5: Agriculture

Assessment of Climate Change Impact on Eastern Washington Agriculture

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Abstract

An assessment of the potential impact of climate change and the concurrent increase of atmospheric carbon dioxide (CO_2) concentration on eastern Washington State agriculture was conducted. Climate projections from four selected general circulation models (GCM) were chosen to evaluate impacts for the periods 2010-2039, 2030-2059 and 2070-2099, identified as 2020, 2040, and 2080 scenarios, respectively. All climate projections reflect a warming future climate, but the individual GCMs vary with respect to precipitation changes – some models reflect wetter conditions and some drier. The assessment included the crops with larger economic value for the state at selected representative locations: irrigated apples at Sunnyside; irrigated potatoes at Othello; dryland wheat at Pullman (high precipitation), Saint John (intermediate precipitation), and Lind and Odessa (low precipitation). To evaluate crop performance, a cropping system simulation model (CropSyst) was utilized using historical (1975-2005) and future climate sequences, including simulations with and without concurrent elevation of atmospheric CO_2 concentration as given by the IPCC A1B CO_2 emission projection. Crops were assumed to receive adequate water (irrigated crops) and nutrient supply and possible negative impacts from pests and diseases were not accounted for. Simulation results project that the impact of climate change on selected but economically significant crops in eastern Washington will be generally mild in the short term (i.e., next two decades), but increasingly detrimental with time (potential yield losses reaching 25% for some crops by the end of the century). However, the projected CO_2 elevation is expected to provide significant mitigation of climate change effects, and in fact result in yield gains for some crops. Yields of winter wheat, without CO_2 effect, are projected to increase 2% to 8% for the 2020 scenario, tending to decline with further warming in high precipitation locations, but continue increasing to reach a 12% gain by the 2080s in low precipitation locations. With CO_2 elevation, winter wheat yields are projected to increase by 15% for the 2020 scenario, with larger increases later in the century. Spring wheat yields are projected not to change for the 2020 scenario, and decline 10% to 15% (2040), and 20% to 26% (2080) without CO_2 effect. However, earlier planting combined with CO_2 elevation is projected to increase yields by 16% for the 2020 scenario.

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Yields of irrigated potatoes are projected to decline 9%, 15%, and 22% for the 2020, 2040, and 2080 scenarios, respectively, but these losses are significantly smaller (2 to 3%) with CO_2 elevation. Varieties with a longer duration of green leaf area, combined with elevated CO_2, could potentially result in yield gains of 15%. However, reductions of tuber quality are a concern under warmer conditions. Apple yields are projected to decline 1%, 3%, and 4% for the 2020, 2040, and 2080 scenarios, respectively, but with projected yields increasing 6% (2020), 9% (2040), and 16% (2080) with CO_2 effect. Growers will need to adapt management to benefit from possible yield increases while maintaining fruit quality standards. Lack of good representation of the frequency and persistence of extreme temperature and precipitation events in current climate projections, which could adversely affect crop yields, and the extent to which the beneficial effects of elevated CO_2 on future crop productivity will be expressed are sources of some uncertainty to the projections in this study.

1. Introduction

The increasing concentration of atmospheric carbon dioxide (CO_2), and concurrent changes in temperature and precipitation patterns are expected to affect many aspects of human activities (IPCC, 2007). Because agriculture is widely exposed to these variables, the potential exists for perturbations in response to these changes in the next few decades and beyond.

The availability and capture of solar radiation, water, and nutrients are basic factors for plant growth and survival. Temperature plays an important role in general biological activity, defining in the case of plants the length of the available season suitable for growth, the speed of phenological development, the incidence of heat or freezing stresses, and the level of enzymatic activity associated with photosynthesis and respiration. Plant growth and development are reduced or halted at low temperatures, cells are damaged by freezing temperatures, and high temperatures can be devastating during flowering and initial stages of yield formation. The interaction of these factors will determine the impact on crop productivity, management, and economics of agriculture under climate change.

The objective of this study was to assess the potential impact of climate change and elevated CO_2 on eastern Washington agriculture, which produces most of the state's agricultural output value. The agriculture of the state is highly diversified with some 300 commodities produced commercially, ranking first in the US for production of 11 commodities, and with a value of production for crops and livestock reaching $6.7B in 2006. The state's food and agriculture industry contributes 11% of the state's economy (WSDA, 2008).

This assessment of climate change impact on agriculture focuses on crops that are most economically significant: apples, potatoes, and wheat (winter and spring varieties). Apples and potatoes are irrigated. For this study, we looked only at dryland wheat, which is the dominant dryland crop.

This assessment relied on computer simulation models and their careful interpretation. Work based on computer simulation has been done to assess climate change impact on agriculture during the last several decades (e.g., Rosenzweig et al., 1996; Brown and Rosenberg, 1999; Tubiello et al., 2002; Thompson et al, 2005). These assessments utilize a variety of climate change and agricultural models, including or not the effect of increasing CO_2. This diversity combined with the large variation in climatic conditions and agricultural crops around the US and the world makes it difficult to apply directly this information to a particular region. Overall, assessments by the Intergovernmental Panel on Climate Change (IPCC) have indicated that global agricultural production will not be seriously affected by climate change as projected by several general circulation models (GCMs), but the regional distribution of change is uncertain and current agricultural production in some areas will be vulnerable and adaptations will be necessary (Thompson et al., 2005). A comprehensive climate change impact study by Parry et al. (2004) also concluded that global production appears stable, but regional differences in crop production are likely to grow stronger through time.

Schlenker and Roberts (2008) related temperature patterns and yields of corn, soybeans, and cotton for the period 1950-2005 and most counties in the US by calculating the length of time a crop is exposed to each 1-degree Celsius temperature interval in each day of the growing season. They found that yields as a function of temperature increased modestly up to a critical temperature and then decreased sharply. Using these functions and climatic predictions from the Hadley 3 model, these authors projected nationwide average yields for corn, soybeans and cotton for the years 2070-2099 to decline by 43%, 36%, and 31%, respectively, under a slow warming scenario, and by 79%, 74%, and 67% under a rapid warming scenario. However, because effects from elevated CO_2 were not included, these results are likely overstating the potential negative climate impact. Nevertheless, for the most northern US latitudes results were more benign, with yields being slightly reduced or neutral and even responding positively to temperature increase, a finding of interest for Washington State.

Tubiello et al. (2002) evaluated the effect of climate change on US crop production with a focus on wheat, maize, potato, and citrus, concluding that although model results suggested that current US food production systems will not be at risk in this century, regional production differences are important to consider, with regional results showing that climate change favors northern areas and can worsen conditions in southern areas. A similar difference in response is expected when comparing northern and southern Europe locations (Olesen and Bindi, 2002).

Assessment efforts worldwide have focused mostly on wheat and corn, while much less is known about possible effects of climate change on potatoes and other crops. We did not find studies addressing the effect of climate change on spring wheat, which is cultivated in high to intermediate precipitation dryland areas of eastern WA, and on apples or other temperate tree fruit crops grown in the region.

Thompson et al. (2005) summarized a US national assessment where crop yields were simulated under a suite of climate change scenarios from three GCMs at two levels of global mean temperature increase, +1 and +2.5 ^{o}C, and two levels of CO_2, 365 and 560 ppm. A regional analysis that included Yakima, WA, projected winter wheat yield increases for all scenarios, fluctuating from 8 to 37%, with some increase in yields due to temperature, and largely enhanced by CO_2 increase. Simulations for temperate climates elsewhere have also indicated climate change being neutral or beneficial for winter wheat production (Harrison and Butterfield, 1996; Nonhebel, 1996; Favis-Mortlock et al., 1991).

Information of climate change effects on potatoes is scarce. Rosenzweig et al (1996) reported computer simulations for Yakima, WA projecting yield reductions of 1.4, 3.8, and 18.5% with temperature increases of 1.5, 2.5, and 5 °C above the baseline. Increased CO_2 resulted in yield increases of 5 to 10% at 1.5 °C increase, compensated for yield losses or resulted in marginal gains at 2.5 °C, and reduced somewhat the losses at 5 °C. Another study by Tubiello et al. (2002) estimated potato yields at Yakima, WA to increase 2 to 5% by 2030 while yields projected in 2090 were estimated to decrease by 10% in two of the three major production sites in the Northwest.

