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Predicting Response of Potato and Barley to Climate Change in Maine Using the Crop Model DSSAT

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PREDICTING RESPONSE OF POTATO AND BARLEY TO CLIMATE CHANGE IN MAINE USING THE CROP MODEL DSSAT

By

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B.S. University of Maine Farmington, 2015

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(in Plant, Soils and Environmental Sciences)

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By Brogan E. Tooley

Thesis Advisor: Dr. Ellen Mallory

An Abstract of the Thesis Presented
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Climate change has the potential to impact yield and yield stability, and thus, sustainability in agriculture. Farmers are confronted seasonally with the challenges and unpredictability weather can bring. Current climate change projections anticipate an overall rise in temperature, precipitation and CO_2 for the Northeast with weather increasing in variability in the forms of heatwaves, drought and heavy rain events. Using the computer simulation model DSSAT (Decision Support Systems for Agrotechnology), we aimed to assess the vulnerability and potential climate adaptation strategies for potato and barley in Maine.

Chapter 1, "Assessing the Vulnerability of Potato and Barley to Climate Change using the Crop Model DSSAT", encompasses the calibration and evaluation of the crop model DSSAT for two varieties each of potato (an early-season and late-season) and barley (a 2-row variety and 6-row variety) in Maine. The growth and development of each variety was assessed across numerous planting dates under a baseline weather scenario (1989-2018) and four future weather scenarios for 2050-2079, varying by emissions scenario and CO_2 concentration. An additional assessment was conducted looking at yield stability under less variable and more variable weather. Following any necessary adjustments, model evaluations found the calibrated model to adequately simulate all four varieties under various management and growing conditions in the state. Subsequent simulations revealed that the late-season variety of potato and the 6-row barley variety may be more stable with climate change in Maine, while the early-season variety of potato may be more vulnerable, particularly with increased weather variability.

The late-season variety of potato and both varieties of barley performed best with the earliest possible planting, while the early-season variety of potato performed better with late planting. Crop growth and development improved with climate change and projected elevated CO_2 for all four varieties in terms of biomass and final yield. Crop quality could not be evaluated.

Chapter 2, "Investigating Soil Health as a Climate Resilience Strategy for Potato and Barley in Maine Using the DSSAT Crop Model", evaluates adaptive management strategies for potato and barley in Maine. Adaptive management strategies included improved soil health in a manure-based system (amended) and irrigation in a fertilizer-based system, both compared to a conventional fertilizer-based system (nonamended). Here, the model was evaluated for a set of data containing many rotations of potato and barley in a nonamended fertilizer-based system and an amended manure-based system. Following minor changes and a successful evaluation, simulations were conducted using a feasible planting date and the five weather scenarios from Chapter 1. Results found the irrigated system to perform best under all five weather scenarios for potato with the amended system a close second in production performance, while the performance of barley in the amended system was equal to that of the irrigated system. While irrigation may not be the most viable option for all Maine farmers, this study illustrated the importance soil health both now and in the future in improving or maintaining current crop production.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

CO_2	Carbon dioxide
CV	Coefficient of variation
d	Wilmott Index of Agreement
EF	Modeling efficiency
GCM	General circulation model
GDD	Growing degree day
HI	Harvest Index
LAI	Leaf area index
MPEP	Maine Potato Ecosystem Project
N	Nitrogen
nRMSE	Normalized root mean square error
PI	Presque Isle
R^2	Coefficient of deviation
RCP	Representative concentration pathway
RTF	Relative temperature factor
SA	St. Agatha
SLPF	Soil fertility factory
SOM	Soil organic matter
T_{avg}	Average daily temperature
T_{max}	Average maximum temperature
T_{min}	Average minimum temperature
WHC	Water holding capacity
WUE	Water use efficiency

