal et al., 2014), and has a more simplified approach that requires fewer parameters (Todorovic et al., 2009), which are usually not available. Furthermore, AquaCrop can be used to evaluate crop irrigation strategies (Araya et al., 2010). For these reasons, AquaCrop is a suitable model for running a parameterization grid search algorithm for barley, canola, and wheat in southern Alberta, and a comparison of AquaCrop's irrigation strategies with a local irrigation model, the so-called Irrigation Requirements Model (IRM) (Association and Committee, 2002).

The objectives of this study are: (1) Parameterize barley, canola and wheat crop files for the AquaCrop model for two distinct locations, the county of Pincher Creek and the county of Taber in southern Alberta; (2) Assess the impacts of climate change on the calibrated barley, canola and wheat yields for five different RCMs; (3) Calibrate irrigated barley, canola and wheat for the county of Taber, assess the impacts of climate change and compare AquaCrop's default irrigation output with a regional irrigation model, IRM.

4.2 Methods

4.2.1 Study site

Two distinct areas in southern Alberta were selected, the County of Pincher Creek and County of Taber. The county of Pincher Creek is situated near to the Rocky Mountains, and the County of Taber is situated farther East into the Canadian Prairies. Pincher Creek has a cooler and wetter climate, and a shorter growing

season than the County of Taber (Table 4-1). Both Counties are situated within the Oldman River Watershed in southern Alberta (Figure 4-1). The Oldman River Watershed is one of four watersheds within the major South Saskatchewan River Basin, and due to its over-allocation of water licenses, one of the three southern basins with a moratorium on any new surface water allocations. Water availability has become an increasing concern in the Oldman River Watershed, especially since roughly 90% of the stream output is already used (Byrne et al., 2006). Therefore, irrigated areas can only be expanded with difficulty.

In recent years, rainfed farming of canola has become the most dominant grown crop in Alberta (Statistics Canada, 2011). As of 2014, dryland crops contained 4.8 million acres of canola, 2.0 million acres of barley, and 4.7 million acres of wheat, compared to the irrigated crops containing 0.11 million acres of canola, 0.10 million acres of barley, and 0.25 million acres of wheat (AgCanada, 2015).

The Canadian prairies have soils that are mostly composed of the Canadian Chernozemic soils group, which have a Mollic epipedon (Pennock et al., 2011). A soil must have a certain thickness, dark enough colour, contain organic carbon, and some other conditions in order to be classified as a Chernozemic soil in Canada (Pennock et al., 2011). The texture can range from coarse sands to finer silts and clay loams. Climate is one of the main characteristics in shaping the soils (Fuller, 2010). Southern Alberta is a semi-arid region that has a landscape of undulating hummocky till plain that has been strongly shaped by the Wisconsinan glaciation

(Beaty and Young, 1975). These factors contribute to the area resulting in the Brown Chernozem (Canadian system of soil classification) soil group for the Taber region and the Black Chernozem soil group for the Pincher Creek region (Canadian Agricultural Services Coordinating Committee, 1998). Brown Chernozems are considered to have the lowest water availability out of the all chernozemic groups and are well-drained soils, while Black Chernozems generally have high percentage organic matter (Pennock et al., 2011).

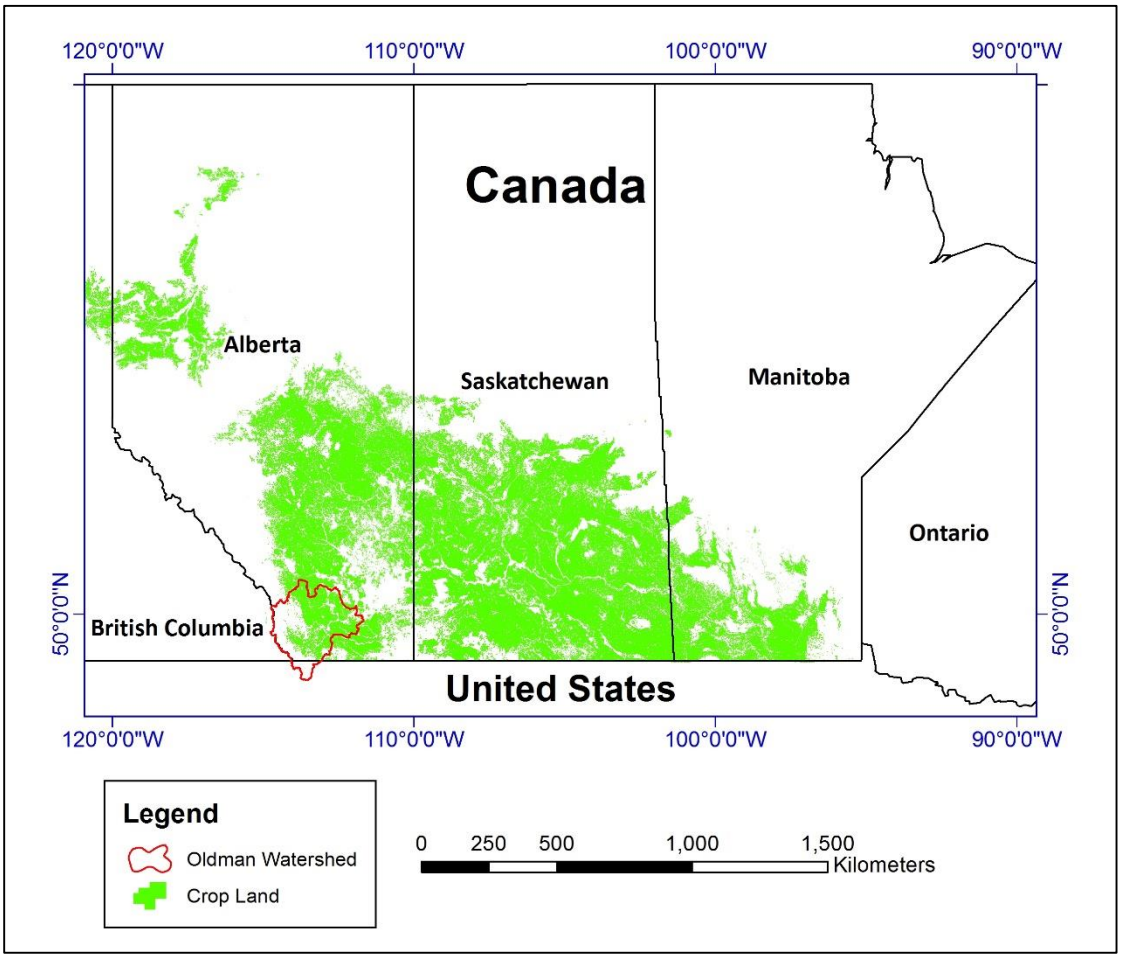


Figure 4-1 Map of the Canadian Prairies (Alberta, Saskatchewan, and Manitoba) agriculture crop land.

4.2.2 AquaCrop Description

The AquaCrop model focuses on water as the main driver for agricultural production (Steduto et al., 2009). Water is connected throughout the soil-crop-atmosphere continuum that AquaCrop is built around. This requires a series of specified input data to run crop simulations. According to Steduto et al. (2009), the aim of AquaCrop is to provide a functional crop simulation model of yield response to water that can be used for agricultural sectors world-wide. AquaCrop provides default values and robust methods for handling missing inputs that are further explained in Raes et al. (2009). However, Steduto et al. (2009) indicated that it is imperative for AquaCrop to be calibrated and validated extensively for crops, before it can be used as a planning or decision making tool.

AquaCrop requires fewer parameters and inputs to simulate yield compared to other models (Kumar et al., 2014), but there is still the need to manually set up some parameters based on local conditions. The AquaCrop model uses four main components for simulating yield: climate, crop, management, and soil. The climate component requires rainfall, potential evapotranspiration (ETo), minimum and maximum temperature, and atmospheric CO_2 concentrations in daily, 10- day, or monthly time steps. The crop component requires various crop parameters describing the development, production, and stresses of the crop. The management component consists of irrigation and field management strategies. For this study the field component is neglected because of the lack of available data. Under the irrigation component, AquaCrop allows input for defining set irrigation schedules with time and depth of each application, or can automatically generate a

schedule based on thresholds of allowable root zone depletion, or fixed intervals. For the soil component, AquaCrop allows for the input of up to five different soil horizons (Raes et al., 2009). Each horizon requires the following soil data: soil water content at saturation (SAT), field capacity (FC), permanent wilting point (PWP), depth of each horizon, and capillary rise coefficients. The capillary rise coefficients are neglected in this study because of no significant groundwater in the study area.

Applying AquaCrop for multiple crops under multiple climatic and soil conditions can be tedious and requires a manual set up of multiple input files and simulations. As a solution, an application similar in principle to that developed by Lorite et al. (2013) was used to automatically manage the inputs for AquaCrop. It addressed the time-consuming issues of manually creating the input files for AquaCrop. Lorite et al. (2013) developed two utility applications called AquaData and AquaGIS that have proven to save very significant time when running the model for a high number of simulations. Similar techniques were used in this study to handle automated creation of input files with use of an open-source database, MySQL (MySQL, 2008).

4.2.3 AquaCrop Input Files:

4.2.3.1 Climate

Agriculture and Agri-Food Canada (AAFC) have developed and thoroughly tested a Canada-wide interpolated spatial model of daily minimum and maximum temperature and precipitation (Hutchinson et al., 2009). The datasets cover all of Canada, except the far North, with spatial grids of 10 by 10 km^2. Each grid contains

daily values for maximum and minimum temperature and precipitation for a time series spanning from 1950-2010. The climate differences between the various study regions are presented in Table 4-1, indicating the cooler and wetter area of Pincher Creek compared to Taber. Only 1991-2004 of the gridded dataset was used for the AquaCrop crop calibration to match the availability of observed crop yield data.

Table 4-1 1950-2010 climate data for the growing season (April 1st to October 31st)for selected regions

Region	Crop	Average annual PPT (mm)	Average Maximum Temperature (°C)	Average Minimum Temperature (°C)
Taber	Barley, Wheat	261.5	19.8	5.1
Taber	Canola	263.4	19.9	5.6
Pincher Creek	Barley	373.1	16.7	3.3
Pincher Creek	Canola	370.5	18.1	4.4
Pincher Creek	Wheat	367.0	18.0	4.3

4.2.3.2 Crop

Barley and wheat crop input parameters were derived from AquaCrop's default *BarleyGDD.CRO and WheatGDD.CRO* files. The file was modified to local conditions based on data collected from various sources. Currently, AquaCrop does not have a default crop file for canola. However, Zeleke et al. (2011) calibrated and validated canola for AquaCrop in Australia. Those crop parameters were used as the basis of the canola crop file in this study. Table 4-2 shows the conservative crop values that were reported to not change with geographical location (Mkhabela and Bullock, 2012), and the other non-conservative parameters that describe key cultivar specific attributes or farm management techniques. The stages of crop phenology, such as GDD from seeding to emergence, start of flowering and

maximum rooting depth, senescence, maturity and length of flowering, were added into a grid search calibration algorithm (Chapter 3). The algorithm searched for the optimal crop parameters based on observed yields for a specific geographical location.

Table 4-2 Conservative and non-conservative crop parameters for barley, canola, and wheat obtained from various sources

Non-Conservative Parameters	Barley	Canola	Wheat	Units/(Symbol)
Base temperature below which crop development does not progress [3,5]	2.0[9]	3[11]	5.0[6,10]	°C
Upper temperature above which crop development no longer increases with an increase in temperature [3,5]	28.0[9]	29[11]	35.0[6,10]	°C
Number of plants per hectare [4]	2,000,000[7]	700,000[7]	2,700,000[7]	plants/ha
Maximum Rooting Depth [1,2]	1.3[9]	1.2[3,4]	1.2[1,2]	m
Harvest Index	52[9]	25[8]	48[def]	%
Conservative Parameters				
Water Productivity normalized for ETo and CO2 (WP*) [5]	15[9],[Def]	18.6[8]	14[10]	gram/m^2
Minimum air temperature below which pollination starts to fail (cold stress) [5]	5[Def]	5[11]	8[10]	°C
Maximum air temperature above which pollination starts to fail (heat stress) [5]	35[def]	38[11]	40[10]	°C
Excess of potential fruits [5]	100[def]	100[def]	50[10]	%
Canopy growth coefficient: Increase in canopy cover (fraction soil cover per day) [5]	0.008697[def]	0.008900[8]	0.011072[10]	unitless
Maximum canopy cover in fraction soil cover [5]	0.80[5], [Def]		0.95[10]	unitless
Canopy decline coefficient: Decrease in canopy cover (in fraction per day) [5]	0.006000[def]	0.005200[8]	0.009067[10]	unitless
Soil surface covered by an individual seedling at 90 % emergence [5]	1.5[def]	5.0[8]	5.0[10]	cm^2
Crop coefficient when canopy is complete but prior to senescence [5]	1.1[9]	0.95[8]	1.1[10]	unitless
Maximum root water extraction in top quarter of root zone [5]	0.019[def]	0.020[irri canola]	0.020[10]	m^3(water) m^{-3}(soil) day^{-1}
Maximum root water extraction in bottom quarter of root zone [5]	0.006[def]	0.005[irri canola]	0.005[10]	m^3(water) m^{-3}(soil) day^{-1}

Effect of canopy cover in reducing soil evaporation in late season stage [5]	50[def]	60[def]	60[10]	unitless
Soil water depletion factor for pollination - Upper threshold [5]	0.85[9]	0.90[def]	0.80[10]	unitless
Soil water depletion fraction for stomatal control - Upper threshold [5]	0.6[5,9]	0.6[8]	0.55[10]	unitless
Shape factor for water stress coefficient for canopy expansion	3[9]	3[8]	4[10]	unitless

Source: (1) Entz et al. (1992); (2) Touré et al. (1995); (3) (Kiniry et al., 1995); (4) (Johnston et al., 2002);(5) Araya et al. (2010); (6) Bennett and Harms (2011); (7) McKenzie et al. (2011); (8) (Zeleke et al., 2011); (9) Abrha et al. (2012); (10) Mkhabela and Bullock (2012); (11) Robertson et al. (2013)

4.2.3.3 Soil

The Agricultural Region of Alberta Soil Inventory Database (AGRASID) version 4.0 provides the latest digital and spatial representation of soil information of the agricultural area in Alberta (AGRASID, 2013). This soil database contains soil landscape polygons as a shapefile with attribute data compiled to a map at scale 1:100,000. Soil surveys began in Alberta in 1920, enabling development of AGRASID to compile all soil information into a digital standard for users. AGRASID 4.0 can be downloaded for free in a geodatabase file format (http://www1.agric.gov.ab.ca/$Department/deptdocs.nsf/All/sag14652). Each polygon can contain up to a maximum of 6 different *PolygonComponents* which requires querying through a series of relationship tables to a soil layers' table (called *SoilLayers*) that includes all the necessary information for input into AquaCrop. The exact location of where the soil samples were taken is not provided in the database. Instead, a percentage of the total area of a particular soil type is provided for each polygon. The soil profiles having produced the highest yields from running the same simulations for all soil profiles within each respected grid are identified in Table *4*-3. The resulting soils are also spatially represented within the

climate grids based on the polygon areas. It is, therefore, considered to be the most representative soil for crop yield simulation purposes. The idea is to focus on reaching the potential maximum yield in the simulations as a best case scenario given the location and climate. Analyzing more soil profiles would benefit the study, however, it would take sufficient data processing and time by adding another dimension to the grid-search calibration algorithm.