Compensation for the negative effect of climate warming by increasing CO_2 has been projected in many studies (e.g., Favis-Mortlock et al., 1991; Nonhebel, 1996; Hatfield et al., 2008; Thompson et al., 2005; Brown and Rosenberg, 1999). However, a better understanding of the likely beneficial effects of the projected CO_2 increase is needed to properly assess possible compensatory effects for yield declines resulting from warming. There is abundant experimental evidence indicating that elevated CO_2 increases plant growth, biomass accumulation, and yields, the latter depending on increases of sink (e.g., grains, tubers) strength proportional to gains in total biomass. The beneficial effect of elevated CO_2 is more significant for crops with the C_3 photosynthetic pathway (e.g., wheat, potatoes, soybeans, and the majority of domesticated plants) and minor for crops with C_4 photosynthetic pathway (e.g., corn and sorghum). In addition, elevated CO_2 causes partial stomatal closure thus reducing crop water losses by transpiration, which coupled with biomass gains result in some gains on water use efficiency, providing advantages to rainfed crops.

Perhaps the most comprehensive review of crop responses to CO_2 is given by Kimball et al. (2002). These authors summarized crop performance under free-air CO_2 enrichment (FACE) experiments, which render results that are closer to field conditions than greenhouse and other controlled environment experiments. All experimental results were normalized to represent crop responses to a CO_2 change from 360 to 550 ppm. Overall, yields of wheat and rice increased by an average of 12% while tuber yields from potatoes increased by a substantial 28%. The boll yields of cotton were increased by 40%. In the only FACE study conducted with grapevines thus far, Bindi et al. (2001) observed increases of 40-50% in both vegetative and fruit biomass with little change in fruit and wine composition. No information is available regarding elevated CO_2 effects on apples and other temperate tree fruit crops.

A more recent evaluation of FACE experiments (Long et al., 2004) concluded that production is increased by about 20% in C_3 plants with similar increase in seed production, and only a modest increase of a few percent points for C_4 plants. It has been argued, however, that the growth stimulation resulting from increased CO_2 would be transient. Oechel et al. (1994), conducted an experiment on an undisturbed patch of tussock tundra at Toolik Lake, Alaska, enclosed in greenhouses in which the CO_2 level was controlled to ambient (340 ppm) and elevated (680 ppm) levels of CO_2 and temperature was kept ambient or elevated 4 °C. For a doubled

CO_2 level alone, initial growth stimulation was lost within three years, but it was sustained when combined with temperature elevation providing better growth conditions. One possible inhibitory mechanism is that when enhanced photosynthesis exceeds the capacity for carbohydrate export from leaves and utilization (plant organs growth cannot accommodate excess carbohydrate), starch accumulates in leaves and photosynthesis is reduced. Plants in FACE experiments have shown both increased biomass production and increased levels of carbohydrates in leaves, but the transient effect has not been duplicated (Long et al., 2004). A long-term study (13 years) exposing sour orange trees to 300 ppm CO_2 concentration above ambient showed a large increase in biomass production during the early years of tree establishment, decreasing afterwards and stabilizing during the last four years at biomass and fruit production levels of 1.8 times those of trees exposed to ambient CO_2 (Idso and Kimball, 2001). Although still of limited duration, this is the best evidence yet of the permanent nature of CO_2 elevation beneficial effect on growth of a managed crop.

Nutrient supply to crops is assumed to be a non-limiting factor in this study. It has been shown that plants exposed to elevated CO_2 have reduced tissue N concentration compared to plants in ambient conditions (e.g., Cotrufo et al., 1998). However, biomass gains from CO_2 elevation can be preserved if ample N is supplied to crops. Kim et al. (2001) grew rice in a FACE experiment and found that, to maximize rice grain yield under elevated CO_2, it was important to supply sufficient N over the whole season. The implication for agriculture is the need to increase crop fertilization to ensure that growth enhancement by CO_2 will not be limited by nutrient supply.

In the simulations presented in this study, we have assumed a gain of 20% in biomass production for a CO_2 increase from 370 to 600 ppm. When evaluating the results presented, it must be kept in mind that the magnitude of projected benefits of CO_2 increase are very likely but not guaranteed. In addition, increases in overall biomass production can be offset by heat stress reducing reproductive development of grains in cereals or tuber growth in potatoes or any other sink representing harvestable portions, or by the inability of harvestable portions to increase in number or size and absorb the additional amount of carbohydrate production. Thus, caution must be used in the interpretation of simulation results that include elevated CO_2.

2. Approach

This study is based on computer simulations of crop yields of selected crops and representative locations in Washington State as follows: Winter wheat (Pullman, Saint John, Lind, and Odessa), spring wheat (Pullman and Saint John), potatoes (Othello), and apples (Sunnyside). In addition, disease (grape and cherry powdery mildew) and insect (codling moth) models were run to provide insight into potential changes in the incidence of pests and diseases under future climate. Weed models were not available and we relied on literature review for the assessment of weed impacts.

Figure 1 shows a generalized agricultural land use map for the State of Washington and the locations included in the study; specific commodity land use maps are not available.

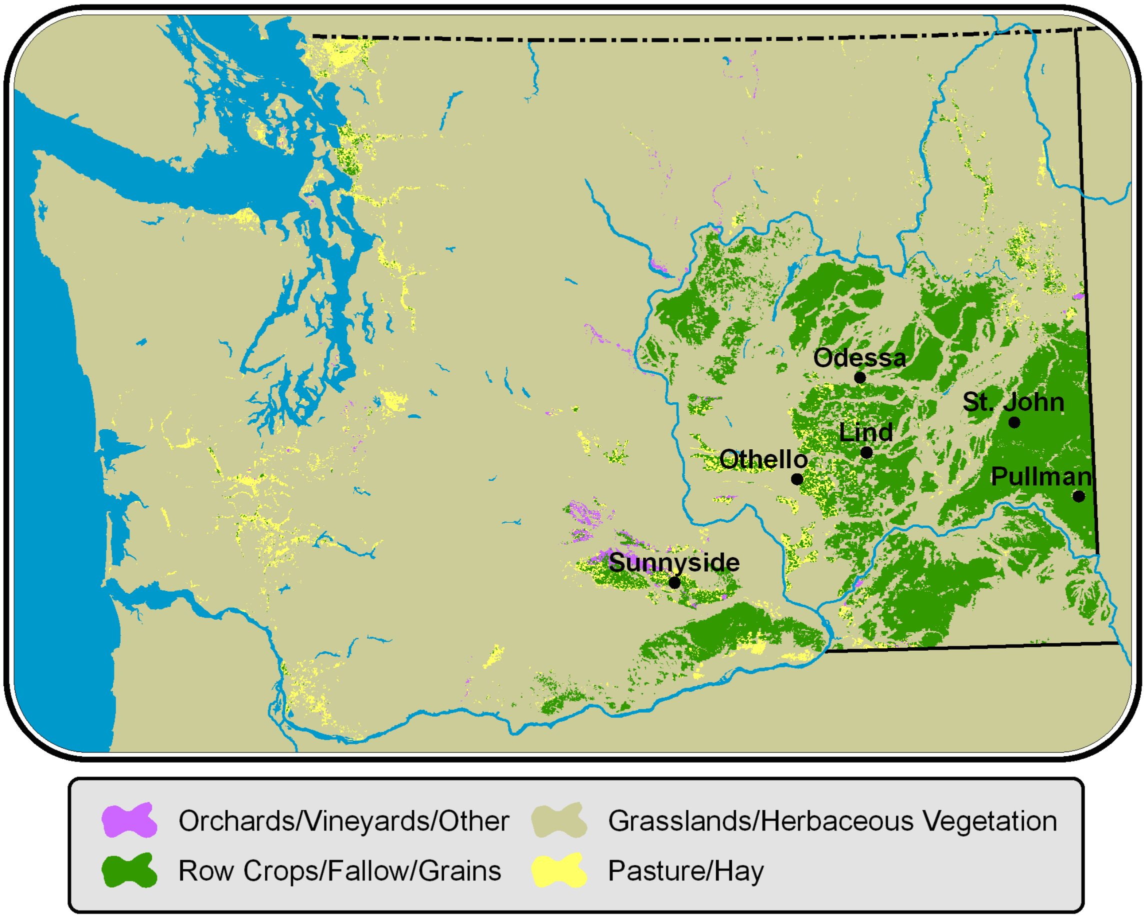


Figure 1. Agricultural land use patterns for Washington state. Locations of simulations are noted on map.