CHAPTER 1: ASSESSING THE VULNERABILITY OF POTATO AND BARLEY SYSTEMS TO CLIMATE CHANGE USING THE CROP MODEL DSSAT

1.1 Chapter Abstract

Potato and grain production systems play a crucial role in Maine's agricultural economy. This study aims to evaluate the vulnerability of potato and barley to climate change in Maine for the years 2050 to 2079. The DSSAT model v4.7 was calibrated and evaluated for contrasting varieties of potato (Atlantic, a short-season variety, and Russet Burbank, a long-season variety) and of barley (Robust, a 6-row feed variety, and Newdale, a 2-row malting variety) using a total of 120 field experiments conducted in Maine. Subsequent simulations were conducted to compare crop yields across multiple planting dates under a baseline period (1989-2018) and under four future weather scenarios (two emissions scenarios, RCP 6.0 and 8.5, with and without elevated CO_2). An additional simulation experiment was performed to evaluate the sensitivity of each variety to increased variability in weather. Following calibration, the model accurately simulated the observed final yields of each variety with a range of modeling efficiencies (EF) from 0.60 to 0.79 and coefficients of determination (R^2) from 0.61 to 0.90. The yields of Atlantic potato, Newdale and Robust barley declined by 6 to 27 % under elevated temperature and precipitation, in the absence of elevated CO_2, while Russet Burbank potato increased 5%. All four varieties yielded highest under climate scenarios with elevated CO_2. Russet Burbank and both varieties of barley performed best with the earliest possible planting date, while Atlantic yielded higher with later planting. Increased variability in weather negatively impacted Atlantic, and positively impacted Robust with Newdale and Russet Burbank relatively unchanged. Results suggest changes in climate may favor longer season or more robust varieties such as Russet Burbank potato or Robust barley, while elevated CO_2 boosted crop growth and development across all varieties.

1.2 Introduction

Measurable changes in Maine's weather patterns have already been documented and changes are projected to intensify in the future (Frumhoff et al., 2007; IPCC, 2014; Fernandez et al., 2015; Wolfe et al., 2018). Over the past century Maine has witnessed a 1.7°C rise in average annual temperature with a 13% increase in total annual precipitation (Fernandez et al. 2015). Between 2035 and 2054, temperature is anticipated to rise an additional 1.0 to 1.7°C in Maine with a 5 to 10% increase in precipitation by 2050 (IPCC, 2014; Fernandez et al., 2015). Between 1958 and 2010, Maine experienced a 70% increase in the amount of rain falling in extreme precipitation events (Fernandez et al., 2015; Wolfe et al., 2018). Increased variability in Maine's weather has already occurred, however, changes in variability of the timing and scale of extreme events is uncertain.

Climate change will present both opportunity and challenges for Maine agriculture (Frumhoff et al. 2007; Wolfe et al. 2018). Increasing temperature has been documented to shorten phenological phases and impact crop development rates (Worthington and Hutchinson, 2005; Eyshi Rezaei et al., 2017), to decrease soil moisture through increased evapotranspiration (Anderson et al., 2010, Williams et al., 2016), and ultimately to reduce crop yield (Worthington and Hutchinson, 2005; Klink et al., 2014). As a result of warmer temperatures the first fall frost is becoming later and the onset of spring is advancing in the Northeast (Frumhoff et al., 2007). This aspect of climate change will increase the number of frost free days, subsequently lengthening the growing season (Frumhoff et al., 2007; Brown et al., 2010; Wolfe et al., 2018). Adversely, increased heavy rains could delay planting, cause physical damage to the crop, degrade fields and increase potential disease pressure (Haltfield et al. 2014; Wolfe et al., 2018). Rising CO_2 concentrations (a driving force of climate change) have been documented to positively impact plant biomass accumulation and yield (Donnelly et al., 2001; Pendall et al., 2003; Trnka et al., 2004; Finnan et al., 2005; Frumhoff et al., 2007) further reinforcing how complicated climate change impacts may be.

Potato-barley rotations are the present industry standard for short rotation potato cropping systems in Maine (Halloran et al., 2005). As the 6th largest potato supplier in the nation (Maine Potato Board, 2016), Maine's potato industry is economically vital to the state's economy (Alford et al., 1996). Potato *(Solanum tuberosum L.)* may be particularly sensitive to changes in weather. With an inherently shallow root system (Opena and Porter, 1994), high transpiration rates (Sharma et al., 2017), and often dry, aerated soils as a result of intensive cultivation (Grandy et al., 2002; Mallory and Porter, 2007), potato is highly susceptible to water stress and wilting. Barley (*Hordeum vulgare*), the third largest crop produced in the U.S., is a profitable rotation crop planted for both malting and feed (Dougherty et al., 2004). Including barley in a cropping system helps maintain soil health by increasing N and C pools in the soil (Grandy et al. 2002), which has been documented to improve tuber quality and yield (Porter and Sisson, 1991).