Table 4-3 AGRASID 4.0 soil information added into the soil component in AquaCrop

Location and Crop	Horizon	Thickness (m)	SAT (vol %)	FC (vol %)	WP (vol %)	Ksat (mm/day)	Description
Taber: Barley, Wheat	1	0.12	52.8	28.9	15.8	250	Loam
	2	0.08	47.2	29.2	16.5	250	Loam
	3	0.36	47.2	33.3	17.8	150	Silt Loam
	4	0.25	49.1	40.6	22.3	15	Silty Clay
	5	0.79	49.1	39.2	21.7	15	Silty Clay
Taber: Canola	1	0.15	52.8	32.9	19.2	100	Clay Loam
	2	0.14	47.2	32.4	18.8	100	Clay Loam
	3	0.33	43.4	35.5	20.3	250	Loam
	4	0.44	45.3	33.9	19.7	100	Clay Loam
	5	0.34	45.3	33.9	19.7	100	Clay Loam
Pincher Creek: Barley, Canola	1	0.18	52.8	36.4	22.8	250	Loam
	2	0.18	47.2	32.7	19.1	100	Clay Loam
	3	0.38	43.4	35.1	20.2	250	Loam
	4	0.26	45.3	40.4	22.9	100	Clay Loam
Pincher Creek: Wheat	1	0.16	58.5	40.2	26.4	250	Silty Clay
	2	0.14	50.9	47.1	29.1	2	Clay
	3	0.44	50.9	48.2	30.3	2	Clay
	4	0.36	50.9	48.5	30.5	2	Clay

4.3.3.4 Seeding Date

The seeding date is determined by searching the annual temperature time series for five consecutive days with an average temperature above the crop's base

temperature. After the five days are found, the following day is set as the seeding date. The searching process begins on April 1st, because regularly occurring warm winter chinooks (foehn winds) could otherwise falsely implement a seeding date in winter. The search method proves to be quite accurate in determining seeding dates that fall within the optimal seeding dates from mid-April to beginning of May (McKenzie et al., 2011). Harvest dates are linked to the growing cycle and end the simulation on the day that the crop reaches maturity.

4.2.4 Observed Yields

Annual Observed Yields from 1991-2004 were recorded by the crop insurance agency AFSC (Agriculture Financial Services Corporation). Observed yields are recorded as the average yield per quarter section (64.7497 ha). These quarter sections are part of the Canada's Dominion Land Survey system which is commonly used in the agriculture sector (McKercher et al., 1986). Yield measurement errors are unknown. Multiple observed yields may exist within a climate grid for a single year. If this was the case, only the maximum yield was considered, because the AquaCrop simulations are based on optimum growing conditions in relation to the soil profile and climate.

4.2.5 Calibration Methods

Barley crop calibration in the Taber region followed the same procedure as wheat that was mentioned in Chapter 3. This includes using the same soil profile and climate grid that was used for wheat. Canola calibration for Taber is in a different spatial location because of a higher number of observed canola yields were

recorded at that location, so it contains different soil and climate data. Pincher Creek does not have as many observed yields. This provided a challenge for calibrating crops based on low sample sizes. Barley and canola contained an adequate amount of observed yields in one climate grid to preform crop calibration. However, observed wheat yields were scattered across Pincher Creek on an annual basis. Therefore, calibration of wheat from the years 1991-2004 contains multiple soil profiles and climate grids. In total, there will be four climate grids with four different soils used for the 1991 to 2004 calibration. In the Pincher Creek region, the period 1997-2000 was excluded, because no observed crop yield data were available. The 10k climate grid which contained the majority of the observed yields was selected as the base site for further RCM analysis. The locations of the crop simulations site are found in Figure 4-2**.**

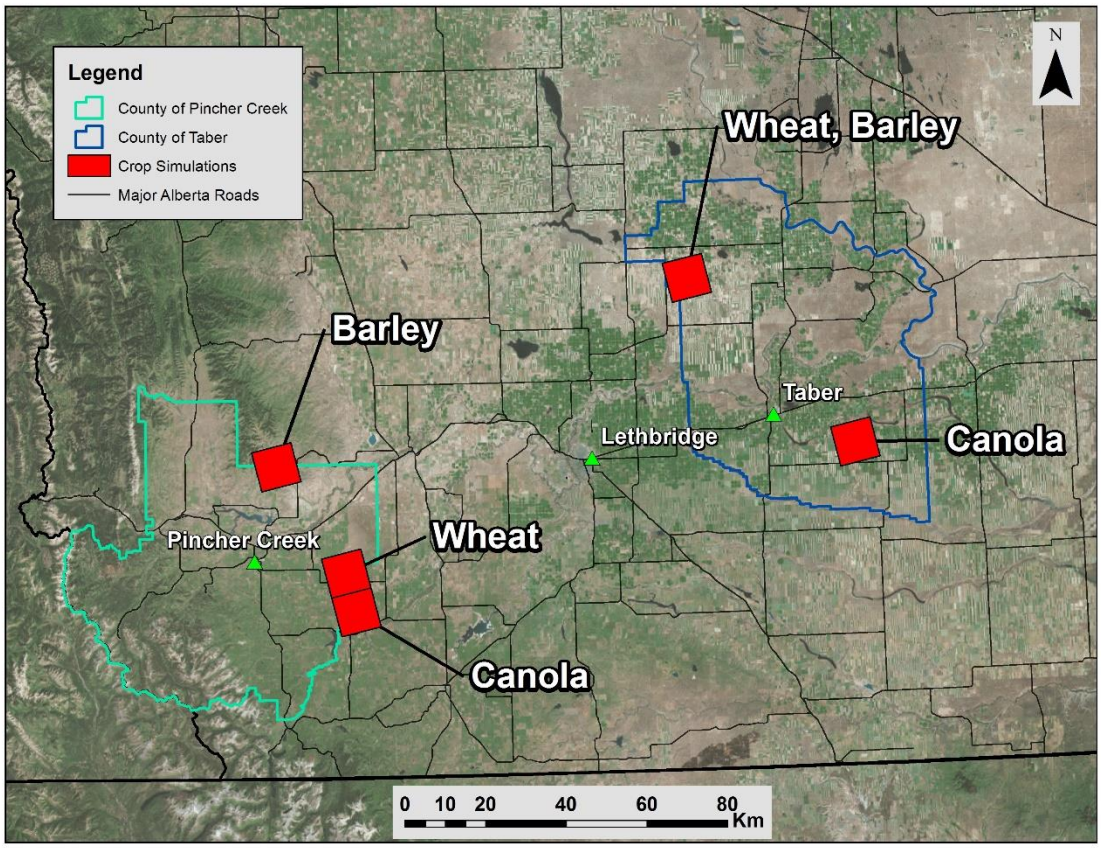


Figure 4-2 Locations of crop calibration for southern Alberta

The final results of the five parameters describing the main crop phenology from the grid search algorithm can be found in Table 4-4. The respective base crop file was constructed with the parameters listed in Table 4-2**.** The beginning of the flowering stage was combined with the maximum rooting depth because evidence has shown that crops slow root down or terminate growth once the flowering stage begins (Canola Council of Canada, "Canola growers manual," 2003; Watt et al., 2013). Each crop calibration was based on 10,584 iterations of AquaCrop simulations and additional 3,125 iterations as a refinement process (see Chapter 3). The final crop parameters (Table 4-4) were based on the lowest RMSE out of all iterations when compared to observed yields.

Table 4-4 Results of the grid search algorithm for barley, canola, and wheat for Taber and Pincher Creek

Region	Crop	Emergence	Max/ Flower	Senescence	Maturity	Length of Flowering	RMSE
Units	Type	GDD from seeding date to:				GDD	Ton /ha
Taber	Barley(1)	90	810	925	1230	170	1.064
	Canola(2)	210	660	975	1320	210	0.431
	Wheat(3)	85	620	750	1100	140	0.432
Pincher Creek	Barley(1)	180	820	750	1360	120	0.429
	Canola(2)	175	660	800	1400	210	0.728
	Wheat(3)	90	480	650	960	140	0.778

(1) Barley: Base Temperature = 2°C, Upper Temperature = 28°C
(2) Canola: Base Temperature = 3°C, Upper Temperature = 29°C
(3) Wheat: Base Temperature = 5°C, Upper Temperature = 35°C

4.2.6 Regional Climate Models (RCMs)

Simulations assessing the impact of climate change on barley, canola, and wheat yields were performed to give a better understanding of the future potential yield in the area. A main problem identified by Barrow and Yu (2005) is the selection of the number of scenarios to use for impact analysis. The Intergovernmental Panel on Climate Change (IPCC) *Task Group on Data and Scenario Support for Impact and Climate Analysis* (TGICA) currently recommends the selection of a range of climate models that will help build a complete picture of the range of future climate variability of a region (Carter et al., 2007). Five models were selected (Table 4-5) following Barrow and Yu (2005): four representing relatively extreme changes in both temperature and precipitation, and one representing median conditions. Three of the five RCMs are based on two Canadian Global Climate Models (GCMs), namely the Coupled Global Circulation Model Version 3 (CGCM3), and the Canadian Earth System Model Version 2 (CanESM2),

both developed by the Canadian Centre for Climate Modelling and Analysis, a division of the Climate Research Branch of Environment Canada, housed at the University of Victoria. Two of the five RCMs are based on Geophysical Fluid Dynamics Laboratory (GFDL), a GCM developed by Princeton University, USA. All of these GCMs, or their earlier versions, have been applied by the IPCC. The general climate differences of each RCM projection are represented in Table 4-6.

Table 4-5 Regional Climate models and their climate description

RCM	Description
RCM3-gfdl	Cooler/drier
RCM3-cgcm3	Cooler/wetter
CRCM-cgcm3	Median
CRCM4_22-canesm2	Warmer/Wetter
HRM3-gfdl	Warmer/Drier

The RCMs with spatial resolutions of 22 to 44 km^2 were downscaled to match the 10 by 10 km^2 climate grids using the delta change method (Hay et al., 2000). Each RCM has two datasets: One historical period ranging from 1971-2000, and one future period ranging from 2041-2070. All future simulations used the AquaCrop's so-called A2-CO_2 file that is based on the IPCC special report emissions scenarios (A2.CO2). The A2 scenario ("business as usual") provides a steady increase of CO_2 concentration throughout the future years (Nakicenovic and Swart, 2000). The RCM time series representing the historical period were calibrated to match the observed gridded climate dataset, and the same calibration was applied to the future dataset. This method has been used widely when studying the impacts of climate change (Semenov and Porter, 1995; Barrow and Yu, 2005; Gobena and

Gan, 2013; Lorite et al., 2013). As the RCMs cannot replicate or project climate for a specific day, the two entire climate periods were compared.

The reference evapotranspiration (ET_o) was calculated by using the RCM weather data of Tmax, Tmin and PPT. The Penman-Monteith method is the recommended formula to calculate ET_o for AquaCrop (Steduto et al., 2009). Historical climate averages of incoming radiation, relative humidity, sunshine hours, and wind speed were used in both time series for all RCMs. Therefore, the only climate differences between RCMs are Tmax, Tmin, and PPT. For the simulation of future wheat yields, the soil characteristics and crop parameter file were the same files found by the grid search calibration procedure. The criterion for the seeding date used was the same dynamic method as described above.

Table 4-6 Climate conditions on a sample grid (barley and wheat in Taber) for historical (H, period 1971-2000) and Future (F, 2041-2070) of five regional climate models for the growing season (April – October)

Variable	RCM3-gfdl		RCM3-cgcm3		CRCM-cgcm3		CRCM4_22-canesm2		HRM3-gfdl	
Time Period	H	F	H	F	H	F	H	F	H	F
Rainfall (mm)	250.5	266.6	250.5	296.2	250.5	271.0	250.5	315.1	250.5	244.1
Rainfall % Difference		6.4		18.2		8.2		25.8		-2.6
Tmax (°C)	19.9	22.2	19.9	22.4	19.9	22.3	20.0	23.5	19.9	23.1
Tmax Difference (°C)		2.3		2.5		2.4		3.5		3.2

Tmin (°C)	5.2	7.0	5.2	7.5	5.2	7.7	5.2	8.5	5.2	7.8
Tmin Difference (°C)		1.8		2.3		2.5		3.3		2.6

4.2.7 Irrigation Management

Raes et al. (2009) indicated that AquaCrop is a useful model for the evaluation of different irrigation strategies. The net irrigation requirement criterion was used to compare against the default conditions used in the local irrigation model, IRM. AquaCrop's irrigation management was set to a net irrigation requirement allowing up to a depletion of 50% of the readily available water (RAW) in the soil as the threshold for irrigation. The same criterion was used in IRM, as it is the default setting used in the model. IRM uses a default fixed planting date of May 1st for cereal and oilseed crops when canal operations are functional. The simplification has been the assumption of a static planting date in southern Alberta, although more recent research has shown higher yield possibilities with earlier planting dates (McKenzie et al., 2011). An AquaCrop irrigation file was made from the output of the IRM model. The IRM module outputs a set time and a fixed amount of irrigated depth based on the irrigation equipment used in that area. Most irrigation systems in southern Alberta are centre pivot systems, representing 70% of the overall systems (Klein et al., 2012). As a result of IRM, the total daily irrigated depth of a pivot system was a fixed at 7.5mm of water. The net irrigation water requirement of AquaCrop (50% is the default), triggers irrigation when the root zone depletion exceeds the set 50% of RAW, and irrigate a small amount of additional water to keep the root zone depletion just above 50% (Raes et al., 2012).