2.1. Simulations

Simulations of crop response to climate change and elevated CO_2 were performed using CropSyst Version 4.12.10 (Stöckle et al, 1994; Stöckle et al, 2003), a cropping system simulation model that represents the response to weather and management of an array of annual and perennial crops and tree fruit crops. Parameters for the simulation of wheat (Pannkuk et al., 1998), potatoes (Peralta and Stöckle, 2002), and apples (Scott et al., 2004) for the region were taken from previous studies and were further refined using available information about crop phenology and morphological, physiological, and biophysical characteristics. The effect of CO_2 on biomass accumulation and crop transpiration was calculated as described by Stöckle et al. (1992). Simulated crops were assumed to receive adequate water (irrigated crops) and nutrient supply. Possible negative impacts from pests and diseases were not accounted for.

2.2. Weather Data

To establish baselines, historical daily weather data for the years 1975-2005 were used in each location. Selected future climate projection scenarios were chosen to evaluate climate impacts for the periods 2010-2039 (2020 scenario), 2030-2059 (2040 scenario) and 2070-2099 (2080 scenario). The climate projections for future scenarios were based on four GCMs: PCM1 (a GCM that projects less warming and more precipitation for eastern WA), CCSM3 (a GCM that projects more warming and less precipitation), ECHAM5 and CGCM3 (GCMs that project intermediate changes compared to the first two).

All daily baseline and future precipitation and temperature data were extracted from a 1/16th degree grid data set available for the region, downscaled from the GCM projections (Mote and Salathé, 2009, in this report). Solar radiation and air humidity were determined from temperature and precipitation using the climate generator ClimGen (Castellvi and Stöckle, 2001; Stöckle et al., 2004), using generation parameters calibrated for stations in an existing agricultural weather network in eastern WA (AgWeatherNet). Climate characteristics for selected locations and GCMs are given in Table 1. Potential evapotranspiration was calculated using the Penman-Monteith model as proposed by Allen et al. (1998).

Table 1. Baseline (current) and projected climate characteristics for precipitation (Precip), temperature (T), and potential evapotranspiration (ETo). Data are for the two extreme GCMs and are presented for the indicated time intervals (annual, seasonal, non-seasonal) at the future periods of interest (2020, 2040, 2080) for each of 3 eastern Washington locations (Pullman, Lind, Sunnyside).

		Baseline	**CCSM3**			**PCM1**		
Pullman			**2020**	**2040**	**2080**	**2020**	**2040**	**2080**
Annual	Precip (mm)	535.8	549.9	543.9	588.3	560.2	568.9	589.5
	Mean T (°C)	8.5	10.2	11.2	12.0	9.6	10.5	11.4
	Mean Tmax (°C)	14.5	16.1	17.1	18.0	15.6	16.5	17.3
	Mean Tmin (°C)	2.4	4.2	5.2	6.0	3.6	4.4	5.4
	ET_o (mm)	914.4	966.6	998.8	1023.6	943.3	971.7	994.2
Seasonal	Precip (mm)	181.7	187.6	183.1	192.9	186.9	196.6	188.5
(Apr 1 – Sep 30)	Mean T (°C)	14.8	16.4	17.7	18.5	15.9	16.5	17.5
	Mean Tmax (°C)	22.6	24.0	25.4	26.2	23.6	24.4	25.1
	Mean Tmin (°C)	7.0	8.7	10.0	10.7	8.1	8.6	9.8
	ET_o (mm)	725.8	760.5	791.2	809.8	749.6	767.2	787.1
Non-seasonal	Precip (mm)	352.6	358.9	359.8	396.5	370.8	371.8	399.6
(Oct 1 – Mar 31)	Mean T (°C)	2.1	4.0	4.7	5.5	3.3	4.5	5.0
	Mean Tmax (°C)	6.3	8.2	8.9	9.7	7.6	8.7	9.2
	Mean Tmin (°C)	-2.1	-0.3	0.4	1.3	-0.9	0.2	0.9
	ET_o (mm)	188.3	204.7	209.5	213.4	196.1	204.1	206.9

Table 1 continued on next page.

Table 1 continued

		Baseline	**CCSM3**			**PCM1**		
Lind			**2020**	**2040**	**2080**	**2020**	**2040**	**2080**
Annual	Precip (mm)	232.3	249.9	244.3	265.5	246.3	250.1	257.2
	Mean T (^{o}C)	10.1	11.5	12.4	13.3	10.9	11.8	12.7
	Mean Tmax (^{o}C)	16.9	18.4	19.4	20.1	17.8	18.8	19.5
	Mean Tmin (^{o}C)	3.2	4.6	5.5	6.4	4.0	4.9	5.8
	ET_o (mm)	975.9	1030.2	1063.9	1086.4	1006.2	1037.3	1068.1
Seasonal	Precip (mm)	76.7	83.2	79.7	84.9	78.2	81.7	85.6
(Apr 1 – Sep 30)	Mean T (^{o}C)	17.3	18.6	19.8	20.6	18.1	18.7	19.6
	Mean Tmax (^{o}C)	26.2	27.3	28.6	29.5	26.9	27.7	28.4
	Mean Tmin (^{o}C)	8.5	9.8	11.0	11.7	9.2	9.8	10.9
	ET_o (mm)	798.6	828.9	856.9	874.3	818.8	836.4	855.5
Non-seasonal	Precip (mm)	156.1	165.4	164.6	180.9	167.2	167.9	174.8
(Oct 1 – Mar 31)	Mean T (^{o}C)	2.8	4.4	5.1	5.9	3.8	4.9	5.5
	Mean Tmax (^{o}C)	7.6	9.3	10.1	10.7	8.7	9.8	10.3
	Mean Tmin (^{o}C)	-2.1	-0.6	0.1	1.0	-1.1	0.0	0.7
	ET_o (mm)	177.7	200.0	208.8	212.9	188.9	200.4	205.0

Sunnyside			**2020**	**2040**	**2080**	**2020**	**2040**	**2080**
Annual	Precip (mm)	184.5	194.1	188.4	202.2	191.8	192.7	199.1
	Mean T (^{o}C)	10.5	12.4	13.3	14.1	11.8	12.7	13.5
	Mean Tmax (^{o}C)	18.1	20.0	20.9	21.7	19.5	20.4	21.1
	Mean Tmin (^{o}C)	2.9	4.8	5.6	6.5	4.2	5.0	5.9
	ET_o (mm)	1045.1	1113.1	1146.1	1168.0	1089.1	1119.1	1149.3
Seasonal	Precip (mm)	60.4	64.1	61.7	62.7	60.6	60.6	62.7
(Apr 1 – Sep 30)	Mean T (^{o}C)	17.5	19.3	20.4	21.3	18.8	19.4	20.3
	Mean Tmax (^{o}C)	26.6	28.5	29.7	30.5	28.1	28.9	29.5
	Mean Tmin (^{o}C)	8.3	10.1	11.2	12.1	9.5	10.0	11.1
	ET_o (mm)	820.9	866.6	893.6	907.3	853.4	870.1	885.1
Non-seasonal	Precip (mm)	125.3	128.8	126.8	140.0	130.5	131.9	136.8
(Oct 1 – Mar 31)	Mean T (^{o}C)	3.6	5.4	6.1	6.8	4.9	5.9	6.5
	Mean Tmax (^{o}C)	9.6	11.4	12.1	12.8	10.9	11.9	12.5
	Mean Tmin (^{o}C)	-2.4	-0.6	0.1	0.8	-1.1	-0.1	0.6
	ET_o (mm)	223.6	246.3	254.4	261.4	236.8	248.8	254.6