The integration of real-world processes and computer simulation, known as the *systems approach* (Kropff et al., 2001), aids in the understanding and prediction of how a system will respond under set conditions (Jones et al., 2003). This approach and subsequent prediction models are effective tools in the exploration of potential climate change impacts and adaptive management strategies (White et al., 2011). The *Decision Support Systems for Agrotechnology Transfer* (DSSAT) computer simulation platform (Jones et al., 2003) incorporates climate and soil characteristics, crop genetic information, and management practices to best simulate crop growth and development for a specific region (Jones et al., 2003; Kassie et al., 2016). Within DSSAT, the SUBSTOR-Potato model has been successfully calibrated for a variety of field conditions and management practices around the world (Maa et al., 2010; Šťastná et al., 2010; Daccache et al., 2011a; Vashisht et al., 2015; Kleinwechter et al., 2016; Fleisher et al., 2017; Raymundo et al., 2017; Adavi et al., 2018). Adavi et al. (2018) used the SUBSTOR-Potato model to evaluate the effects of climate change on potato production in Iran with changes in variety and planting date as possible adaptation strategies. For the predominant variety of the region, Adavi et al., (2018) found maximum leaf area, days to reach crucial development stages, and yields, to decline as a function of increased temperature with climate change, while earlier maturing varieties performed better. Raymundo et al. (2017) found that the SUBSTOR model used in DSSAT v4.5 underestimated the impacts of high temperature and elevated CO_2 on crop growth, however, these critiques have been addressed in DSSAT v4.7 (G. Hoogenboom, personal communication, 2019).

The CERES-Barley model within DSSAT has been calibrated for a number of locations, although most studies have been implemented outside of the U.S. (Holden et al., 2003; Trnka et al., 2004; Alexandrov and Eitzinger, 2005; Hlavinka et al., 2010; Rötter et al., 2012). For barley, the timing and intensity of stress events has been documented to adversely affect yields (Hakala et al., 2012; Rötter et al., 2012). Hakala et al. (2011) used the CERES-Barley model to evaluate the sensitivity of spring barley to climate change in Finland. Here, drought or excess rain early in the growing season and elevated temperatures around heading severely reduced the yield of 22 barley cultivars, while heavy rains later in the season delayed harvest leading to pre-harvest sprouting and a reduction in grain quality. The objectives of this study were to: 1) Calibrate and evaluate SUBSTOR-Potato and CERES-Barley for two varieties each, for Maine 2) assess the sensitivity of potato and barley to changes in climate anticipated for 2050 to 2079 and various planting dates 3) evaluate the impact of weather variability on crop yields and yield stability.

1.3 Materials and Methods

1.3.1 Study Site and Field Experiments

Two potato varieties were simulated using SUBSTOR-Potato, Atlantic a mid-season, round-white variety, grown primarily for the chip industry and Russet Burbank a widely grown, late-season variety used primarily for french-fries and baking. Field experiment data from the three major production areas in the state were used to calibrate and evaluate the model. For Atlantic, tuber yields and accompanying crop management information were obtained from two sources: 1) 44 potato variety trials conducted from 2007 to 2010 and 2014 to 2018 at the University of Maine Aroostook Research Farm, Presque Isle (46.653902N, -68.010704W), and at two commercial farms in St. Agatha (47.240972N, -68.366430W) and Exeter (44.988243N, -69.107795W), Maine (G.A. Porter, unpublished data, 2018); and 2) the Maine Potato Ecosystem Project, a long-term cropping systems trial conducted from 1992 to 2008 in Presque Isle, Maine (Alford et al., 1996; Gallandt et al., 1998; Mallory and Porter, 2007; Mallory et al., 2010). In addition, in 2017 and 2018, time-series growth and development data including above-ground and tuber biomass, soil moisture, and soil inorganic N were collected according to DSSAT methods (Hoogenboom et al., 1999) from all three locations of the potato variety trials. For Russet Burbank, yields and accompanying crop management information were obtained from three sources: 1) 17 potato variety trials conducted from 2007 to 2010 and 2014 to 2018 in Presque Isle and St. Agatha, Maine (G.A. Porter, unpublished data, 2018); 2) 4 nitrogen rate trials conducted 2015-2018 in Presque Isle, Maine (G.A. Porter, unpublished data, 2018); and 3) the CRISPI cropping systems trial (Larkin et al., 2017) conducted from 2007 to 2010 in Presque Isle, Maine. Planting dates varied by year for all sites and experiments. Experiments were rainfed at all sites except Exeter, where supplemental irrigation was applied as needed. Dominant soil types at the three locations are Caribou gravelly loam (Fine-loamy, isotic, frigid Typic Haplorthods), Thorndike channery silt loam (Loamy-skeletal, isotic, frigid Lithic Haplorthod), and Penobscot gravelly silt loam (Coarse-loamy, isotic, frigid Typic Dystrudepts) for Presque Isle, St. Agatha, and Exeter, respectively.