Calibration of irrigated barley, canola, and wheat were performed only in the Taber region. Currently Pincher Creek does not have established irrigation systems in the area so there was an insignificant amount of observed irrigated yields for calibration. The crop parameters were set to the same as rainfed crops (Table 4-2), with the exception that seeding rates and harvest indices were increased. Seeding rates are usually increased for irrigated crop because of reduced water limiting stress (McKenzie et al., 2005). Barley and canola seeding rates were increased to 3,000,000 and 1,200,000 plants/ha respectively. As seeding rate variations between rainfed and irrigated wheat are low McKenzie et al. (2011). Harvest Indices will also increase under improving soil moisture conditions (Kang et al., 2002; Unkovich et al., 2010; Aslam et al., 2014). Barley, canola, and wheat harvest indices were set to 55, 30, and 55% respectively, based on the near maximum harvest indices found by Unkovich et al. (2010). Results of the irrigated crop phenology parameters from increasing both the seeding rates and harvest index crop parameters, and running the grid search calibration method are found in Table 4-7.

Table 4-7 Results of the grid search algorithm for irrigated barley, canola, and wheat for Taber

Region	Crop	Emergence	Max/ Flower	Senescence	Maturity	Length of Flowering	RMSE (ton/ ha)
Taber	Barley(1)	80	820	1150	1440	190	1.294
	Canola(2)	110	700	850	1400	145	0.400
	Wheat(3)	70	640	1150	1300	130	0.384

(1) Barley: Base Temperature = 2°C, Upper Temperature = 28°C
(2) Canola: Base Temperature = 3°C, Upper Temperature = 29°C
(3) Wheat: Base Temperature = 5°C, Upper Temperature = 35°C

4.3 Results and Discussion

4.3.1 Crop Calibrated Results

The calibrated results of the grid search algorithm are found in Table 4-8. In Taber, yield RMSE of barley was 1.065 ton/ha, canola was 0.431 ton/ha and wheat was 0.432 ton/ha in Taber. Pincher Creek simulations resulted in a yield RMSE of 0.429 ton/ha for barley, 0.728 ton/ha for canola, and 0.778 ton/ha for wheat. The correlation between simulated and observed yields are found in Figure 4-3. It is important to emphasize that the use of fertilizer is not considered and that AquaCrop does not simulate pests and diseases (Steduto et al., 2009), which can result in larger yield errors. As well, there is no knowledge of extreme weather events such as hail, extreme wind and wild fires that could lower crop yields. These differences could explain some of the over-simulated yields shown in Figures 4-3. For under-simulated results, the observed yields could be achieved on specific farm management strategies that help produce higher yields.

Table 4-8 Statistical comparison between simulated and observed yields for years 1991-2004

Crop	Location	Avg Observed (ton/ha)	Avg Simulated (ton/ha)	RMSE (ton/ha)	# of Annual Observations	R^2
Barley	Taber	3.428	3.184	1.065	14	0.414
	Pincher Creek	1.400	1.400	0.429	13	0.001
Canola	Taber	1.510	1.591	0.431	13	0.568
	Pincher Creek	1.383	1.310	0.728	5	0.018
Wheat	Taber	2.258	2.264	0.432	14	0.565
	Pincher Creek	1.683	1.868	0.777	10	0.053

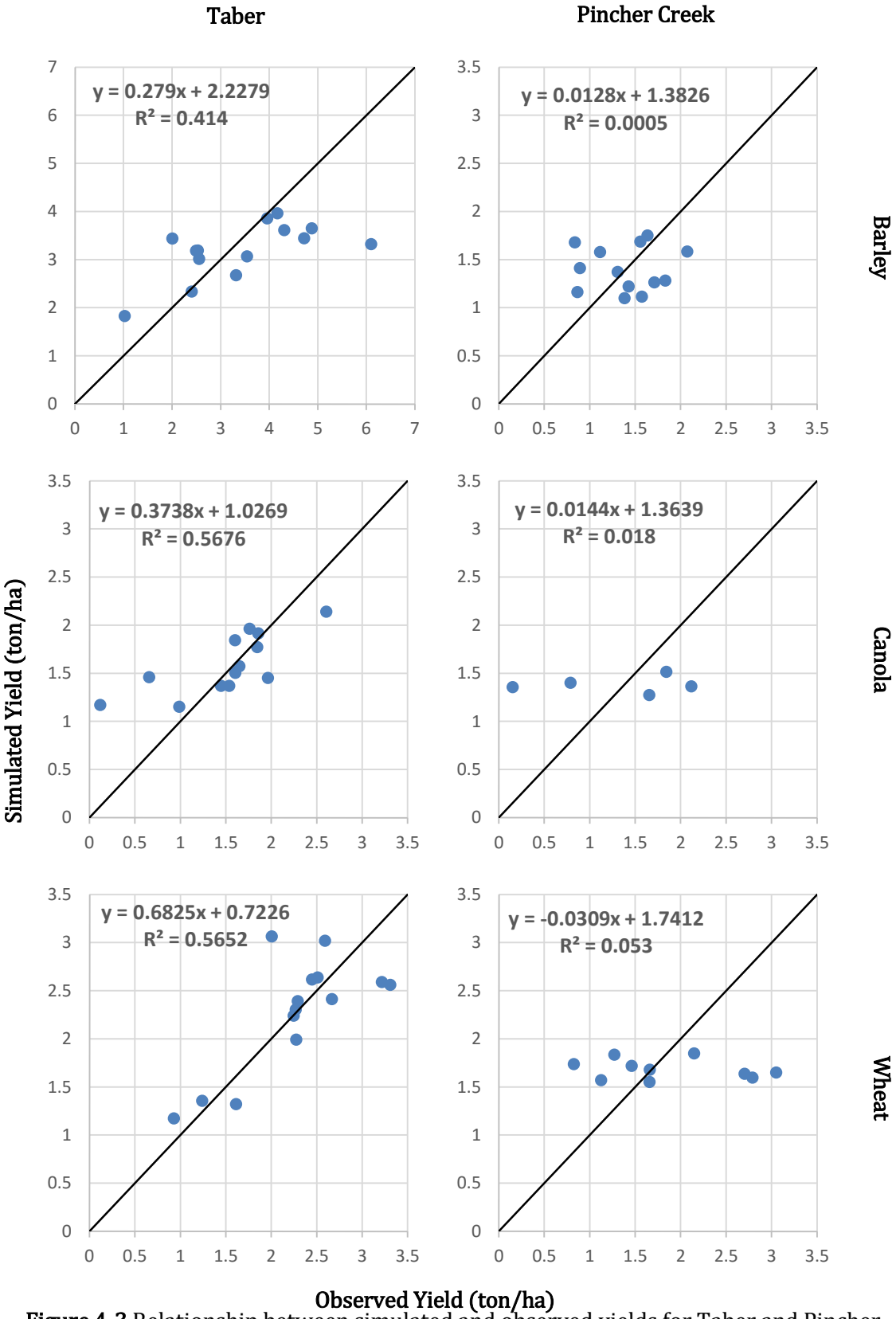


Figure 4-3 Relationship between simulated and observed yields for Taber and Pincher Creek for annual yields from 1991-2004

4.3.1.1 Barley

Despite the implementation of the grid search calibration algorithm, barley simulations in Taber resulted in the highest RMSE error out of all other scenarios. As seen in Figure 4-4, the observed yields of barley in Taber contains a high variability that ranges between 1.021 and 6.097 ton/ha. Using the RMSE as a way to evaluate the crop calibration is perhaps not the most meaningful statistic to use with a high variability of observed values. Willmott and Matsuura (2005) conclude that RMSE is an inappropriate measure of average error and that the mean absolute error (MAE) should be used instead. Regardless, RMSE is still widely used for model performance and results from this study can be easily compared to other studies on evaluations of AquaCrop. Abrha et al. (2012) conducted a validation of AquaCrop on simulating barley in four different countries (Ethiopia, Italy, Syria, USA) and achieved an overall RMSE of 0.340 ton/ha. Araya et al. (2010) simulated barley in Ethiopia and achieved a validation of an RMSE ranging from 0.270 ton/ha to 0.07 ton/ha only for single years. The purposefully chosen conservative parameters based on these studies were used for this calibration (Table 4-2), but may require updates for regions in higher northern latitudes, such as southern Alberta. Although Abrha et al. (2012) had listed one study site from Montana, USA, the field experiment was carried out in 1977, which is outdated. Barley in Pincher Creek performed much better with a yield RMSE of 0.439 ton/ha, indicating that the crop parameters used performed better for the cooler and wetter climate. Although the yield variability was significantly lower in Pincher Creek compared to Taber, which may indicate some uncertainties with the observed yield data for the Taber region.

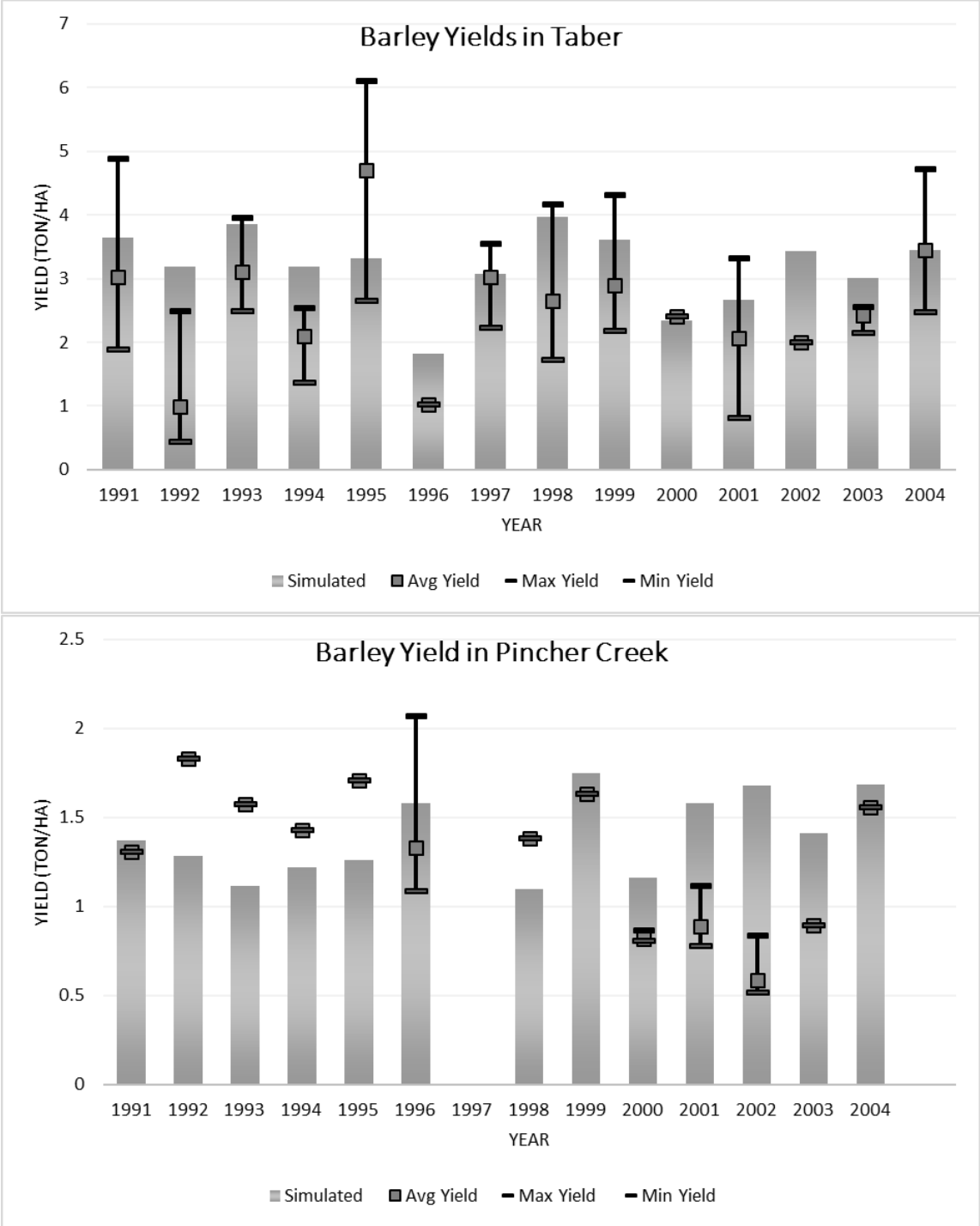
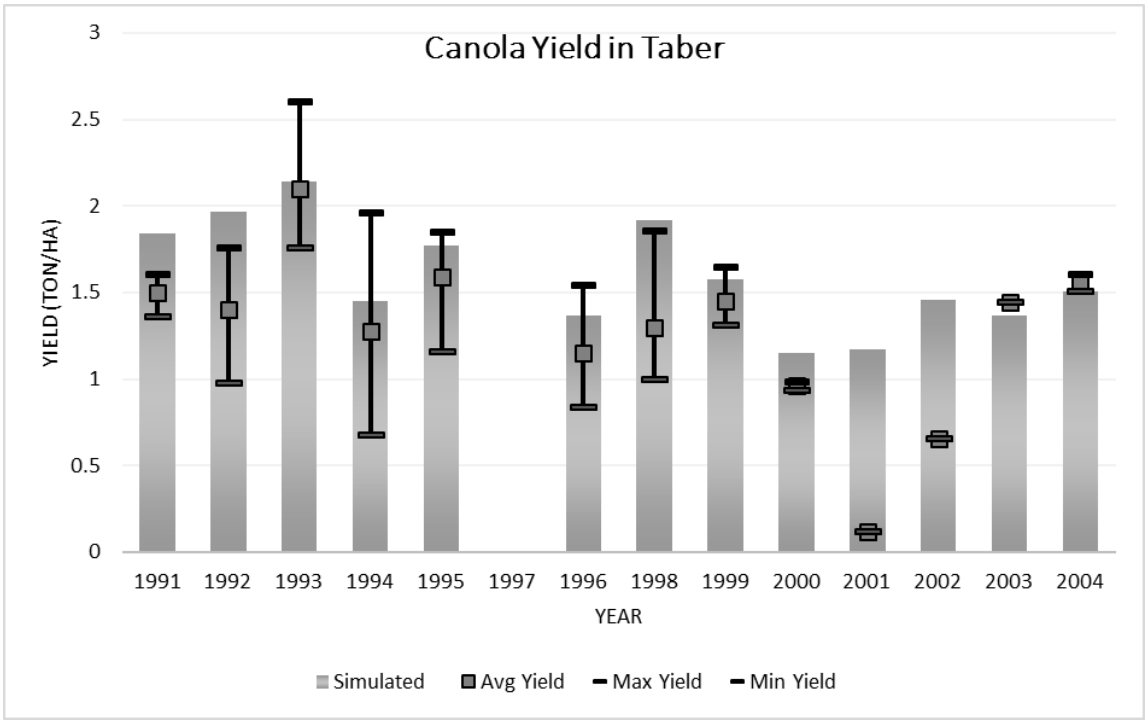


Figure 4-4 Comparison of barley yields between the calibrated output and the observed yields from AFSC

4.3.1.2 Canola

Canola does not contain a default crop file in the current version of AquaCrop 4.0 (Raes et al., 2012), which made it difficult to parameterize. The crop parameters used in this study were based on parameters used by Zeleke et al. (2011), who calibrated canola in Australia with AquaCrop. Zeleke et al. (2011) concluded that AquaCrop provided a good agreement of simulating grain yield but was less satisfactory in simulating yield under severe water stress conditions. In this study, AquaCrop canola simulations provided a reasonable low RMSE of 0.4312 ton/ha for Taber and 0.7275 ton/ha for Pincher Creek (Figure 4-5). Results from the Taber region provided comparative results from an older study by Kiniry et al. (1995), who used the EPIC crop model to achieve a yield RMSE of 0.4123 ton/ha. Pincher Creek simulations were limited to five years of data for calibration because of the lack of observed yields in the region. More data would be necessary for increasing the model validation for canola yields in Pincher Creek. Results from this study also agree with conclusions reached by Zeleke et al. (2011), that AquaCrop over-simulates canola under severe water stress. AquaCrop simulations of canola yields under the known drought years, 2001 and 2002 (Wheaton et al., 2008), over-simulated yield considerably compared to the observed yield. In agreement with Zeleke et al. (2011), more development of standardized conservative crop parameters for canola is required for AquaCrop under different environmental and management conditions.