3. Results

3.1. Climate Change

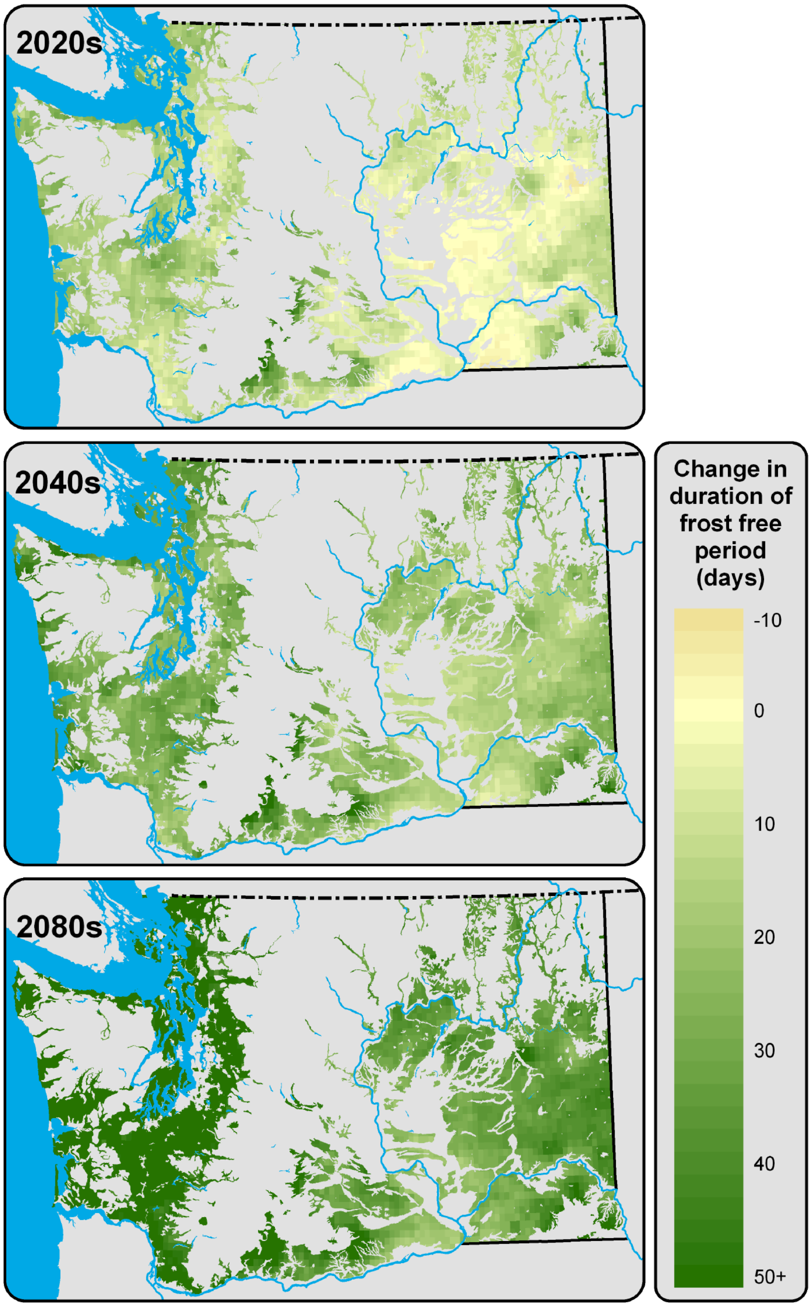
Table 1 summarizes baseline and projected climate characteristics including precipitation, temperature, and potential evapotranspiration. Given space limitations, only projections from the two extreme GCMs included in this study for three distinctive locations in the state are presented.

Table 1 shows annual precipitation increasing by about 10% to 14% and 8% to 10% for the CSSM3 and PCM1 projections, respectively, but with the spring-summer precipitation becoming a smaller fraction of the total increase. The changes in atmospheric evaporative demand (evapotranspiration) are roughly similar to precipitation changes but with a larger proportion of the increase during the spring-summer period.

Annual temperature increase for the CCSM3 GCM is projected as 1.4, 2.3 and 3.2 ºC at Lind, and ~1.7, 2.7, and 3.5 ºC at Pullman and Sunnyside for the 2020, 2040 and 2080 scenarios, respectively. For the PCM1 projection, the temperature change is expected to be 0.8, 1.7, and 2.6 ºC at Lind, 1.1, 2.0, and 2.9 ºC at Pullman, and 1.3, 2.2, and 3 ºC at Sunnyside for the 2020, 2040, and 2080 scenarios, respectively. The increase is slightly larger for the spring-summer period and CCSM3 projection with changes of 3.3, 3.7, and 3.8 ºC for the 2080 scenario at Lind, Pullman, and Sunnyside, respectively, but slightly lower for the PCM1 projection (2.3, 2.7, and 2.8 ºC). Overall, the changes for the average maximum and minimum temperatures are similar to those projected for average temperatures.

The projected warming trend will increase the length of the frost-free period throughout the state (Fig. 2), increasing the available growing season for crops, which will continue to be limited in eastern WA by water availability, and likely by extreme heat events in some instances. This will continue the trend observed from 1948 to 2002, during which the frost-free period has lengthened by 29 days in the Columbia Valley (Jones, 2005). The warming trend may also create opportunities for better adaptation of C_4 crop species (e.g., corn). On the other hand, temperate tree fruits grown in the state require a minimum accumulation of chilling units during the winter for adequate and uniform budbreak

Figure 2. Changes in the length of the frost free period (days), based on the CCSM3 climate projection, for the indicated future periods of interest.



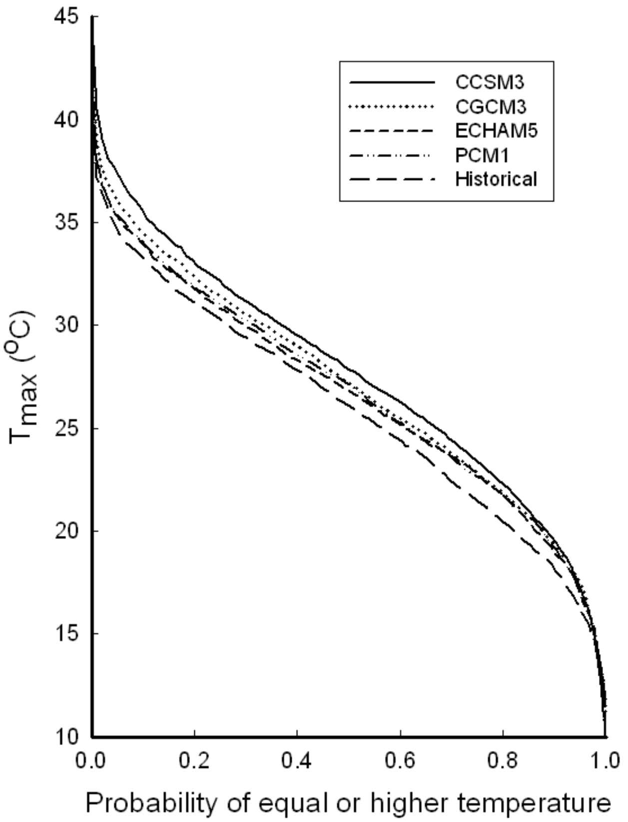


Figure 3. Probabilistic distribution of maximum June/July temperature for Pullman for the 2020 scenario.

and flowering. The opportunity to meet this requirement will be reduced as the climate becomes warmer. Weeds and insects will adapt to the longer season with more favorable conditions.

3.2. Wheat Projections

The impact of climate change on wheat was analyzed for three distinct production regions: a higher precipitation annual cropping region (Pullman site); an intermediate cropping zone in which winter wheat is typically grown in a rotation of summer fallow, winter wheat, and a spring grain (St. John site); and two lower precipitation zones in which winter wheat follows summer fallow in a two-year rotation (Lind and Odessa sites).

Table 2 summarizes simulated winter wheat yields at four locations in response to current and projected climate, with and without inclusion of elevated CO_2 effects on plant growth. At all locations, future climate is beneficial for winter wheat production, with yields increasing by 2% to 8% compared to the baseline for the 2020 scenario. As warming continues to increase, however, yields at Pullman (high rainfall) are projected to drop 4% below current values and yields at Saint John (intermediate rainfall) are maintained at current levels for the 2040 scenario, while yields at Lind and Odessa (low rainfall) continue to increase to 12% by the 2080 scenario. Higher yields are the result of earlier crop maturity while the duration of the grain filling period remains unchanged. The earlier maturity provides a degree of avoidance of the terminal water stress that is typical of the region. As climate warming continues, high temperature events during flowering will negatively affect grain formation, counteracting the effect of water stress avoidance. Figure 3 shows the probabilistic distribution of maximum temperatures in June/July in Pullman for the 2020 scenario, showing an increase in probability of temperatures above 30 °C from a baseline of 22% to 35% depending on the GCM considered. Ferris et al. (1998) showed that increasing the number of hours of exposure to temperatures above 31 °C resulted in reduction of grain numbers and lower grain biomass at harvest.