Field experiment data used to calibrate and evaluate CERES-Barley for varieties Newdale and Robust were from barley variety trials conducted from 2015-2018 at two sites, Old Town (44.931008, -68.695286) on a Nicholville sandy loam soil (Coarse-silty, isotic, frigid Aquic Haplorthods) and Presque Isle on a Caribou gravelly loam soil. Additional yield data for Robust barley came from the Maine Potato Ecosystem Project mentioned above, with 13 experiments from 1993-1997 and 2003-2005 in Presque Isle. Detailed soil moisture, soil nitrogen and plant nitrogen data from the Maine Potato Ecosystem Project from 2003-2005 were used for initial soil evaluation and the calibration of Robust. Similar to potato, barley growth and development time-series data for both varieties were collected in accordance with DSSAT methods (Hoogenboom et al., 1999) in 2017 and 2018 from the variety trial at the Old Town location. A planting date trial with four planting dates ranging from April 30th to May 30th in 2017 using Newdale was also sampled using DSSAT Methods. Time-series data included above-ground barley biomass, growth stages, soil moisture, and soil inorganic nitrogen, with additional measures taken at harvest.

1.3.2 The DSSAT Model

The DSSAT crop model was chosen to simulate yield under current and future climate conditions in Maine. DSSAT has been widely used for evaluating crop performance under climate change scenarios

(Holden et al., 2003; Hakala et al., 2012; Mereu et al., 2015; Dias et al., 2016; Kleinwechter et al., 2016), including with elevated CO_2 (Tubiello et al., 2002; Trnka et al., 2004; Daccache et al., 2011a; Bao et al., 2015; Kassie et al., 2016; Raymundo et al., 2017) and various adaptation strategies (Trnka et al., 2004; Vashisht et al., 2015; Eitzinger et al., 2016; Adavi et al., 2018). DSSAT consists of component models that incorporate soil and weather inputs to compute soil moisture and nitrogen dynamics, crop growth, and crop yield on a daily time step (Jones et al., 2003). Minimum data inputs include daily weather, site-specific soil characteristics, initial field conditions, and management. Atmospheric CO_2 can be adjusted in the model to remain constant, increase, or decrease from a starting value with additional options for the methodology used to simulate soil organic matter processes, photosynthesis, evaporation, and hydrology (Jones et al., 2003) .

SUBSTOR-potato is the crop model used by DSSAT to simulate the phenological development, biomass accumulation, and partitioning of potato (IBSNAT et al., 1993). Tuber initiation, growth rate, and leaf area expansion are controlled by cultivar-specific coefficients ('genetic coefficients') within the model. Within SUBSTOR, relative temperature factors (RTF) provide a non-linear function that simulates plant response across a range of temperatures while accounting for the negative effects of both high and low temperatures on potato growth. As plant organ response to temperature varies, RTFVINE describes vine growth relative to atmospheric temperature, while RTFSOIL describes root and tuber growth relative to soil temperature. Relative temperature factors were used in assessing the number of optimal growing days for each factor with climate change. Here, the number of optimal days for vine growth within each growing season was calculated as the total number of days with average daily temperature greater than 17°C and less than 24°C, while the number of optimal days for root and tuber growth was calculated as the total number of days that had an average daily soil temperature between 15°C and 23°C.

Similar to the SUBSTOR-potato model, the CERES-Barley model simulates growth and yield through variety-specific simulation of daily-growth and development (Jones et al., 2003). Cultivar-specific genetic coefficients within the CERES-Barley model control: plant response to photoperiod and temperature, phenological development phases, biomass accumulation, grain characteristics (i.e. number and size) and tiller weight. Both CERES-Barley and SUBSTOR-Potato break plant development into major growth stages with the rate of development dependent on growing degree days (GDD) (IBSNAT et al., 1993; Jones et al., 2003).