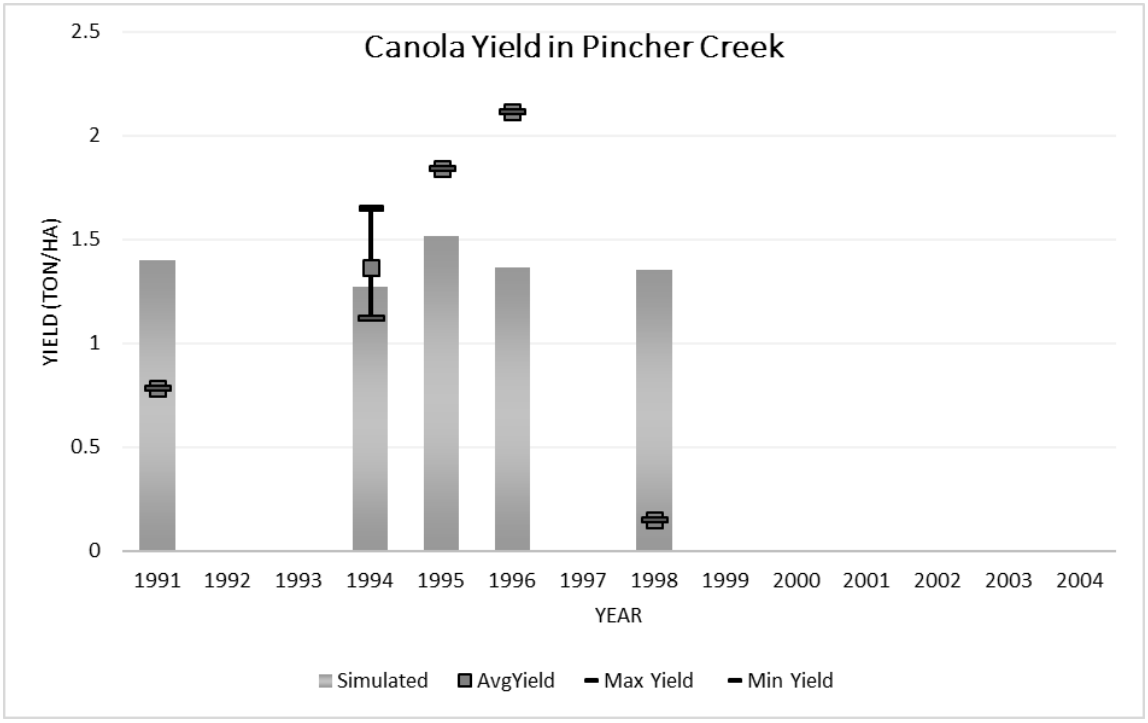
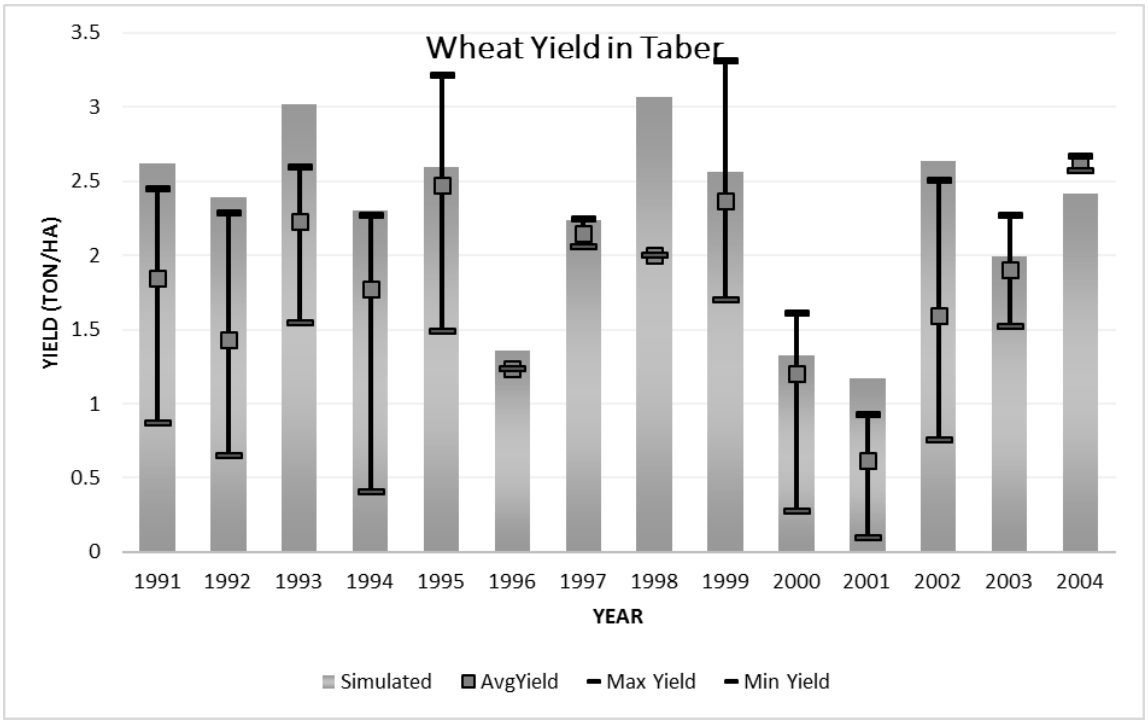


Figure 4-5 Comparison of canola yields between the calibrated output and the observed yields from AFSC

4.3.1.3 Wheat

The final result of wheat crop parameters provided realistic simulations of yield (Figure 4-6). Wheat yield RMSE of Taber was 0.4320 ton/ha which compared well to nearby experiments in Manitoba and Saskatchewan by Mkhabela and Bullock (2012), who achieved yield RMSE of 0.7434 ton/ha. However, the model runs in the Pincher Creek region were less satisfactory in simulating wheat yields, because of the spatial scatter of different climate grids and using different soil profiles. Nonetheless, Pincher Creek wheat simulations resulted in a reasonable yield RMSE of 0.7768 ton/ha for determining average long-term average yields but struggled with the yield variability on an annual basis that resulted in a low R^2 of 0.053 (Figure 4-3). The colder growing season in the Pincher Creek region may benefit for more focus on winter wheat, instead of spring wheat which has a lower base crop temperature of 0°C (Xiangxiang et al., 2013). The correlation between simulated and observed yields resulted in the Taber region performed better with a moderate R^2 of 0.565.



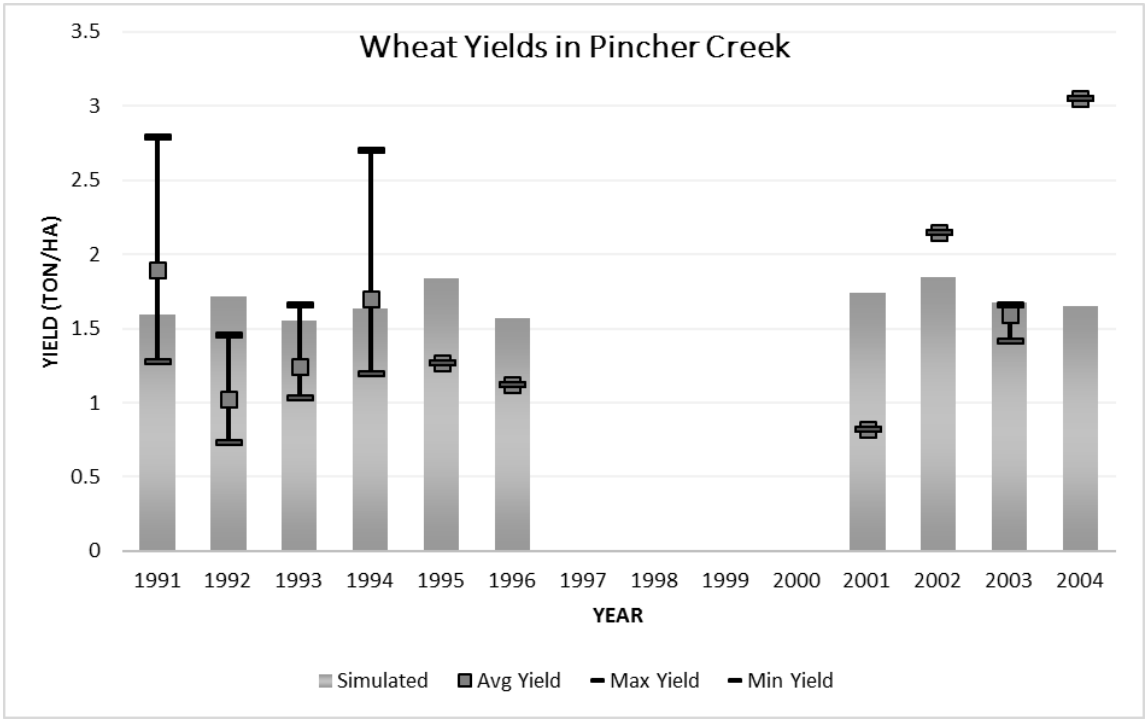


Figure 4-6 Comparison of canola yields between the calibrated output and the observed yields from AFSC

4.3.2 RCM Analysis

4.3.2.1 Barley

Future climate projections of simulated barley yield provided estimates that differ between the Taber and Pincher Creek regions (Figure 4-7). Based on the overall projections of the RCMs, barley yield is expected to increase in both regions. Significantly more in the Taber region, with a maximum increase of 71.3% from the CRCM4_22-canesm2 model and a minimum increase of 33.5% from the RCM3-gfdl model. The Pincher Creek results were lower with a maximum increase of 36.3% from the CRCM-cgcm3, and a minimum increase of 25.1 % from the HRM3-gfdl model. The yield results vary quite a bit between the regions and the models, indicating a greater uncertainty in future barley production. Without the effect of the CO_2 fertilization, all barley yields would decline in Pincher Creek and only two of the five models (CRCM4_22-canesm2 and RCM3-cgcm3) indicated positive average yield increases of 18.3% and 10.3% (Table 4-9). Future climate projections of barley yields were predicted to decrease, based on another study in eastern Atlantic Canada by Bootsma et al. (2005), but their study excluded the increased atmospheric CO_2 concentrations.

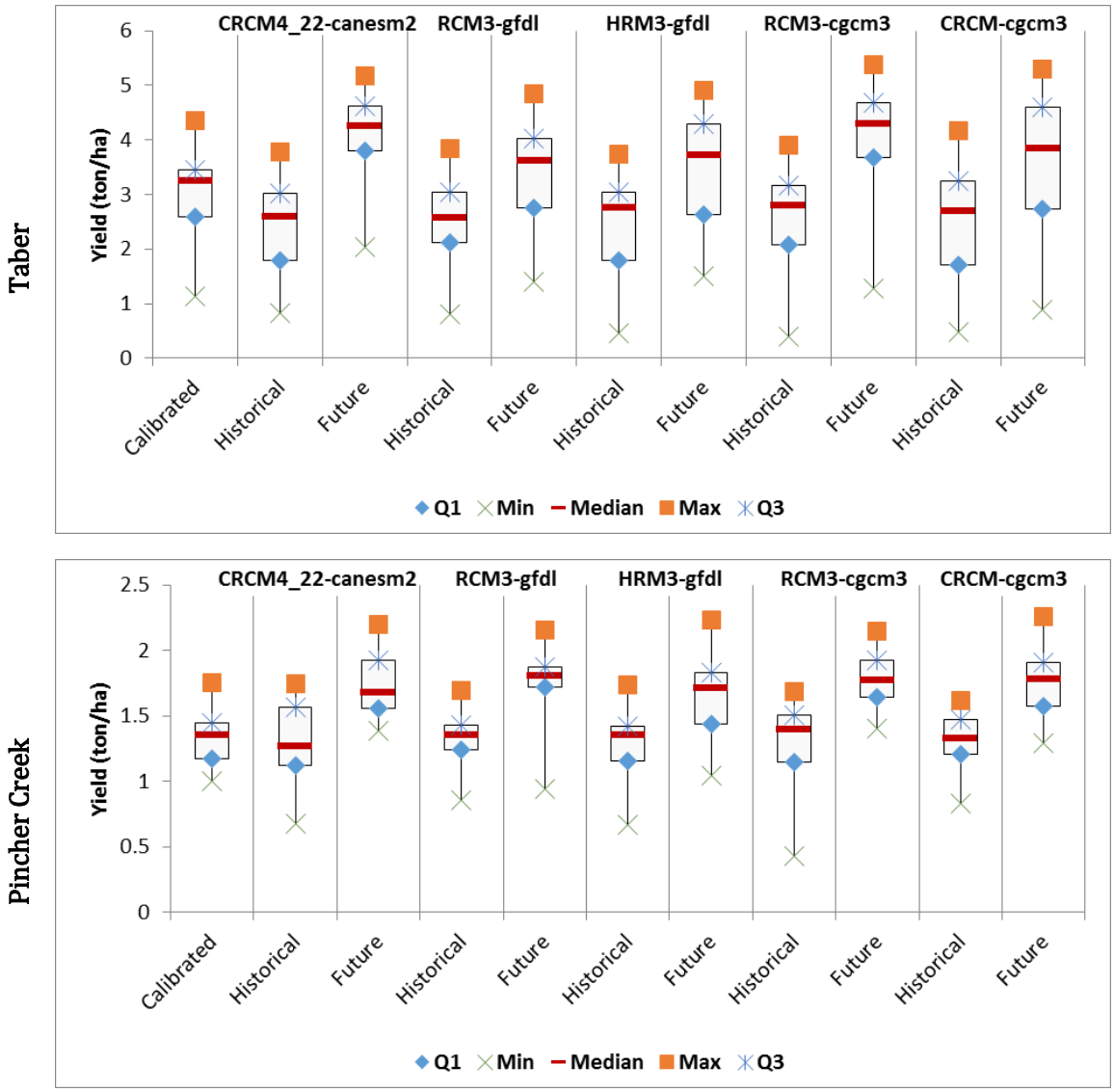
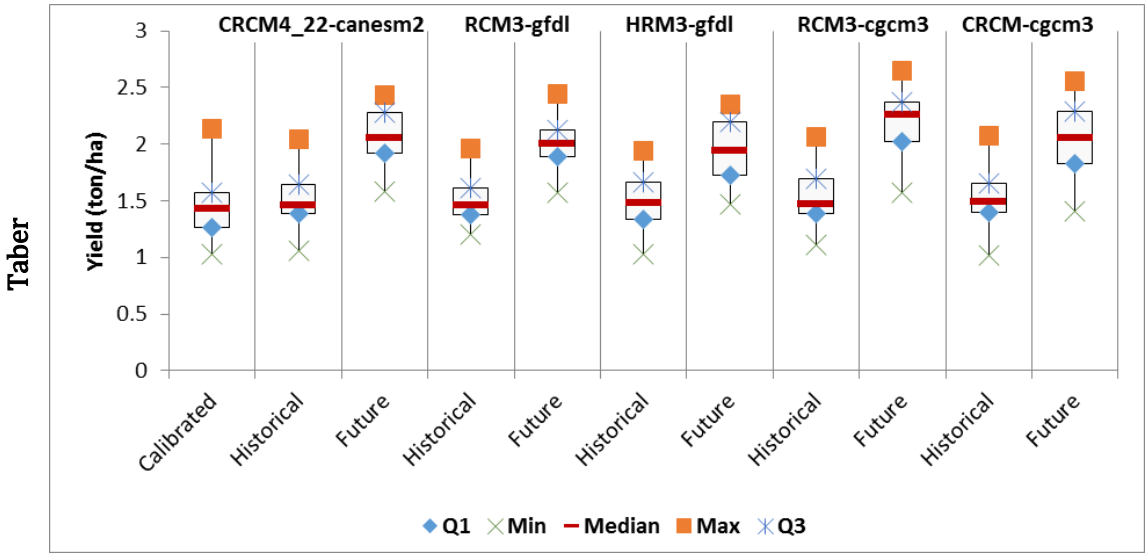