When the effect of elevated CO_2 is added, a positive picture emerges for winter wheat at all locations, time scenarios and GCM predictions, with yields increasing steadily as the century progresses. For the short-term future (2020 scenario) yields are projected to increase by 12% to 15%, increasing to gains of 23% to 35% by the end of the century. Limitations in the number and size of grains could impede a proportional expression of increased biomass production caused by elevated CO_2 on yields of future varieties. In addition, changes in the frequency of extreme high temperature events, which are not well represented by GCM projections, could limit yield formation. On the other hand, there is sufficient plasticity in photoperiod and vernalization requirements of winter wheat varieties to adapt to warming conditions (Masle et al., 1989).

Table 2. Baseline (current) and simulated dry winter wheat yields (kg/ha) at four eastern Washington locations. Scenarios were run for indicated future periods of interest (2020, 2040, 2080) under the indicated climate projection with (CO_2) and without (no CO_2) the effects of elevated CO_2 on plant growth.

Location baseline yield	CO_2 effects	Scenario		Weather projection			Average yield	Ratio of future to baseline yield
			CCSM3	CGCM3	ECHAM5	PCM1		
			Yield (kg/ha)					
Pullman								
5713 kg/ha	No CO_2	2020	6022	6374	5996	5846	6060	1.061
		2040	5116	6376	5040	5398	5483	0.960
		2080	5209	5752	5187	5002	5288	0.926
	CO_2	2020	6546	6952	6515	6367	6595	1.154
		2040	6034	7503	5881	6430	6462	1.131
		2080	7033	7887	7105	6863	7222	1.264
St. John								
4647 kg/ha	No CO_2	2020	4878	5062	4464	4637	4760	1.024
		2040	4338	4975	4640	4573	4631	0.997
		2080	4275	4749	4469	4377	4468	0.961
	CO_2	2020	5156	5862	5130	5305	5363	1.154
		2040	5491	6187	5722	5776	5794	1.247
		2080	5353	6116	5656	5724	5712	1.229
Lind								
3975 kg/ha	No CO_2	2020	4261	4503	4415	4025	4301	1.082
		2040	4363	4801	4255	4212	4408	1.109
		2080	4332	4610	4564	4296	4451	1.120
	CO_2	2020	4522	4818	4759	4255	4588	1.154
		2040	4867	5308	4645	4571	4848	1.220
		2080	5216	5667	5688	4920	5373	1.352
Odessa								
3728 kg/ha	No CO_2	2020	4000	4003	3935	3808	3937	1.056
		2040	4087	4255	3807	3969	4029	1.081
		2080	4086	4265	4353	4021	4181	1.122
	CO_2	2020	4260	4273	4224	4024	4195	1.125
		2040	4527	4664	4139	4289	4405	1.182
		2080	4896	5083	5445	4490	4979	1.336

Table 3 shows current and projected yields for spring wheat. For the 2020 scenario, no changes are projected compared to current yields. However, yields are projected to show declines, becoming progressively larger for the 2040 and 2080 scenarios. The main factors leading to these yield declines are high temperatures that reduce grain biomass as previously discussed, and a small reduction of grain filling duration. Again, elevated CO_2 is projected to counteract most of the negative effects, with yields being relatively stable or showing a small reduction throughout the century. A possible adaptation for spring cereals will be earlier planting. As shown in Table 3, a two-week earlier planting will reduce the effect of climate change alone, and will result in important yield increases (~17%) for the 2020 scenario when the CO_2 effect is added, with the benefit declining later in the century. Planting dates could be adjusted earlier than two weeks later in the century.

3.3. Potato Projections

Projections for potatoes (Table 4) indicate significant yield declines due to warming, with losses of 9%, 15%, and 22% for the 2020, 2040, and 2080 scenarios, respectively, with a larger decline for the GCM with larger warming prediction (CCSM3). Rosenzweig et al. (1996) projected potato yields in Yakima WA to decline by 1.4%, 3.4% and 18.5% with temperature increases of 1.5, 2.5 and 5.0 ^{o}C, respectively, with elevated CO_2 assumed to have a low beneficial impact on growth and yields, compensating for losses only at temperature increases of 2.5 ^{o}C or lower. In our simulations, increasing CO_2 compensated significantly for temperature increases, but still resulted in 2% yield declines for the 2020 scenario, increasing to 3% later in the century.

Two main factors contributed to the projected decline of potato yields. The first is a shorter growing season of up to 9 days by the end of the century due to the accelerated development and earlier leaf area senescence that accompany warmer temperatures. The second is an increasing occurrence of high temperatures during tuber bulking, which reduces the translocation of carbohydrates from the aboveground canopy to the tubers (Timlin et al., 2006). Although not simulated by the model, high temperature during tuber bulking may contribute to lower tuber quality (Alva et al., 2002), affecting market value.

One possible adaptation is to modify planting dates to decrease the exposure to high temperature during tuber growth and to obtain a longer duration of leaf area. However, in our simulations we tested 2 and 4 weeks planting delay without benefits. We also tried earlier planting without benefit. Similar results were obtained by Rosenzweig et al. (1996), who concluded that changes in planting date will not alleviate the negative trend in potato yields associated with higher temperatures.

Another possible adaptation is to utilize later maturity class cultivars that maintain a green leaf area for a longer period thus taking advantage of the longer available growing season. Simulations performed assuming a variety able to maintain green leaf area for an extra 9 to 10 days (Table 4) resulted in yield increases of 7% and 1%, for the 2020 and 2040 scenarios, respectively, declining to an 8% loss by 2080. With the addition of CO_2 effects, yields with this strategy increased 15% for all time scenarios.

Table 3. Baseline (current) and simulated dry spring wheat yields (kg/ha) at two eastern Washington locations. Scenarios were run for indicated future periods of interest (2020, 2040, 2080) under conditions of standard (baseline) planting date or adaptation, which was planting two weeks earlier, under the indicated climate projection, and either with (CO_2) or without (no CO_2) the effects of elevated CO_2 on plant growth.

Location/ baseline yield	Condition	Scenario	Weather projection				Average yield	Ratio of future to baseline yield
			CCSM3	CGCM3	ECHAM5	PCM1		
			Yield (kg/ha)					
Pullman	**Standard**							
4085	No CO_2	2020	3845	4500	3983	3913	4060	0.994
kg/ha		2040	3289	4164	3712	3495	3665	0.897
		2080	3135	3540	3213	3078	3241	0.794
	CO_2	2020	4159	4902	4327	4240	4407	1.079
		2040	3720	4774	4235	3994	4181	1.024
		2080	3946	4456	4016	3863	4070	0.997
	Adaptation							
	No CO_2	2020	4225	4696	4306	4188	4354	1.066
		2040	3429	4530	3928	4026	3978	0.974
		2080	3284	3792	3591	3280	3487	0.854
	CO_2	2020	4579	5121	4680	4551	4733	1.159
		2040	3879	5208	4495	4632	4554	1.115
		2080	4194	4870	4542	4147	4438	1.087
St John	**Standard**							
3381	No CO_2	2020	3345	3618	3224	3334	3381	1.000
kg/ha		2040	2637	3268	2771	2751	2857	0.845
		2080	2652	2704	2387	2275	2505	0.741
	CO_2	2020	3564	3885	3451	3557	3614	1.069
		2040	2895	3643	3057	3026	3155	0.933
		2080	3179	3306	2852	2726	3016	0.892
	Adaptation							
	No CO_2	2020	3644	3889	3669	3717	3729	1.103
		2040	2738	3535	3086	3207	3142	0.929
		2080	2520	3010	2869	2388	2696	0.798
	CO_2	2020	3878	4162	3926	3965	3983	1.178
		2040	3021	3960	3408	3548	3484	1.031
		2080	3049	3694	3452	2889	3271	0.967

Table 4. Simulated dry yields of potatoes at Othello, Washington using a cultivar adapted to baseline conditions (standard) and a cultivar with a longer duration of green leaf area of 9 to 10 days (adaptation). Scenarios were run for indicated future periods of interest (2020, 2040, 2080) either with (CO_2) or without (no CO_2) the effects of elevated atmospheric CO_2 concentration on plant growth. Baseline yield for potato is 16207 kg/ha. Fresh yields are obtained by dividing by 0.2.