1.3.3 Model Inputs

Soil

Soil files in DSSAT were customized for each experiment using site-specific soil characterization by depth, experiment-specific top-soil traits and soil data from NRCS (NRCS, 2018). Soil was characterized every 20 cm to a depth of 80 cm when possible, during the 2017 field season. Characterizations included bulk density and soil water content via the Core and Oven-drying method, respectively (Hoogenboom et al., 1999) and chemical (organic matter, pH, CEC) and textural (particle size) properties via standard soil testing. The chemical composition of the soil was known for the first 20 cm of each year and experiment establishing year-to-year field-specific soil differences. Where measurements could not be obtained for deeper layers in the profile at some locations, region-specific soil data from NRCS was used.

Weather

For the Presque Isle site, average daily precipitation and maximum (T_{max}) and minimum (T_{min}) temperature were acquired from the National Climatic Data Center through NOAA (National Oceanic and Atmosphere Administration). Consistent NOAA data was not available within a 25km radius of the other sites (Exeter, St. Agatha, and Old Town). Instead these data were obtained from PRISM, which provides interpolated measures at a 4km x 4km resolution (PRISM, unpublished data, 2019). For all sites, solar radiation data was obtained from NASA-POWER (Prediction of Worldwide Energy Resources) (NASA-POWER, unpublished data, 2019).

Other Inputs

Simulation options and methods within the model remained in their default-state with the exception of CO_2 and the ‘method of soil organic matter’, where the Keeling-Curve and the CENTURY model were applied. Initial field conditions were established in the model with estimated soil nitrogen by depth using field data from Zebarth et al. (2003) for the top layer and an estimated average soil-specific percent change based on NRCS soil data. Other initial field conditions included crop residue amounts and characteristics estimated using field observations. Passive, or stable carbon within the soil profile was estimated from data collected in the Maine Potato Ecosystem Project, where stable carbon in conventionally managed plots averaged 65% of the total carbon pool. All management inputs were specific to site, experiment, and year.

1.3.4 The Climate Model

DSSAT-Perturb (ClimSystems, 2019) was used to generate future weather data. It is an add-on tool based on the SimCLIM climate model (ClimSystems, 2019) that uses a statistical downscaling approach with monthly general circulation model (GCM) behavior and daily region-specific historical weather to generate subsequent daily weather on a local scale (Yin et al., 2013). Future weather, 2050-2079 for Presque and St. Agatha, was generated from site-specific historical weather for 1989-2018 using an ensemble of three GCM's: GFDL-CM3, GISS-E2, HadGEM2-ES recommended for use in the Northeast (S. Birkel, personal communication, 2019). For each location of interest, weather was generated for two Representative Concentration Pathways (RCP's), the intermediate scenario RCP 6.5 and the high greenhouse gas (GHG) emissions scenario RCP 8.0 (IPCC, 2014).

1.3.5 Model Calibration and Evaluation

Prior to the calibration of variety-specific parameters, time-series soil moisture data from the Ecosystem project from 2003 to 2005 for Robust barley was used to evaluate the performance of the soil model. Barley experiments were used to compare simulated and observed soil dynamics, as the inherently high spatial variability of potato made it difficult to measure and compare soil moisture with the model. A soil fertility factor (SLPF) was calibrated for all sites to account for site-specific differences related to the effects of soil nutrients other than nitrogen (Romero et al., 2012). To estimate the SLPF, the final yield from experiments used in variety-specific calibration for all four cultivars at each location were used. The normalized Root Mean Square Error (nRMSE) between observed and simulated yields was used to identify the SLPF within a range of 0.75 and 1.0 for each site, with the lowest nRMSE representing the best fit. Resulting SLPFs were: 0.96, 0.83, 1.0 and 0.94 for Presque Isle variety trials, Presque Isle Ecosystem project, St. Agatha, and Exeter, respectively.

Model parameter estimation, also referred to as *calibration*, requires a set of observed data from the ‘real system’ that, when compared to the behavior of the simulated system, can be used to minimize differences between the two (Jones et al. 2011). Initial simulations were conducted to gauge how well the model performed for each variety. The model’s ability to predict for the Atlantic variety of potato resulted in no further calibration from the predetermined Atlantic genetic coefficients in DSSAT 4.7 (Table 1.1). Calibration of the soil fertility factor resolved site-specific differences considerably. Russet Burbank required calibration prior to simulating. Data from the 2015-2017 variety and nitrogen rate experiments listed above were selected for calibration. The parameter estimation tool, GLUE (Generalized Likelihood Uncertainty Estimation), was unsuccessful in estimating the genetic coefficients. Genetic coefficients were calibrated with 2015-2017 growth and development data using the Sensitivity Analysis tool in DSSAT and the nRMSE of simulated and observed yields to identify the best fit (Table 1.1). Growth parameters including leaf area expansion rate and tuber growth rate were adjusted first, followed by phenological parameters for tuber growth suppression and sensitivity to photoperiod and temperature. Baseline coefficients used in calibration were from SUBSTOR v2.0 (IBSNAT et al., 1993).