Figure 4-7 Barley yield (ton/ha) comparison between simulations of the calibrated dataset and the five RCMs of the historical and future time series. Top is in Taber and bottom is in Pincher Creek. Q1 is the 25th percent quartile, Q3 is the 75th percent quartile that represent the distribution of barley yield

4.3.2.2 Canola

Future projections of canola yields for both Taber and Pincher Creek shared similar results in terms of RCM rankings based on the percentages of increasing yields (Figure 4-8). The RCM3-cgcm3 model projected the highest increases of canola yields, 44.5% for Taber and 34.5% for Pincher Creel. The lowest increases of

projected canola yield were the HRM3-gfdl RCM, with increased yields of 30.2% Taber, and 23.7% in Pincher Creek. As canola is sensitive to higher temperatures (Qaderi et al., 2006; Robertson et al., 2013), the "cooler and wetter" projection provided the highest yield, rather than the CRCM4_22-canesm2, which is expected to be the more favorable "warmer and wetter" climate as seen with barley in Taber and wheat for both regions in this study. Qaderi et al. (2006) indicated that higher temperatures and droughts are harmful for canola yields but with elevated CO_2 concentrations may help mitigate some of the negative climate change effects. Without the CO_2 fertilization effect, only the RCM3-cgcm3 projection in the Taber region would show signs of increasing yields. All other future projections without CO_2 fertilization indicated a decrease in canola yields in both the Taber and Pincher Creek region.



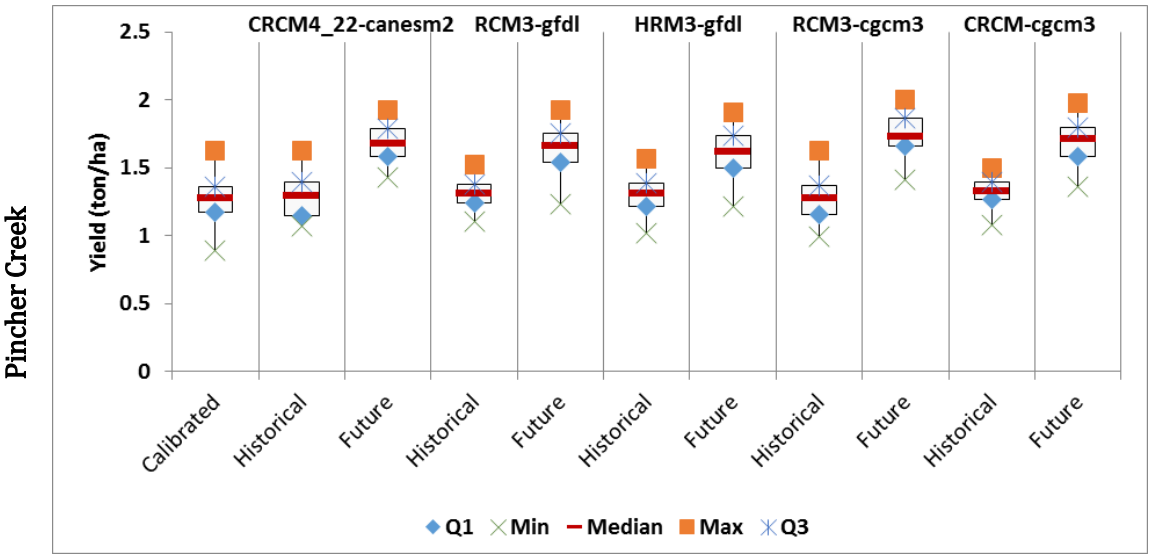


Figure 4-8 Canola yield (ton/ha) comparison between simulations of the calibrated dataset and the five RCMs of the historical and future time series. Top is in Taber and bottom is in Pincher Creek. Q1 is the 25th percent quartile, Q3 is the 75th percent quartile that represent the distribution of canola yield.

4.3.2.3 Wheat

Wheat was simulated to undergo the greatest potential increase of yield with increases of 88.0% in Taber and 80.1% in Pincher Creek from the CRCM4_22-canesm2 RCM (Figure 4-9). The lowest potential increase was still a highly positive yield increase of 42.6% in Taber, and 43.8% in Pincher Creek. Both regions shared very similar results of projected wheat yields (Table 4-9). Only RCM3-gfdl, without CO_2 increases, resulted in yield decrease of -4.5% and -3.7% for Taber and Pincher Creek respectively. Positive effects of climate change on wheat yields in the Canadian Prairies has been widely reported (Brklacich and Stewart, 1995; McGinn and Shepherd, 2003; He et al., 2012). However, this is not the case for other regions, such as Australia, where Luo et al. (2005) stated that climate change impacts would have negative effects on Australian wheat yields and were projected to decrease.

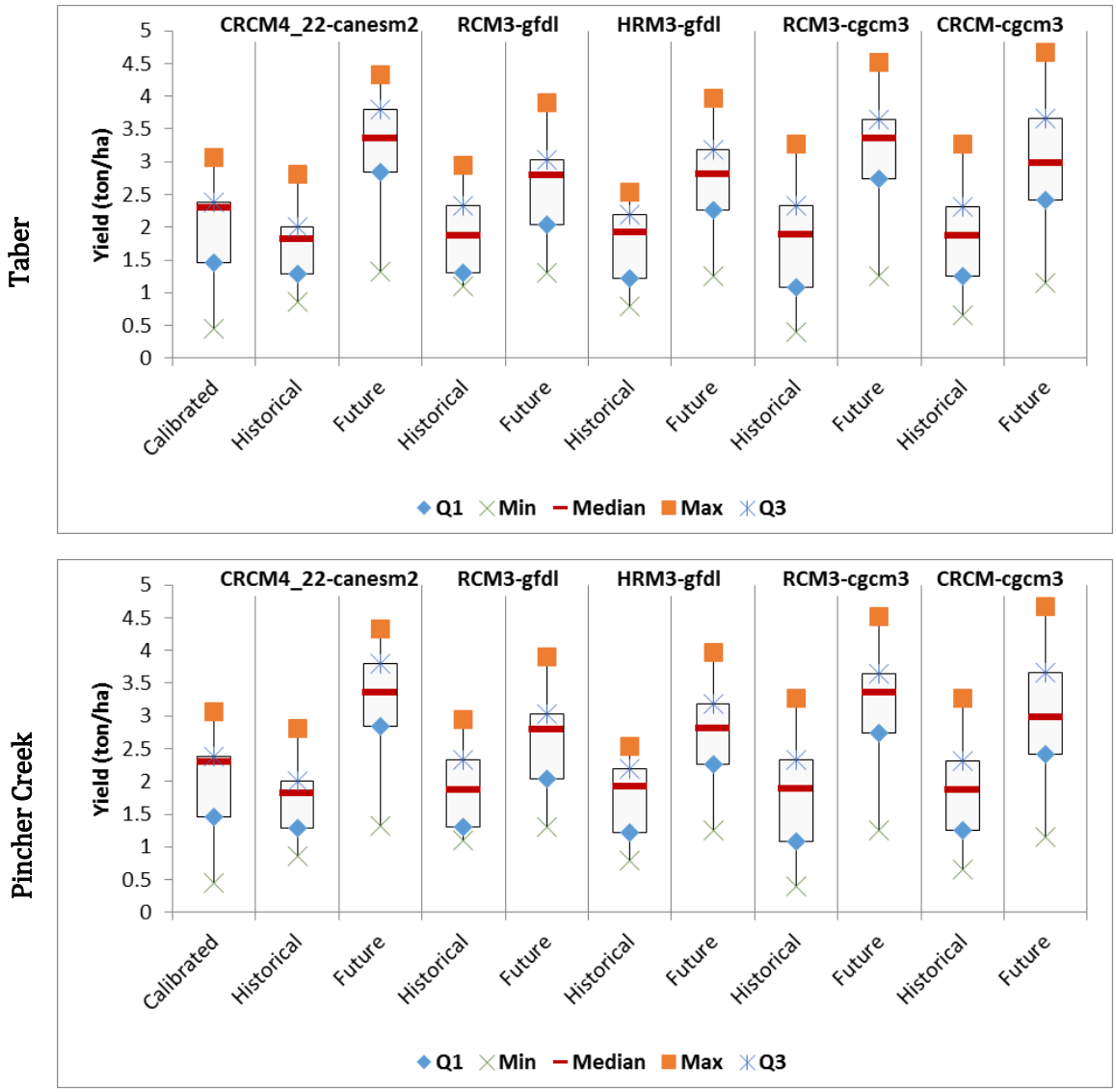


Figure 4-9 Wheat yield (ton/ha) comparison between simulations of the calibrated dataset and the five RCMs of the historical and future time series. Top is in Taber and bottom is in Pincher Creek. Q1 is the 25th percent quartile, Q3 is the 75th percent quartile that represent the distribution of wheat yield.

4.3.3 RCM Discussion

The "warmer and wetter" scenario was expected to result in the largest yield increase, because it is associated with more GDDs in the growing season, which the model used to determine the crop development and phenology (Raes et al., 2009). The addition of a wetter environment results in less water-limited stress

on the crop, which should enable higher yields. However, barley in Pincher Creek and canola for both regions did not have this outcome (Table 4-9). The "cooler and drier" scenario is affected by the conditions previously mentioned, but an associated shorter number of GDDs and more water limitations were expected to provide the lowest increases, or even decreases, of crop yield. Projections of barley in Pincher Creek, and canola in both regions, the "warmer and drier" RCM resulted in the lowest increases of yield. The overall mean yields of all RCMs are projecting yield increases in the future. The variability between the minimum and maximum yields is generally higher during the future simulation period than in the historical one.

Based on the AquaCrop simulations with the increased CO_2 concentrations, crop yields of barley, canola, and wheat can be positively viewed, with climate change impacts increasing potential yields in southern Alberta. An additional simulation was performed by matching the same CO_2 input for both historical and future time series. Without the effect of a CO_2 fertilization, crop yields are drastically lower and some show potential of decreasing (Table 4-9). AquaCrop simulations of barley, canola and wheat yields are strongly impacted by the effect of a CO_2 fertilization causing yields to increase up to 50% for wheat yields and barley yields in Taber, roughly 30% for canola yields in both regions and barley yields in Pincher Creek, based on the elevated A2 CO_2 scenario for the 2041-2070 climate period. The results indicate encouraging possibilities of future climate change impacts for agriculture production with increased atmospheric CO_2 concentrations in southern Alberta.

Table 4-9 Simulated crop comparison between the history and future time series of all five different RCMs.

RCM	Barley (T)		Barley (PC)		Canola (T)		Canola (PC)		Wheat (T)		Wheat (PC)	
	Yield Difference Between Historical and Future RCMs (%)											
CO_2 Scenario	A2	None	A2	None	A2	None	A2	None	A2	None	A2	None
Warmer - Wetter	71.3	18.3	30.9	-4.5	37.1	-1.3	29.9	-5.1	88.0	30.1	90.1	24.3
Cooler-Wetter	61.2	10.3	35.8	-0.3	44.5	4.2	34.5	-1.7	74.6	19.4	79.1	22.3
Median	47.4	-0.4	36.3	-1.5	35.3	-3.1	29.1	-6.0	60.5	9.2	59.7	8.9
Warmer - Drier	42.3	-5.3	25.1	-11.0	30.2	-6.8	23.7	-10.3	55.5	5.0	51.6	2.8
Cooler-Drier	33.5	-12.7	36.0	-2.1	31.7	-5.9	25.5	-8.9	42.6	-4.5	43.8	-3.7

4.3.4 Uncertainties and limitations on the impacts of climate change on agriculture

It is predicted in the literature that above-ground biomass will increase with elevated CO_2 levels (Ainsworth and Long, 2005; Raines, 2011; Vanuytrecht et al., 2011). The high yields in all five RCMs can be explained by an effect of a CO_2 fertilization which there is much uncertainty in crop predictions (Kulshreshtha, 2011; Raines, 2011; White et al., 2011; Asseng et al., 2013). The AquaCrop model was known to overestimate yields under conditions of elevated CO_2 (Vanuytrecht et al., 2011), compared to FACE experiments (Ainsworth and Long, 2005). This led to the development on a new crop parameter to lower the response of the water productivity to elevated CO_2 concentrations in AquaCrop 4.0. The added sink

strength parameter lowers yields from elevated CO_2 concentrations, resulting in a possible change of simulated yield by up to 27% (Vanuytrecht et al., 2011). Lowering results from this study by 27% would still show benefits of increased yields of barely, canola, and wheat for Taber and Pincher Creek among the five RCMs, with the exception of barley and canola in Pincher Creek. It is worth noting that the CO_2 scenarios contain uncertainties as well, and the AquaCrop's A2 emissions scenario is now outdated and could benefit from being updated to the Representative Concentration Pathways (RCPs) that are now being used and are recommended to replace SRES emission scenarios for climate change impact studies (Meinshausen et al., 2011; Deryng et al., 2014).