Condition	Scenario		Weather projection			Average yield	Ratio of future to baseline yield
		CCSM3	CGCM3	ECHAM5	PCM1		
		Yield (kg/ha)					
Standard							
No CO_2	2020	14042	14748	15353	15014	14789	0.913
	2040	12654	14260	14208	14289	13853	0.855
	2080	11899	12888	12562	13081	12607	0.778
CO_2	2020	15024	15792	16437	16068	15831	0.977
	2040	14371	16205	16144	16240	15740	0.971
	2080	14817	16041	15639	16301	15700	0.969
Adaptation							
No CO_2	2020	16656	17399	17976	17596	17407	1.074
	2040	15160	16868	16781	16800	16402	1.012
	2080	14261	15282	14856	15534	14983	0.924
CO_2	2020	17824	18633	19248	18834	18635	1.150
	2040	17220	19170	19069	19095	18639	1.150
	2080	17761	19022	18491	19356	18658	1.151

3.4. Apple Projections

Without considering the possible effect of elevated CO_2, future climate is predicted to slightly decrease the production of apples by 1%, 3%, and 4% for the 2020, 2040, and 2080 scenarios (Table 5). Under a warmer climate, the seasonal phenological development will proceed at a faster rate, and the period from budbreak to harvest will be shortened reducing the opportunity for biomass gain. This has already been observed in Alsace (eastern France) where the period between budbreak and harvest in grapes has become shorter and ripening of fruit occurs under warmer conditions (Duchene and Schneider, 2005). When the effect of CO_2 is added, yields are projected to increase by 6%, 9%, and 16% for 2020, 2040, and 2080 scenarios compared to current levels. Growers will need to adapt crop load management targets to maintain fruit quality standards at the higher yields.

Table 5 also shows apple yields that would be potentially attainable given the extended favorable conditions for growth due to warming. These are given as a reference of hypothetical potential benefits of climate change for apple growers in eastern WA, assuming the availability of varieties able to use the extended season or assuming that other adaptive technologies not currently available are developed. Depending on conditions, apple yields could potentially increase 5% to 11% for the 2020 scenario, and reaching

Table 5. Simulated dry yields of apples at Sunnyside, Washington. Scenarios were run for indicated future periods of interest (2020, 2040, 2080) either with (CO_2) or without (no CO_2) the effects of elevated atmospheric CO_2 concentration on yield. Fresh yields are obtained by dividing by 0.30.

Crop/ baseline yield (kg/ha)	Condition	Scenario	Weather projection				Average yield	Ratio of future to baseline yields
			CCSM3	CGCM3	ECHAM5	PCM1		
			Yield (kg/ha)					
Apples 18153								
	Standard							
	No CO_2	2020	17856	18215	18183	17880	18034	0.99
		2040	17251	18239	17682	17520	17673	0.97
		2080	17165	17806	17650	17360	17495	0.96
	CO_2	2020	18987	19367	19299	19010	19166	1.06
		2040	19363	20449	19807	19638	19814	1.09
		2080	20744	21345	21158	20850	21024	1.16
	Adaptation							
	No CO_2	2020	19101	19384	19027	18777	19072	1.05
		2040	18645	19617	18869	18729	18965	1.04
		2080	18537	19175	18980	18773	18866	1.04
	CO_2	2020	20305	20549	20146	19952	20238	1.11
		2040	20823	21455	20996	20882	21039	1.16
		2080	21541	21600	21565	21562	21567	1.19

19% for the 2080 scenario with elevated CO_2.

Even under reduced duration of the period from budbreak to harvest, warming may provide an extended period postharvest that may be beneficial for carbohydrate accumulation by trees –flowering and early growth in the subsequent season utilize stored carbohydrate and nutrient reserves. Greer et al. (2002) reported greater carbohydrate reserves and crop yields in 'Braeburn' apple trees exposed to higher temperatures after harvest. Moreover, bud winter hardiness in apple is positively related to tissue carbohydrate content (Raese et al., 1978), another potential benefit.

Wolfe et al. (2005) reported advances in spring phenology (days to bloom and days to first leaf) ranging from 2 to 8 days for grapes and apples in northeastern USA for the period 1965 to 2001. Although average temperatures are projected to increase for all climate scenarios, minimum temperatures during early spring will still provide conditions for damaging frost events, with added vulnerability due to earlier flowering. Figure 4 shows the distribution of minimum temperature for the month of April for current climate and the 2020 projections of each of the four GCMs included in this study, showing ~20% probability of minimum temperatures below freezing for the latter, not much different from the current condition. Under the projected climate change, flowering will tend to occur about 3 days earlier in the 2020 scenario, which will tend to increase slightly the exposure to frost events of flowers and fruits in initial stages of formation. This could increase current levels of yield loss from frost damage or increase the need and expense for frost protection, factors that are not simulated by the model.

Another factor not accounted for in the model is the effect on quality of apples of decreasing chill hours during the dormant period. Sufficient exposure to cold winter weather is required for uniform budbreak and flowering. This is not likely to be a significant problem since accumulation of sufficient chilling is usually satisfied for most apple cultivars by January.

3.5. Disease, Insect and Weed Pressure Projection

It is of interest to address possible changes in pest and disease pressures on agriculture in response to climate change because they can cause yield reductions and/or increase the cost of control. Only a generalized assessment is presented here, using projections from a few disease and insect models as an indication of possible overall effects. Models of weed-crop competition are very scarce and not suitable for this assessment, so we rely on empirical evidence to offer a projection of changes on weed pressure.

3.5.1. Diseases

One of the most problematic diseases of cherries and grapes in the irrigated production regions of Washington State are the powdery mildews. Powdery mildews are unique aerial plant pathogens because they are less reliant on free water than other fungal pathogens. The powdery mildews of cherry (Grove and Boal, 1991) and grape (Grove, 2004) have an early-season wetting requirement. Once wetting requirements are met, temperature becomes the factor limiting to the incidence and severity of powdery mildew epidemics. In general these powdery mildews reproduce most rapidly between 18 and 29 ^{o}C. Temperatures above 35 ^{o}C are lethal and below 18 ^{o}C are inhibitory (Gent et al., 2008).

Seasonal increases in precipitation could promote the establishment of diseases previously undocumented or considered minor in Eastern Washington. Examples include the downy mildew of grapevines, black rot of grapevines, and cherry leafspot. The emergence or increased importance of these diseases could potentially result in increases in disease management costs.

Projections of risk of infection for cherry and grape powdery mildew at Sunnyside are presented in Fig. 5. Cherry powdery mildew is predicted to increase under the CCSM3 (2020 only) and the CGCM3 projected climate. Small increases or no change in the risk from grapevine powdery mildew were predicted for all climate projections. Overall, warmer climate but with small changes in precipitation during the growing season will tend to maintain and eventually reduce the incidence of these diseases, unless there is an increase in precipitation early in the growing season.

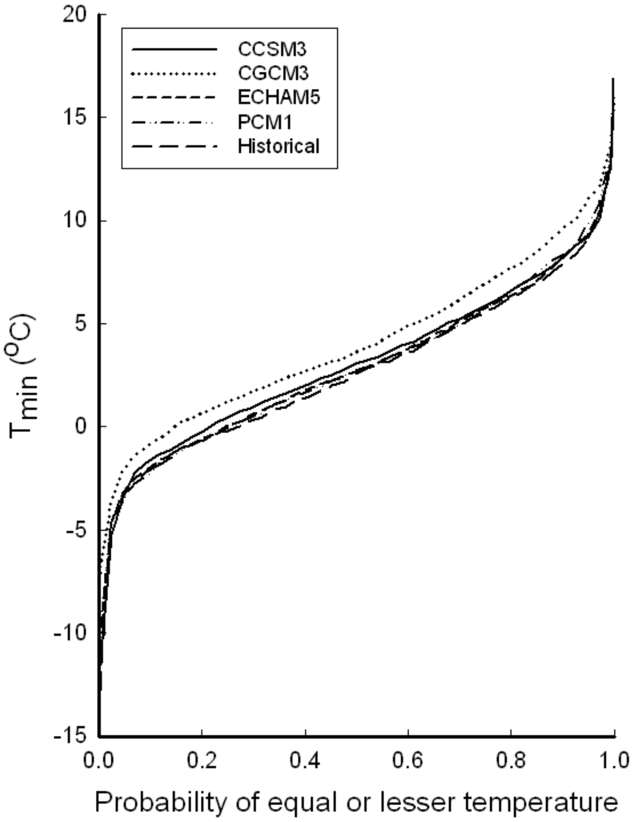


Figure 4. Probabilistic distribution of minimum April temperature for Sunnyside for the 2020 scenario.