Table 1.1. Genetic coefficients for the varieties used to assess the effects of climate change on potato and barley in Maine.

	Codes	Definitions	Coefficients	
			Atlantic	Russet Burbank
Potato	G2	Leaf area expansion rate after tuber initiation (cm^2 m^{-2} d^{-1})	1000	1650
	G3	Potential tuber growth rate (g m^{-2} d^{-1})	30	29
	PD	Suppression of tuber growth following tuber induction (relative index)	0.8	0.4
	P2	Tuber initiation sensitivity to long photoperiods (relative index)	0.1	0.5
	TC	Upper critical temperature for tuber initiation (°C)	21	17
			Newdale	Robust
Barley	P1V	Optimum days for vernalizing	0	0
	P1D	Photoperiod response (% reduction per 10-hour drop in a photoperiod)	120	2
	P5	Grain filling (excluding lag) phase duration (Degree days (°C.d))	192	700
	G1	Kernel number per unit canopy weight at anthesis (# g^{-1})	28	20
	G2	Standard kernel size under optimum conditions (mg)	33	55
	G3	Standard, non-stressed mature tiller wt. (incl. grain) (g, dry wt)	0.7	2.7
	PHINT	Interval between successive leaf tip appearances (Degree days) (°C.d))	70	60

Genetic coefficients for the barley variety Robust were estimated with GLUE using 2003, 2005 (Presque Isle) and 2017 (Old Town) time-series growth and development data and over 6,000 iterations. The Sensitivity Analysis tool in DSSAT was used for additional calibration of the genetic coefficients. Adjustments to the optimized parameters from GLUE included the ‘P1V’ coefficient, changed to 0 as days to vernalization did not apply (Choudhury et al. 2018). The ‘G3’ coefficient was also adjusted to the value measured in Old Town, 2017 (Table 1.1). Newdale barley genetic coefficients were calibrated without the use of GLUE. Calibration was performed using the Sensitivity Analysis tool and time-series growth and development data from the 2015 variety trials conducted in Presque Isle and Old Town, and the 2017 variety trial conducted in Old Town. Similar to Robust, the ‘P1V’ coefficient was changed to 0 and the ‘G3’ coefficient was adjusted to the average of the measured values.

Model performance was evaluated for each variety using a different number of field experiments because, as stated above, the total number of experiments available differed among varieties and in all cases except Atlantic, some were used for model calibration. Model evaluation was conducted using 44 experiments over 19 years for Atlantic, 11 experiments over 7 years for Russet Burbank, 11 experiments over 9 years for Robust, and 7 experiments over 2 years for Newdale. Model performance was evaluated using the following statistics: coefficient of determination (R^2), normalized Root Mean Square Error (nRMSE), modeling efficiency (EF), and Willmott index of agreement (d) (Willmott et al. 1981).

1.3.6 Simulations

Simulations were conducted using a set of standard initial soil conditions and crop management practices for each crop, variety, and location that were based on the most common conditions and management practices for the field experiments (Table 1.2). Weather scenario treatments included: historical weather (1989-2018) and four predicted weather scenarios for 2050-2079 based on RCP 6.0 and 8.5, using current atmospheric CO_2 concentrations and using estimated future CO_2 concentrations relative to each emissions scenario (527 ppm and 638 ppm for RCP 6.0 and 8.5, respectively). Planting date treatments included four dates spaced 10 days apart, starting 2 May, for potato, and five dates spaced 10 days apart, starting 12 April, for barley. SUBSTOR-Potato does not estimate crop maturity, thus, maturity for potato had to be estimated based on variety-specific phenological responses to environmental cues. Termination *(maturity*) for Atlantic was established using the average cumulative growing degree days (GDD) between planting and harvest, calculated with observed maturity dates relative to corresponding weather. Russet Burbank being a late-season variety, will typically grow until the first fall frost or period of drought (G.A. Porter, personal communication, 2019). Based on yearly weather evaluations, first frost ranked foremost. Average season length from planting to first frost (< 0°C), with a maximum growing period of 150 days (G.A. Porter, personal communication, 2019) was used as termination in the model for Russet Burbank. The CERES-Barley model determined maturity for Robust and Newdale barley as a function of phenology and environmental conditions. The extent to which each crop is affected relative to planting date and climate scenarios is best depicted via the number of days to reach ‘maturity’ (Table 1.3).