This study was limited to five RCMs and the use of one crop model (AquaCrop) for predicting crop yields in southern Alberta. There has been a growing interest and recommendations in using larger multi-model ensembles for impacts of climate change on agriculture production (Pierce et al., 2009; Semenov and Stratonovitch, 2010; Asseng et al., 2013; Deryng et al., 2014). This study would benefit from the use of more than one crop model and additional RCM projections to provide a deeper understanding of the uncertainties in crop predictions in southern Alberta. Vanuytrecht et al. (2015) recommend using both RCMs and GCMs for assessments of climate change for crop production because using RCMs derived from GCMs alone would not give the full range of possibilities.

Other important factors, such as extreme climate conditions and pests, diseases, weeds and nutrient management, were not included in this study.

Increased frequencies of extreme climatic events such as droughts, floods, wild fires and wind erosion are very plausible in the future, and are expected to provide great challenges for future agriculture production (Burton and Lim, 2005; Fraisse et al., 2006; PaiMazumder et al., 2013; Gizaw and Gan, 2015). Higher temperatures can provide an increased possibility of over-winter survival of many pests, weeds and diseases that can effect crop yields (McGinn and Shepherd, 2003). Sudden surges of extreme heat shock could potentially become more frequent (He et al., 2012), and potentially damage crops, resulting in lower yields. It is important to consider these uncertainties of future climate change impacts on crop yields and more research is necessary to fully understand the positive and negative risks in future crop production.

4.3.5 Assessment of climate change impacts on irrigated crops in Taber and comparison of irrigation models

The irrigated crop results of the grid search algorithm are found in Table 4-10. In Taber yield RMSE of barley was 1.100 ton/ha, canola was 0.400 ton/ha and wheat was 0.384 ton/ha. The correlation between simulated and observed yields are found in Figure 4-10. As expected, irrigated crop yields show much less yield variability compared to the rainfed simulations. AquaCrop simulations under-estimated yields for all the crops in Taber. This could be an indication of the unrealistic use of an irrigation schedule set by the default conditions of AquaCrop.

Table 4-10 Statistical comparison between simulated and observed irrigated yields for years 1991-2004 in Taber

Crop	Avg Observed (ton/ha)	Avg Simulated (ton/ha)	RMSE (ton/ha)	# of Annual Observations	R^2
Barley	6.384	5.602	1.100	12	0.010
Canola	2.416	2.280	0.400	10	0.196
Wheat	5.666	5.424	0.384	6	0.435

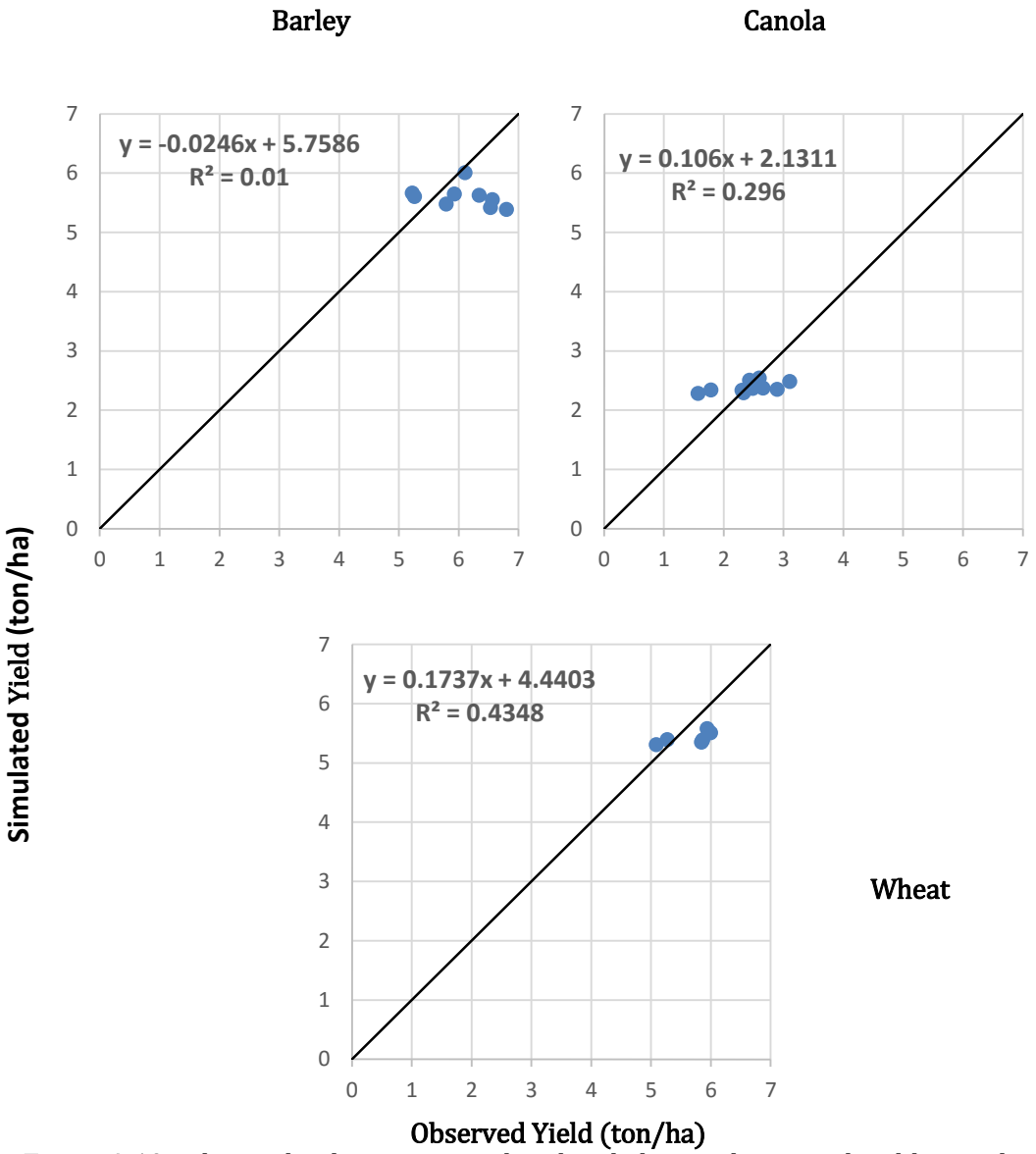


Figure 4-10 Relationship between simulated and observed irrigated yields in Taber for annual yields from 1991-2004.

4.3.5.1 Barley

Irrigated barley was simulated to have the greatest yield RMSE of 1.10 ton/ha. The grid search calibration algorithm did not result in crop parameters combinations that enabled AquaCrop to simulate high yields (Figure 4-11). Results from this study may indicate a need to update the barley crop parameters used here to achieve better yield simulations. Araya et al. (2010) were able to simulate

irrigated barley in semi-arid regions of Ethiopia with much better results. It should be noted that the variability between observed yields is quite large between the minimum and maximum yields, which may be explained by different irrigation techniques used by different farmers.

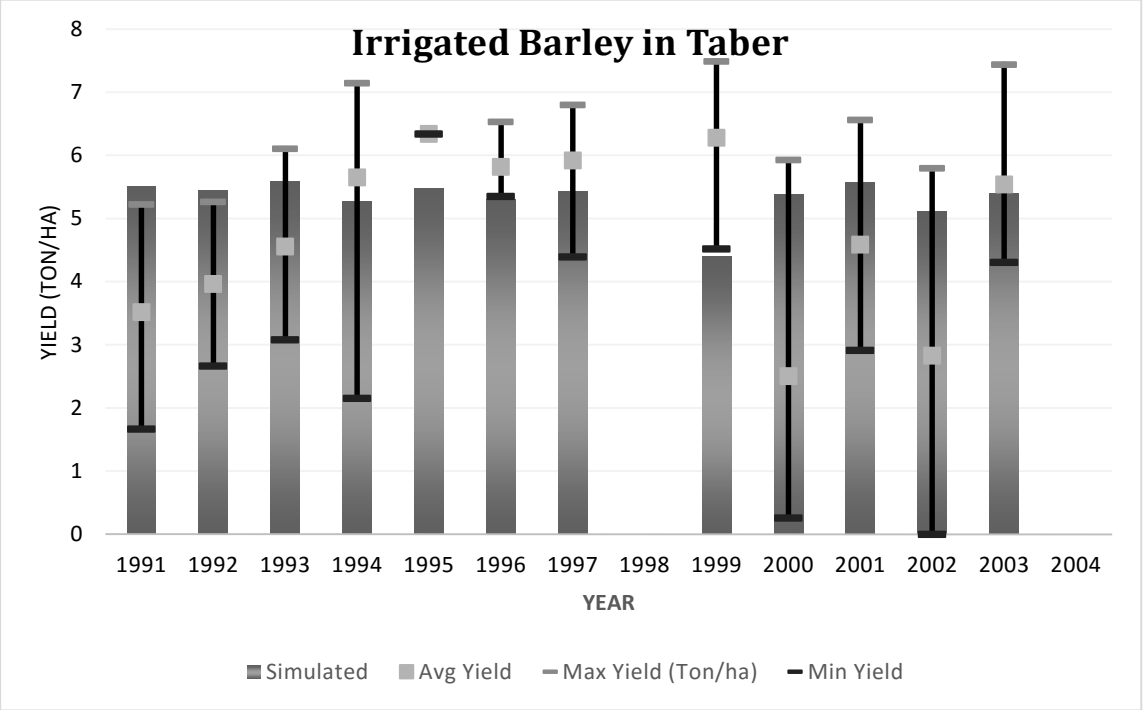


Figure 4-11 Comparison of barley yields between the calibrated output and the observed yields from AFSC.

4.3.5.2 Canola

Irrigated Canola yields were simulated with a reasonable RMSE of 0.400 ton/ha (Figure 4-12). The observed yields contained much lower variability between minimum and maximum values. Without provision of a default crop file by AquaCrop, only Zeleke et al. (2011) used AquaCrop for simulating rainfed canola, and currently no other studies exist for using AquaCrop for simulating irrigated canola.

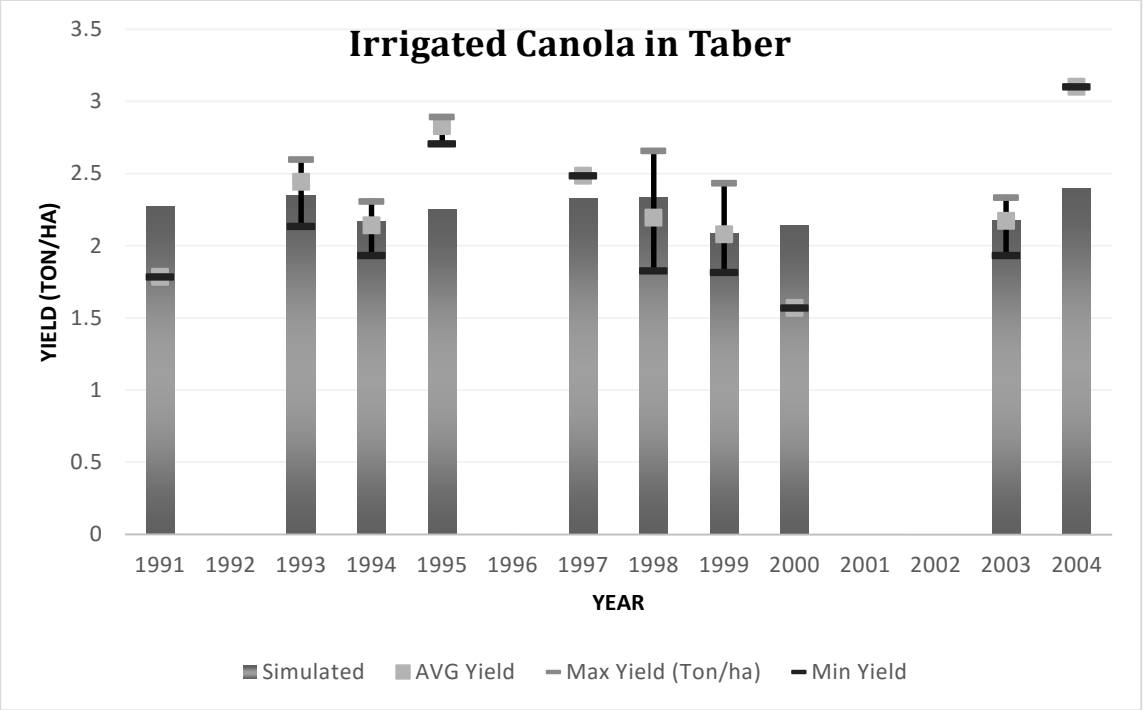


Figure 4-12 Comparison of canola yields between the calibrated output and the observed yields from AFSC.

4.3.5.3 Wheat

Simulations of irrigated wheat yields performed the best with an RMSE of 0.384 ton/ha (Figure 4-13). However, only six observed yields were used for the crop calibration, as other years provided unreasonable or missing observed values. AquaCrop has been used extensively for irrigated wheat studies (Xiangxiang et al., 2013; Iqbal et al., 2014; Kumar et al., 2014). Results from this study compared fairly well with simulations of irrigate winter wheat in China, achieving estimate yield RMSEs ranging from 0.50 to 1.44 ton/ha (Xiangxiang et al., 2013), 0.580 ton/ha (Iqbal et al., 2014), and Andarzian et al. (2011) achieved a low RMSE of 0.270 ton/ha.