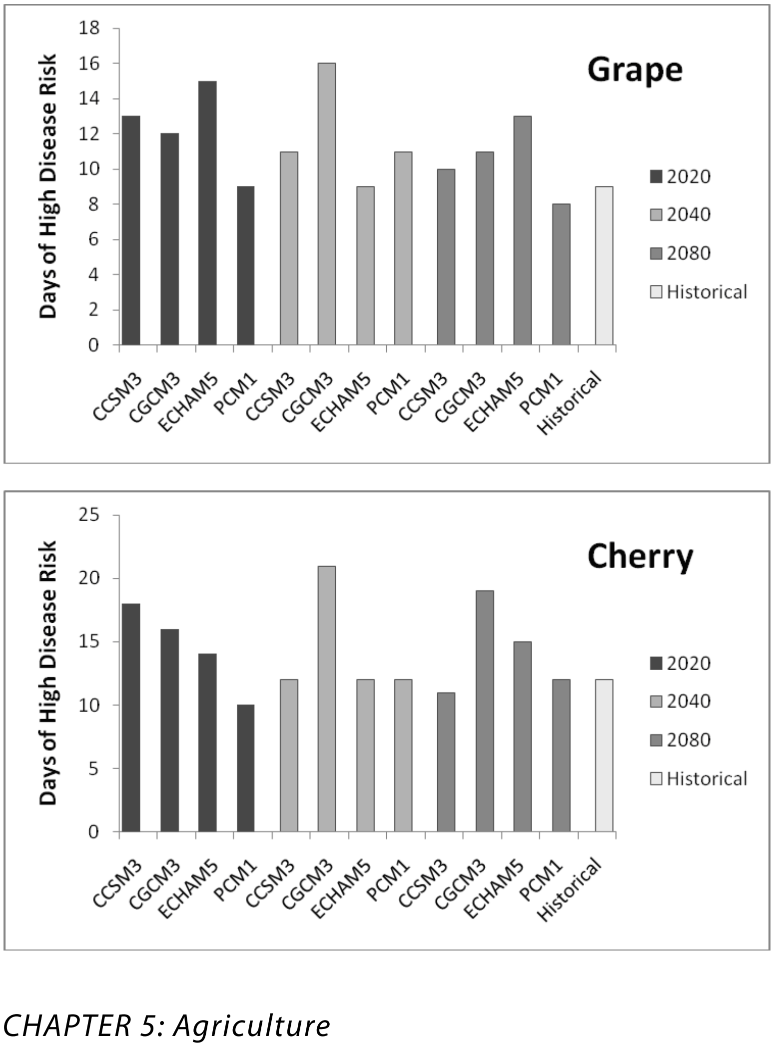


Figure 5. Influence of various climate change scenarios on the predicted risk of powdery mildew infection for grapes and cherries.

3.5.2. Insects

As a model for insects, we selected the codling moth, Cydia pomonella (L.), which is the most important pest of apples in Washington State (Beers et al. 1993). More insecticide applications and quantity of insecticide are applied per acre to control the codling moth than any other pest in Washington (NASS 2006). A model was developed to predict the seasonal life history of codling moth using an accumulation of degree-days (Riedl et al. 1976, Welch et al. 1978, Beers and Brunner 1992). Insect development is governed primarily by temperature so changes in precipitation are not expected to contribute to changes in pest status for most insects. The codling moth model has been primarily used to help growers time the first applications against the first and second generation of this pest and to predict the percent of third generation egg hatch, providing growers some indication of late season risk of crop damage.

The codling moth model was run for Sunnyside using baseline climate and the projection of the four GCMs in this study. Results of these simulations (Table 6) showed first adult flights occurring 6, 9, and 14 days earlier on average than the baseline for the 2020, 2040, 2080 scenarios. The beginning of the first generation egg hatch was advanced by 6, 8, and 13 days, and the beginning of the second generation egg hatch was advanced by 10, 14, and 21 days for the 2020, 2040, and 2080 scenarios.

The predicted fraction of third generation egg hatch was increased dramatically with warming. Earlier emergence of adults in the spring coupled with warmer temperatures in the summer would result in most apple-growing locations in the state experiencing a complete third generation egg hatch. Pheromones used as a control for codling moth would not last the entire season unless more pheromone was added to dispensers, which would increase the cost to growers. In addition, an increase in one to two additional sprays per season would most likely be needed to protect fruit late in the fall, especially on later maturing varieties. Warmer winter temperatures could result in an extended emergence pattern for codling moth making it more difficult to precisely time control applications, further increasing control costs for growers.

3.5.3. Weeds

Weeds account for $7 to 10 billion dollars in agricultural losses in the U.S. (Bridges, 1992) and economic losses from all weeds in the U.S. exceed $36 billion each year (Pimental et al. 2000). Weed species, weed/crop competition, and weed control vary widely among cropping systems and geographic regions. Uncontrolled weeds in annual crops can result in anywhere from 15% to total crop loss depending on weed and crop species present and their density. Weed management in annual crops is necessary to prevent or reduce yield losses.

Currently, few climate models consider the impact of weeds on crop yield as it is generally assumed weeds must be controlled to produce a crop. Estimates of yield stimulation by elevated CO_2 might need to be reduced if effects from competition with weeds are ignored, unless growers adapt accordingly. Most studies on climate change predict that pests

Table 6. Simulated codling moth response to indicated climate projections at Sunnyside, Washington. Scenarios were run for indicated future periods of interest (2020, 2040, 2080).

Weather projection	Scenario	First adult flight	First generation	Second generation	Fraction of third generation
		(day of year)			
Historical		113	142	206	6.0
CCSM3	2020	106	137	195	46.4
	2040	104	134	189	73.8
	2080	97	127	182	90.8
CGCM3	2020	102	132	195	43.4
	2040	98	130	193	54.7
	2080	95	128	186	80.4
ECHAM5	2020	109	139	200	22.3
	2040	108	137	194	44.3
	2080	98	128	187	79.5
PCM1	2020	108	137	197	32.7
	2040	107	136	194	45.4
	2080	104	133	188	70.7
Average	2020	107	136	197	35.9
	2040	104	134	192	54.8
	2080	98	129	186	81.0

will become better able to expand their geographic ranges in a changing climate. An expansion of pest populations may require increased use of agricultural chemicals, implying health, ecological, and economic costs (Rosenzweig et al. 2000). Weeds and other crop pests are projected to expand to higher latitudes (Dahlsten and Garcia 1989; Sutherst 1990).

Anticipated warmer and wetter fall and winter will result in greater numbers and growth of winter annual weeds and require additional herbicide or cultivations to control these weeds. Many winter annual weeds germinate in the late fall and small increases in rainfall and temperature could have large impacts on weed germination and growth during the fall and winter. Volunteer potato, a serious weed in climates with mild winter temperatures, would likely become more abundant with elevated winter temperatures as more tubers would survive in warmer soils. Control of volunteer potato in wheat and corn is accomplished with multiple herbicide applications and cultivation (Boydston, 2004, Steiner et al., 2005).

Overall, there are strong empirical reasons for expecting changes in temperature and CO_2 to have significant effects on weed biology, growth, and weed management. Elevated CO_2 will enhance growth of C_3 weeds allowing them to better compete with C_4 crops, which will obtain only marginal benefits from CO_2 elevation (Ziska, 2003). Stinson and Bazzaz (2006) showed that for a mixed population with two species, the smaller plant might benefit from CO_2 enrichment to a greater extent than the larger plant because of light interception properties, which would give weeds a competitive advantage. The physiological plasticity of weeds and their high degree of intraspecific genetic variation could provide weeds with a competitive advantage in a changing environment. New weed species and more competitive and prolific weeds may require improved timing of weed management practices, improved weed identification and scouting, and more frequent weed control practices (herbicide, mowing, and cultivation).

4. Avenues for Adaptation and Recommendations for Research

Our assessment indicates that, with the possible exception of winter wheat, the main agricultural commodities in eastern Washington State could be affected negatively by future climate warming, even as soon as the next few decades. However, the concurrent elevated atmospheric CO_2 is projected to compensate for the effect of warming and result in yield gains. To cope with the effect of warming and capture the potential benefits of elevated CO_2, adaptation of agricultural cropping systems and management to changing conditions will be critical. Research will play an important role by providing technologies for adaptation.

It is difficult to predict the economic environment under which agriculture will operate as we progress into this century, except that we know that an increasing population projected to reach nine billion people by mid century and the rapid development of highly populated countries such as China and India will ensure high demand for agricultural products. The state's diversified agriculture is likely to be an important factor of adaptation to changing conditions under global climate change. In addition, consequences of climate change appear less severe for higher than lower latitudes, which may favor the relative competitive position of the agriculture of the state and facilitate adaptation.