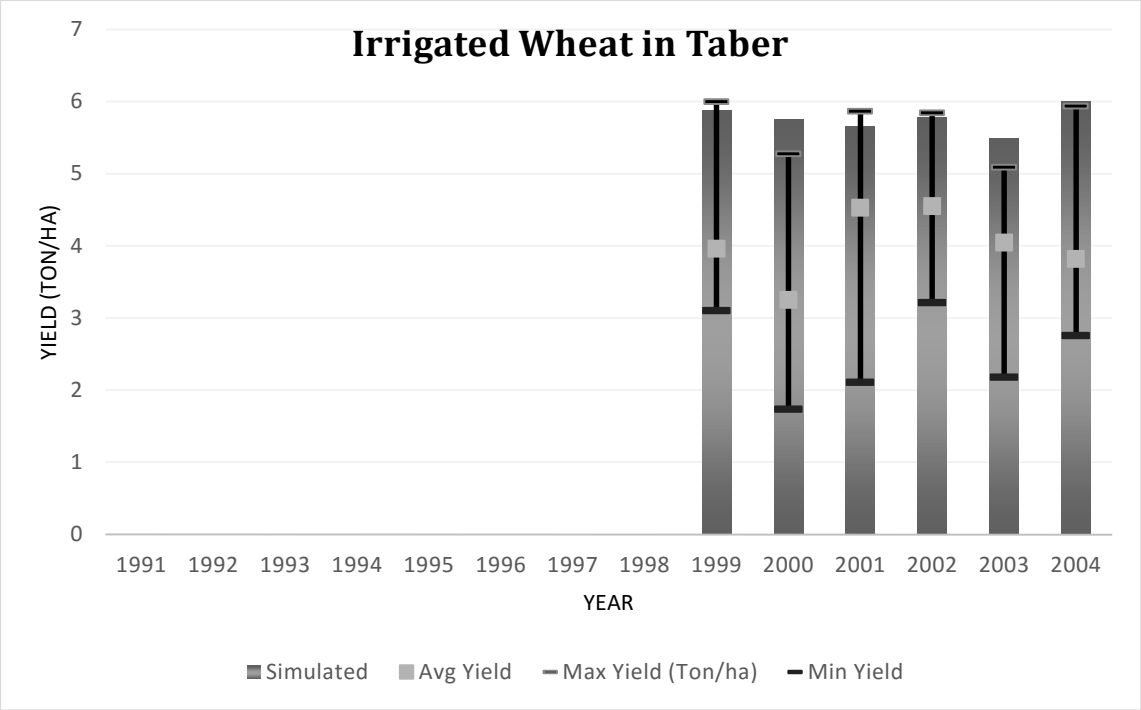


Figure 4-13 Comparison of wheat yields between the calibrated output and the observed yields from AFSC.

4.3.5.4 RCM analysis

In Taber, all five RCMs resulted in projected yield increases for irrigated barley (23-31%), canola (23-30%) and wheat (23-31%) (Figure 4-13 to 4-16). The "cooler and wetter" RCM resulted in the highest projected increase, while the "warmer and wetter" RCM provided the lowest increases. The CO_2 fertilization effect was lower than under rainfed conditions, with roughly 30% in yield increases (Table 4-11). However, without the effect of CO_2 fertilization all the yields decreased.

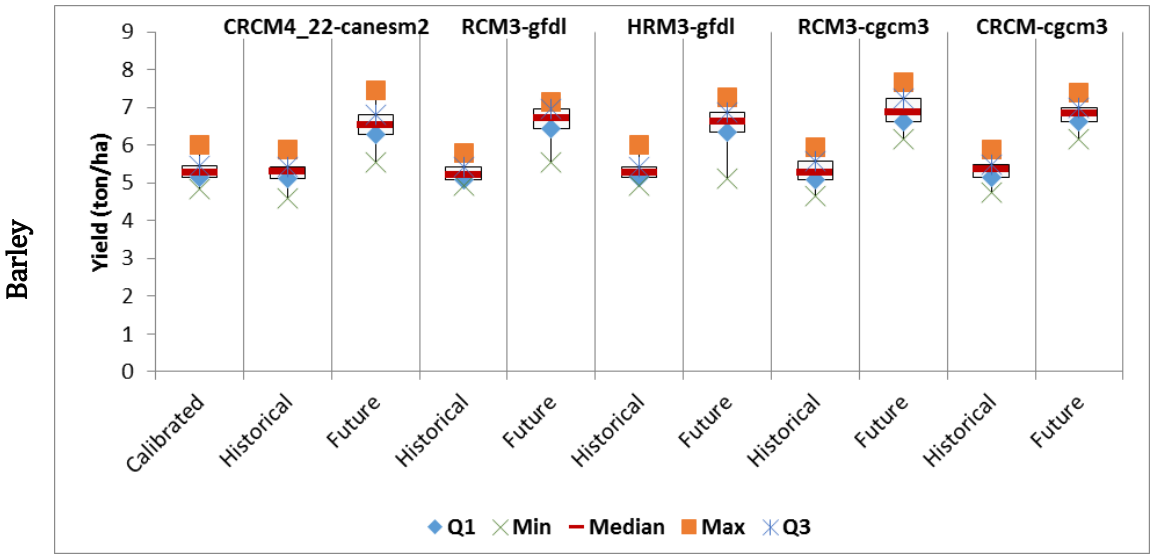


Figure 4-14 Irrigated barley yield (ton/ha) comparison between simulations of the calibrated dataset and the five RCMs of the historical and future time series. Q1 is the 25th percent quartile, Q3 is the 75th percent quartile that represent the distribution of wheat yield

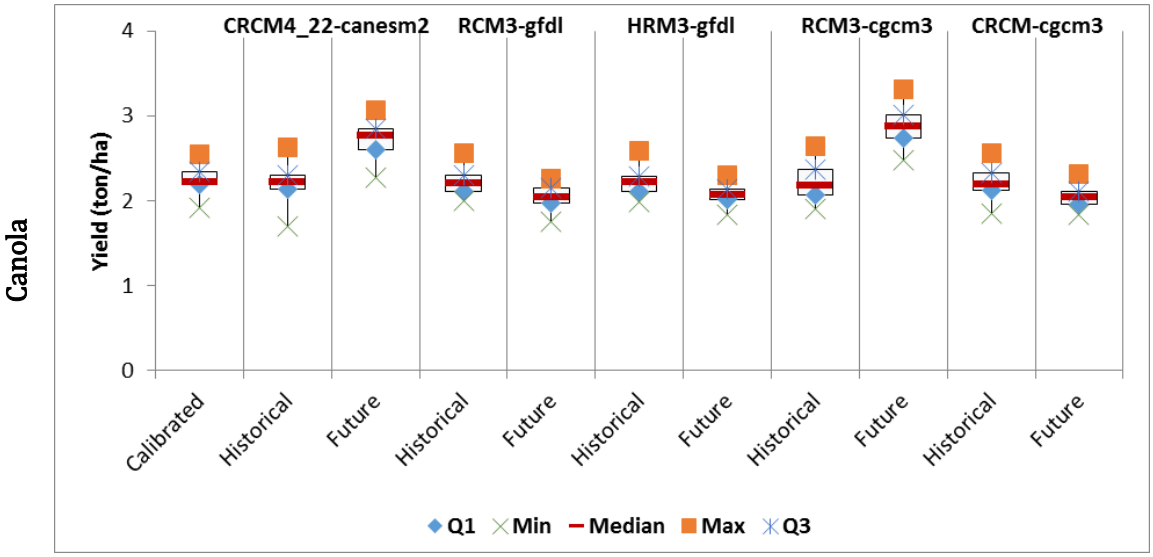


Figure 4-15 Irrigated canola yield (ton/ha) comparison between simulations of the calibrated dataset and the five RCMs of the historical and future time series. Q1 is the 25th percent quartile, Q3 is the 75th percent quartile that represent the distribution of wheat yield.

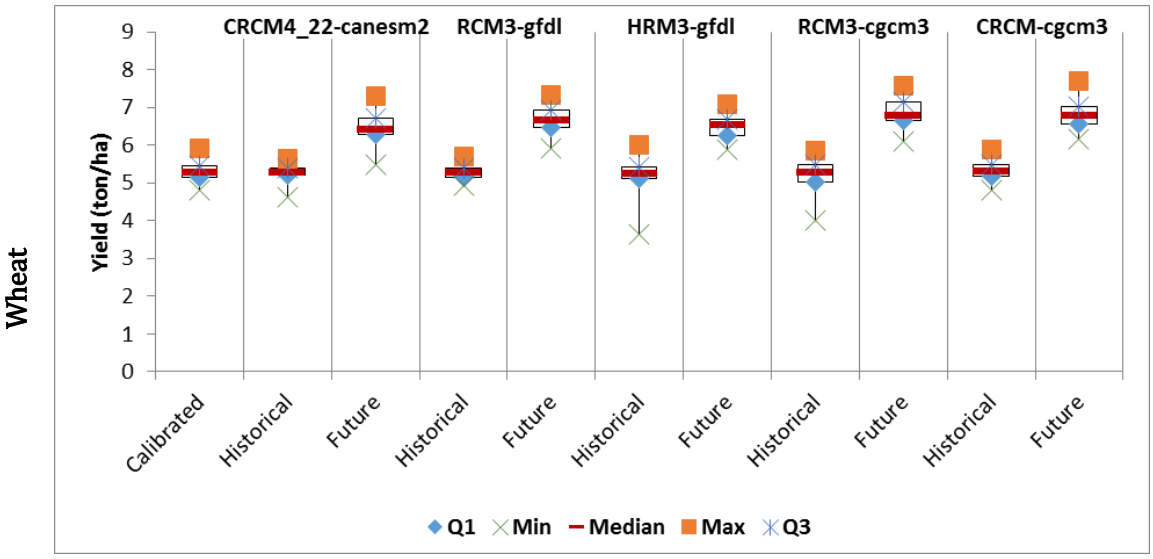


Figure 4-16 Irrigated wheat yield (ton/ha) comparison between simulations of the calibrated dataset and the five RCMs of the historical and future time series. Q1 is the 25th percent quartile, Q3 is the 75th percent quartile that represent the distribution of wheat yield.

Table 4-11 Simulated irrigated crop comparison between the history and future time series of all five different RCMs.

RCM	Barley (T)		Canola (T)		Wheat (T)	
	Yield Difference Between Historical and Future RCMs (%)					
CO_2 Scenario	A2	None	A2	None	A2	None
Warmer-Wetter	22.5	-10.0	22.7	-9.8	22.7	-9.85
Cooler-Wetter	30.8	-3.88	29.7	-4.7	31.2	-3.6
Median	28.05	-5.89	25.6	-7.7	27.4	-6.4
Warmer-Drier	24.22	-8.7	27.0	-6.6	24.2	-8.7
Cooler-Drier	25.7	-7.6	25.5	-7.8	26.4	-7.1

4.3.5.5 IRM and Default Comparison

The IRM is built for local irrigated conditions in southern Alberta. It follows procedures of water availability through the use of standard starting and closing dates of canal operations used in southern Alberta. Based on the default criteria of a

net requirement of 50% soil water depletion to trigger irrigation, AquaCrop applied much more water to the crops than IRM, based on a totaled of 61 years (1950-2010) of crop simulations (Table 4-12). IRM simulated less water needed for irrigation for all crops, barley (-36.1%), canola (-9.4%), and wheat (-25.3%). More importantly, the water productivity output from IRM was slightly better with increased percentages ranging from 7.5-9.5%. IRM has a built-in database that provides information of the irrigation equipment used that restricted irrigation to only an irrigated depth of 7.5mm, where AquaCrop was not constant and could irrigate less or more, based on the soil root zone depletion. In addition, IRM is set to begin irrigation five days after canal operations start up and not irrigate 14 days before harvest. By focusing on using default conditions for simulations, IRM resulted in a much more efficient use of water, although the average yields were slightly lower. For the increasing demand of water resources in southern Alberta, increasing the WP or raising irrigation efficiencies is critical in meeting future demands (Klein et al., 2012). Detailed outlooks of local irrigated conditions should be incorporated into AquaCrop to improve crop simulations, instead of relying on default settings.

Table 4-12 Comparison of the IRM and default AquaCrop models for simulating crops from 1950-2010 in Taber.

	Sum of Irrigation (mm)			WP (kg/m^3)			Yield (ton/ha)		
Crop	**DEF**	**IRM**	**% Diff**	**DEF**	**IRM**	**%Diff**	**DEF**	**IRM**	**%Diff**
Barley	17182	10976	-36.1	1.021	1.105	8.2	5.064	4.972	-1.8
Canola	13169	11928	-9.4	0.517	0.566	9.5	2.118	2.102	-0.8
Wheat	18735	13992	-25.3	0.734	0.789	7.5	3.793	3.746	-1.2

Conclusion

Based on the overall results of this study, AquaCrop simulations of barley, canola, and wheat yields have the potential to increase in southern Alberta under both rainfed and irrigated conditions. Keeping in mind that the study focused on ideal conditions of simulating the maximum potential yields with the most optimal soil profile for understanding the maximum potential in the distinct areas. Rainfed crops simulated the greatest potential of yields increases, even without the CO_2 fertilization effect boosting yields. Irrigated crop should increase as well, but appear to only truly benefit from the CO_2 fertilization improving the crop water productivity. Rainfed agriculture is still highly dominant in Alberta (AgCanada, 2015), and the enthusiastic results from this study encourage the positive impacts of a warmer climate for creating new opportunities in the agriculture sector (Kulshreshtha, 2011). Especially with the increasing demand for water resources (Klein et al., 2012), the potential for expanding irrigated crops is limited.

By using conservative crop parameters from various areas around the world, and running a grid search calibration algorithm, AquaCrop was able to predict crop yields reasonably for southern Alberta. Barley simulations did not perform as well as canola and wheat. Barley simulations may benefit from updating the crop parameters to local conditions, representing barley cultivars used in southern Alberta. Simulations of canola and wheat yields would also benefit from an updated list of conservative crop parameters to improve the projection of future crop yields. It is important to use the AquaCrop default irrigation settings with caution, because of the overuse amount of water used in simulations. Applying local

practices used in the field can greatly improve the water productivity of irrigated crops.

While the results are progressive, there are many uncertainties and gaps that need to be assessed on the positive and negative impacts of climate change on crop yields. Sunlight plays an important factor in the photosynthesis of a crop (Long et al., 2006; Zhu et al., 2008; Betts et al., 2014), where cloud cover is often neglected or too challenging to relate with climate change scenarios (Andrews et al., 2012). In addition, southern Alberta is susceptible to high winds, which can lead to wind erosion of soils (Burton and Lim, 2005). Other factors such as pests, weeds, and diseases require a better understanding with surface warming having the potential to raise over-winter survival rates (McGinn and Shepherd, 2003; El-Sharkawy, 2011). By including these additional climate parameters and improved knowledge of some risks associated with global warming, a lowering of the uncertainties of future climate impacts on agriculture production can be achieved.

Chapter 5
Summary, Discussion, and Future Considerations

5.1 Summary

This thesis applied the FAO's AquaCrop model to simulate barley, canola, and wheat yield's response to water in southern Alberta. The first objective of this study was to parameterize AquaCrop to local conditions, and to develop automation procedures for improving runtime efficiency. The second objective was to simulate future crop yields based on five Regional Climate Models (RCMs), and evaluate the impacts of climate change on crop production in southern Alberta. The third objective was to make a comparison between AquaCrop's default irrigation settings and a local irrigation model (IRM) for irrigated crops in Taber.

AquaCrop attempts to achieve some balance of simplicity, accuracy, and robustness in crop modelling by using a relatively small number of parameters (Steduto et al., 2009). Use of the AquaCrop model within Canada has been limited to date. Currently the only published research is based on a study by Mkhabela and Bullock (2012), which simulated wheat yields for areas in Saskatchewan and Manitoba.

The first research objective (Chapter 3) was to implement external applications for handling large datasets and automating AquaCrop for parameterizing wheat for southern Alberta. Input data were added to a MySQL database and applications were written in the C# programming language to automatically create input files for AquaCrop. These applications enabled running a grid search calibration algorithm for determining optimal crop parameters based on

observed yields. Over 13,000 simulations of AquaCrop were analyzed in determining the most optimal crop parameters. The final results (Table 3-8 and Figure 3-6) proved to be adequate with a yield RMSE of 0.432 (ton/ha), compared to results of yield RMSE of 0.743 (ton/ha) from Mkhabela and Bullock (2012). After the reasonable parameterization was achieved, an assessment on the impact of climate change on wheat yield was performed based on five RCMs.

The RCMs represent projected climate changes of cooler and drier (CD), cooler and wetter (CW), median (M), warmer and drier (WD), and warmer and wetter (WW) to the future climate period of 2041-2070. All RCMs were also available for the historical period 1971-2000, thus enabling the comparison between future and historical climate periods. Results are considered to be slightly high (Figure 3-8), with simulated potential increases of yield over the entire climate period ranging from 43% (CD) to 88% (WW). These increased yields are caused by a substantial portion of a simulated CO_2 fertilization effect causing a boost in yields by improving the crop water productivity.

The CO_2 fertilization effect on crop yields is an area of uncertainty in future crop yield predictions (Ainsworth and Long, 2005; Leakey, 2009; Vanuytrecht et al., 2011; Justin and David, 2013; Deryng et al., 2014). In order to quantify the effect of CO_2 fertilization, instead of using elevated CO_2 concentrations from the predicted future, the same historical time series of CO_2 concentrations was applied to future simulations. Results still revealed predicted yield increases with only one of the five

RCMs showing a decrease in yield of -4% (CD). The rest of the RCMs ranged from increases of yield between 5% (WD) up to 30% (WW).

Based on these results, wheat yields have a high potential to increase based on future climate conditions with and without increases of CO_2 concentrations from an optimistic view of achieving maximum yields. However, there is still some uncertainty with CO_2 fertilization and other factors such as pests, diseases, or soil salinity that were excluded from this study. Using these automated methods to parameterize wheat for AquaCrop for southern Alberta was helpful for determining optimal crop parameters that can be otherwise difficult to acquire. These methods can be used as a procedure for parameterizing different crops throughout Alberta.

Once it was concluded that the methods were valid for parameterizing wheat for AquaCrop in southern Alberta, the study area was expanded to a region of a cooler and wetter environment than Taber, defined here as the County of Pincher Creek, and in addition to wheat, barley and canola were also analyzed. The grid search calibration performed well for parameterizing all crops in both regions (Table 3-8 and Figure 4-3), in comparison to other evaluation studies of similar crops done with AquaCrop (Araya et al., 2010; Zeleke et al., 2011; Abrha et al., 2012; Mkhabela and Bullock, 2012; Xiangxiang et al., 2013). In Taber, barley yield simulations resulted in a RMSE of 1.065 ton/ha. Barley yield simulations in Pincher Creek performed better with a RMSE of 0.429 ton/ha. Other studies simulating barley with AquaCrop from other regions of the world were able to achieve a yield RMSE of 0.340 (ton/ha) (Abrha et al., 2012) and 0.270 (ton/ha) (Araya et al., 2010).

For simulating canola, the current version of AquaCrop 4.0 did not have a default crop file for use, so most crop parameters were obtained from a study in Australia by Zeleke et al. (2011) before the grid search algorithm was executed. The simulations of canola yield resulted in a RMSE of 0.431 ton/ha in Taber and 0.728 ton/ha in Pincher Creek. Comparative results from an older study by Kiniry et al. (1995) used the EPIC crop model to simulate a yield RMSE of 0.412 ton/ha. With a yield RMSE of 0.777 ton/ha, wheat simulations in Pincher Creek resulted in a larger error than Taber (0.432 ton/ha).

These simulations could be improved with more refined crop parameters based on local conditions for southern Alberta. Most of the conservative and non-conservative crop parameters were obtained from different locations around the world, which may not be viable for the crop cultivars used in southern Alberta. Most of the barley parameters used from Abrha et al. (2012) and Araya et al. (2010) contain crop calibration done in Ethiopia, Italy, Syria, and an older experiment in Montana, USA. Barley simulations were the most tentative in predicting yields in southern Alberta, which may reflect of the introduction of potential errors by using crop parameters derived from other regions. Canola performed well without having a default crop file from AquaCrop, and using crop parameters from Zeleke et al. (2011), based on their canola calibration in Australia. Wheat calibration done in Pincher Creek was difficult because of the very limited amount of observed yield data in the region. For wheat calibration, observed yields from a diverse region, containing different climate grids and soil profiles were used to obtain a dataset large enough to run the grid search algorithm.

After calibration, the analysis of the five RCMs was applied to all crops in both the Taber and Pincher Creek regions. The overall results indicated that barley, canola, and wheat are likely to increase based on all five RCMs for both Pincher Creek and Taber. The WW RCM provided the highest potential yield increases for barley (71%) in Taber, and wheat (80%) in Pincher Creek (and Taber, previously discussed). The CW RCM projected the highest yield increases for canola in both regions (45% for Taber and 35% for Pincher Creek). The M RCM showed the greatest increase for barley (36%) in Pincher Creek. The results were very optimistic for all three crops in two distinct climates in southern Alberta, but some depend on the effect of the CO_2 fertilization for improving yields. Barley and canola yields decline in Pincher Creek without CO_2 fertilization, similarly with the majority of RCMs for Taber. Wheat in both regions has shown potential for increased yields without CO_2 fertilization, except for the CW RCM which was the only one to show a decrease.

The final objective of this study was to perform the same analysis for irrigated barley, canola, and wheat, and also to compare irrigation methods used by IRM and AquaCrop default settings. Only Taber was considered, as no observed yields were available for Pincher Creek due to the lack of irrigation systems in that region. Crops behave differently under irrigation because of reduced water-limiting stress, so an additional crop calibration was necessary for optimizing the phenology parameters for all three crops (Kang et al., 2002; McKenzie et al., 2005; Unkovich et al., 2010; Aslam et al., 2014). The resulting yield RMSE's of the irrigated crops were, 1.294 ton/ha for barley, 0.400 ton/ha for canola, and 0.384 ton/ha for wheat.

The RCM analysis contained a different outcome than the rainfed conditions, with the CW RCM projecting the highest increases of yields and the WW projecting the lowest increases for all three crops. Increases of yield were only achieved with CO_2 fertilization. Otherwise, without CO_2 fertilization, all five RCMs crop yields were projected to decrease. Only the AquaCrop default settings for irrigation were used for the previously mentioned analysis. By comparing the local IRM with AquaCrop's default settings, a conclusion could be made that AquaCrop might be simulating to apply too much water to the crops, thus lowering the simulated crop water productivity. In simulations between years 1950-2010, irrigated barley, canola, and wheat resulted in IRM using less water for barley (-36%), canola (-9%), and wheat (-25%), therefore slightly increasing the crop water productivity. Those results emphasize the importance of using local irrigation strategies and incorporating those methods into AquaCrop for improving irrigated water use simulations.

5.2 Discussion

5.2.1 AquaCrop

AquaCrop was developed for the purpose of having a simple model using a relatively small amount of parameters while creating a balance between simplicity, accuracy, and robustness (Steduto et al., 2009). For those reasons, AquaCrop was selected for this study due to the lack of ability to obtain detailed, lab-produced, crop parameters. Overall AquaCrop performed well in achieving the desired balance of simplicity, accuracy, and robustness, by simulating satisfactorily yields compared to observed records. However, the demand for a wide range of crop parameters can

be a challenge without having a background in agronomy or having specific and detailed crop phenology data. The scientific literature lacks some of the key crop parameters needed for localized AquaCrop studies in Canada, and some of the provided conservative parameters required updates for the study region. In order to quantify these unknown crop parameters, the grid search algorithm was developed as a solution for quantifying crop parameters based on observed yields. El-Sharkawy (2011) claims that most crop models (with a few exceptions) have some bias from a specific group of model coders and/or a distinct scientific group. AquaCrop and other crop models would benefit from attempting to develop a more objective crop calibration approach based on local climate and soil conditions. In Canada, extensive research has been done in crop breeding programs developing new cultivars to improve agriculture production (Bell, 1982; McCaig and DePauw, 1995; Juskiw et al., 2001; McCallum and DePauw, 2008). Yield reports (AgCanada, 2015) show newly introduced cultivars used on an annual basis. Assessing long-term crop yields requires more simple and dynamic methods for addressing the constant change in cultivars used. AquaCrop was a positive step forward for being a more simplified model with potential global application, although it still favours certain areas around the world based on the evidence of existing research literature.

5.2.2 Grid Search Algorithm

Some of the methods used by the grid search algorithm are questionable, or could be improved. The crop calibration procedure relied on using observed yields over the range between 1991 and 2004 for determining one single set of crop parameters. As mentioned before, the crop cultivars used can change on an annual

basis. The algorithm could be improved by performing a crop calibration on an annual basis to create dynamic crop files for the set years. This would require much more added processing time, which would mean that the algorithm itself needs to be optimized. Optimization could be achieved by first running an analysis to determine an optimal grid size for calibrating crops in AquaCrop, then find a threshold limit for the size of the refinement grid where any more additional runs will not achieve better results. Once the limit is narrowed down, then the algorithm could perform a better grid search with a lower amount of iterations for determining the optimal crop parameters.

Using the RMSE to describe the average model performance error is widely referred to in the research literature, but the statistic could lead to an inappropriate or misinterpreted measure of average error (Willmott and Matsuura, 2005). Therefore, the algorithm could benefit from other statistics. The mean absolute error (MAE) was indicated by Willmott and Matsuura (2005) as a good indication of average model performance error. Moriasi et al. (2007) performed an analysis on determining the best way to evaluate a model and recommended using a combination of three quantitative statistics: Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and a ratio of RMSE to the standard deviation of measure data (RSR). Using other statistics or a combination of statistics can aid in achieving better results and provide a better determination of the optimal crop parameters.

Additionally, the potential of overtraining (or overfitting) the parameters to match the observed data can be an issue. Unknown attributes associated with used

observed yield data can result in an unreliable output. The output parameters of the grid search algorithm can fit too well to biases of the training data set (observed yields) (Amari et al., 1997). One way to better approach this problem is to expand the study region to acquire more observed yield data and split the dataset into a training set and a validation set. By performing a cross-validation between the two different datasets will test the optimization of the parameters outputted by the grid search algorithm.

5.2.3 Uncertainties

Projections of climate change impacts on future crop yields still contain a range of uncertainties. The known uncertainties of crop models are related to crop responses to heat stress and elevated CO_2 concentrations and are specifically stated in the literature (Bootsma et al., 2005; Burton and Lim, 2005; Asseng et al., 2013; Bassu et al., 2014; Li et al., 2015; Vanuytrecht et al., 2015). Recommended solutions are to use multi-model ensembles containing a greater amount of different crop models, GCMs, and RCMs used to determine the likelihood of certain scenarios based on all results. These types of approaches are much more data intensive, and require a greater amount of resources that may not be readily available to everyone. Another area of uncertainty in this study involves the crop parameters used. Crop parameters can be problematic as they are typically derived from demo farms in specific areas that might not be applicable to other study locations. As a result, some of the parameters could be questionable for use in southern Alberta.

Uncertainties outside of crop modelling can also provide challenges for predicting crop yields. Human error can arise in recording observed yields such as those used in the calibration procedures of this study. Another, often overlooked uncertainty is the actual hands-on farm techniques used by local farmers. In southern Alberta, most farmers have a tendency to under-irrigate their crops (Personal communication from Dr. Ross McKenzie). Typically, crops are most optimal from 60-90% of soil field capacity, but some areas are known for barely achieving 60% of soil field capacity. It is desirable to establish direct communication between farmers and researchers because of gaps between the potential quantified and actual farm crop yields (Lobell et al., 2009; Grassini et al., 2015). Some crop models do not adequately account for different pieces of land with diverse spatial arrangements (Grassini et al., 2015). For example, spatial representation of slope, rock debris, and potential water ponds, as well as pests, weeds, and diseases, are a few factors that are not taken into consideration with in AquaCrop simulations. All of these uncertainties provide challenges in making assumptions for the methods used in this study, potentially adding to the errors of crop yield simulations.

5.3 Future Considerations

There are many ways to build on the methods and outcomes reached in this study. A few suggestions and considerations are listed below to help improve the prediction of climate change impacts on crop yields:

- Obtain well documented observed crop yields with information on seeding dates, seeding rates and farm management methods used

- Couple a hydrological model with AquaCrop, such as Agricultural Catchments Research Unit (ACRU), to provide simulations of soil moisture over the winter months for determining whether soil moisture is too wet or too dry for seeding
- Increase the number of RCMs with a broader range of CO_2 scenarios (RCP scenarios) for painting a more complete picture of the future
- Compare different crop models and use multi-model ensemble methods for better determining the uncertainties of climate change impacts
- Look for potential new areas for crop production by performing a broader scale study outside of the current agriculture zone
- Incorporate drought indices with predicted yields to determine the model performance of more water-limiting years and assess future risk with RCMs
- Interact directly with farmers to obtain a more realistic understanding of local farming methods used in the field as opposed to the quantified scientific approaches from literature

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