As shown in Fig. 6, winter wheat yields in the Palouse region around Pullman WA have increased from 3,300 to 5,400 kg ha^{-1} from 1972 to 2003 (perhaps including minor help from CO_2 increase during the period) while yields were only 1,300 kg ha^{-1} 90 years ago (Sievers and Holtz, 1922). This indicates that the contribution of technology (e.g., plant breeding, biotechnology, better crop management) to yield increases should be counted for as a factor that could contribute to mitigate the economic effect of negative climate change impacts, although it is uncertain if the pace of technology improvement will be the same in the future as it has been in the past.

Apples and other temperate tree fruits are projected to benefit from warmer weather combined with elevated CO_2, but management and varieties

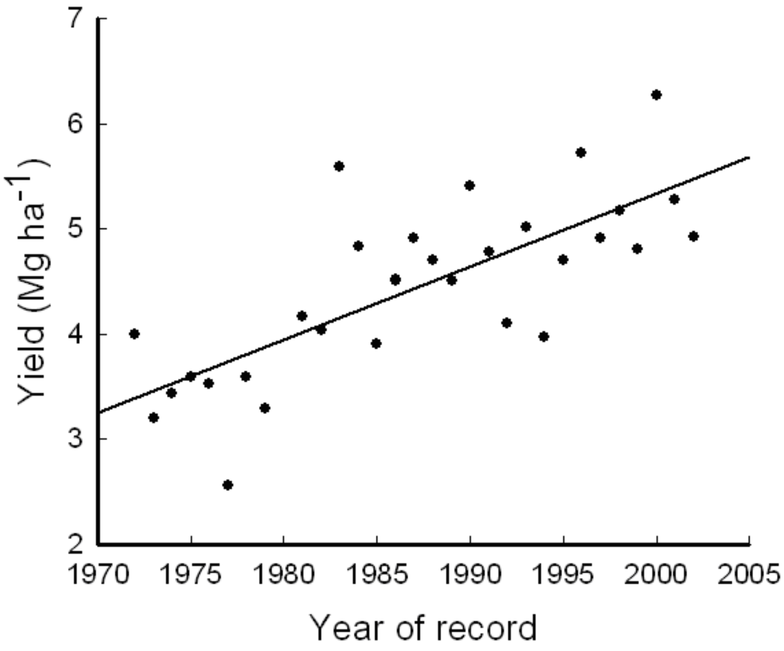


Figure 6. Winter wheat production in Whitman County (based on historic records).

will need to constantly adapt to harvest the benefits of future conditions. Eventually, warming may affect over-winter chill requirements of temperate tree fruits and require replacement by new cultivars or species. In the case of annual crops, modification of planting dates and use of varieties better adapted to the available growing season will be required, particularly in the case of potatoes. For annual and tree fruit crops, the search for more effective and environmentally friendly approaches for controlling more aggressive (or new) insects and weeds will be needed.

Overall, conventional and biotechnology-based breeding will be important to preserve the competitive position of existing commodities. Selection of materials from world regions where the developing future climate conditions already exist in present time is an option, recognizing that the current niche of successful commodities in the state is due to suitable current climatic conditions in eastern WA compared to other regions. Research in automation, sensors, information technologies, and overall improvement of agricultural management will be required to reduce costs. Agricultural research efforts should be targeted to prioritize research that helps to cope with potential negative effects of climate change and to capture the benefits of elevated CO_2, considering that adaptation to evolving future conditions is likely among the largest long-term challenges for agriculture.

Finally, an activity that should be urgently implemented by agricultural research and extension in the state is to maintain a state-of-the-art monitoring network and information center to gather and interpret data on the many manifestations of climate change impacts on agricultural production. This network is extremely important to track the actual speed of change and guide the basic and applied research that will be needed for adaptation.

5. Caveats of Projected Impact of Climate Change on Agriculture

This assessment of possible effects of climate change on Washington agriculture is based on computer simulation models, which are approximations of reality drawing from experimental research to represent the mechanistic processes that relate crop growth and yield and associated factors with climate. However, our projections of the direction and magnitude of yield changes for annual crops generally agree with previous studies. Projections for apples are more uncertain as tree fruit models are less developed and previous studies are not available.

We have selected 4 GCMs for this study out of 20+ available, encompassing the high and lower end of the range of expected warming. We found consistency in the ultimate effects of warming on agriculture regardless of the GCM used. However, changes in extreme heat and cold weather and extreme precipitation events will have impacts that are generally not well represented either by the GCMs themselves or the downscaling procedure that we used to relate the GCM output to local conditions. Other associated factors such as changes in cloudiness affecting solar radiation and changes in air humidity are not considered in our projections, and may have significant effects on future crop yields.

6. Conclusions

The impact of climate change on the agriculture of eastern Washington State is assessed in this study by focusing on the major commodities in terms of output value: Apples, potatoes, and wheat. Agricultural impacts depend on the direct effects of climate, but they also depend on increasing atmospheric CO_2 independent of CO_2's influence on climate. Increased CO_2 in the atmosphere can increase crop yields for some plants and also increase water use efficiency, which in turn may provide additional benefits in dryland crop yields. Projections presented assume that plants have adequate supply of nutrients and are well protected from pests and weeds, and for irrigated crops they assume adequate availability of water for irrigation. Crop response to climate change is assessed based on changes for 2020, 2040, and 2080 scenarios with respect to a baseline climate (1975-2005).

It is projected that the impact of climate change on selected but economically significant crops in eastern Washington will be generally mild in the short term (i.e., next two decades), but increasingly detrimental with time (potential yield losses reaching 25% for some crops by the end of the century). However, the projected elevated CO_2 is expected to provide significant mitigation of climate change effects, and in fact result in important yield gains for some crops. There is some debate about whether the CO_2 effect on plants will be temporary (perennial plants may adapt to new conditions or growth of plants in natural environments may be limited by other factors), but mounting experimental evidence involving well-managed agricultural crops show a definite beneficial effect of "CO_2 fertilization" on growth and yield of many crops, even for perennial crops such as fruit trees that are expected to be in production for many years.

Yields of dryland winter wheat are projected to increase (2 to 8%) for the 2020 scenario or remain generally unchanged or with some gains for the 2040 scenario because earlier maturity in response to warming will provide a degree of water stress avoidance. However, yield reductions (4 to 7%) are projected for the 2080 scenario in the higher precipitation region. When CO_2 elevation is added, yields are projected to increase by 13-15% (2020s) to 13-24% (2040s), reaching gains of 23% to 35% by the 2080 scenario, with the larger gains in drier sites. No change in spring wheat yields is projected for the 2020 scenario, but declines of 10% to 15% for the 2040 scenario, and 20% to 26% for the 2080 scenario are projected due to climate change. Increased CO_2 will compensate for decreased yields, leading to increases of 7% and 2% for the 2020 and 2040 scenarios at Pullman, but a 7% increase (2020s) followed by a 7% reduction (2040s) at Saint John. Earlier planting combined with CO_2 elevation is projected to increase yields by 16% for the 2020s.

Yields of irrigated potatoes are projected to decline by 9%, 15%, and 22% for the 2020, 2040, and 2080 scenarios, respectively, with smaller losses of only 2% to 3% for all scenarios when the effect of CO_2 is included. The development of varieties with a longer duration of green leaf area, combined with elevated CO_2, could potentially result in yield gains of ~15%. However, tuber quality is a concern due to tuber growth limitations under warmer conditions.

Without the effect of elevated CO_2, future climate change is projected to decrease apple production by 1%, 3%, and 4% for the 2020, 2040, and 2080 scenarios, respectively. When the effect of CO_2 is added, yields are projected to increase by 6% (2020s), 9% (2040s), and 16% (2080s). To realize potential yield gains and maintain fruit quality standards at higher yields will require management adaptations.

Caveats of the projection of climate change impacts on agriculture presented in this study are: a) possible changes in the frequency and persistence of extreme temperature (both frosts and heat waves) and precipitation events are not well represented in current climate projections, which could adversely affect crop yields, b) the extent to which the potential benefits of elevated CO_2 will be realized has a degree of uncertainty that should be considered by decision makers, and c) it is also possible that changes in impacts by pests, weeds and invasive species could affect agriculture in ways not described here.

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