Table 1.2. Crop management practices and initial soil characteristics used in simulations, by crop, location, and variety.

		Management				Initial Soil Conditions (0-20cm)			
		Previous Crop Type	Seeding Rate	Fertilizer	Method to Determine Harvest Date†	Total Residue	Nitrogen (NO3)	Organic Carbon	Stable Carbon
			# m^{-2}	kg ha^{-1}		kg ha^{-1}	ppm	—— % ——	
Potato									
Presque Isle	Atlantic	Barley	4.31	191	GDD	1930	10.5	2.09	1.35
	Russet Burbank	Barley	2.72	191	First frost	1930	10.5	2.09	1.35
St. Agatha	Atlantic	Barley	4.31	197	GDD	1930	10.5	2.38	1.55
	Russet Burbank	Barley	2.72	197	First frost	1930	10.5	2.38	1.55
Barley									
Presque Isle	Newdale	Potato	400	79	Maturity	929	10.5	2.09	1.35
	Robust	Potato	400	79	Maturity	929	10.5	2.09	1.35
St. Agatha	Newdale	Potato	400	79	Maturity	929	10.5	2.38	1.55
	Robust	Potato	400	79	Maturity	929	10.5	2.38	1.55

† Harvest date was set for Atlantic at 1385 cumulating growing degree days (GDD) after planting and for Russet Burbank at the first day when temperatures fell below 0°C or the reached maximum 150 days after planting. For barley varieties, harvest date was at crop maturity as determined by the CERES-Barley model.

Table 1.3. Days to maturity for site-specific planting date treatments and average number of days from planting to maturity and yield as a function of GDD, first frost, planting date and climate.

	Days to Maturity									
	Presque Isle					St. Agatha				
Potato planting dates	5.02	5.12	5.22	5.30		5.05	5.15	5.25	6.05	
Atlantic										
1989-2018 Historical	108	103	98	96	-	119	113	111	114	-
2050-2079 RCP 6.0	97	92	86	84	-	105	100	95	93	-
2050-2079 RCP 8.5	92	88	83	80	-	101	95	90	87	-
Russet Burbank										
1989-2018 Historical	145	135	125	117	-	147	137	127	116	-
2050-2079 RCP 6.0	150	148	138	130	-	150	146	136	126	-
2050-2079 RCP 8.5	150	150	142	134	-	150	150	143	132	-
Barley planting dates	4.12	4.22	5.02	5.12	5.22	4.12	4.22	5.02	5.12	5.22
Newdale										
1989-2018 Historical	86	78	71	66	61	90	81	74	68	63
2050-2079 RCP 6.0	80	81	74	68	63	83	75	68	63	59
2050-2079 RCP 8.5	77	69	63	59	55	80	72	65	61	57
Robust										
1989-2018 Historical	109	101	95	90	86	115	105	99	94	89
2050-2079 RCP 6.0	102	94	88	83	79	105	97	91	86	82
2050-2079 RCP 8.5	98	91	85	80	77	101	94	88	83	79

The potential impact of predicted increases in weather variability on crop yields and yield stability was explored by isolating periods with high and low weather variability within the 1989 to 2018 historic weather record and comparing subsets of the simulated yield from both historic and future weather for planting date 3 (5.22 for Potato and 5.02 for Barley). The two contrasting time periods were identified based on the variability of seasonal and day-to-day rainfall and temperature: a stable period (1992-2004) and more variable period (2006-2018).

1.3.7 Statistical Analysis

Simulation results were analyzed using a REML mixed effects model in JMP (JMP®, Version 14.3). The REML model included planting date, weather scenario, and their interaction as fixed effects, and replicates (years) as a random effect. Due to a lack of homogeneity of variances that could not be resolved with data transformation, analyses were conducted separately by site and variety. The unequal variance of crop yields between the more stable and more variable time-periods were evaluated using a Levene's test in JMP.

1.4 Results and Discussion

1.4.1 Model Evaluation

The DSSAT model adequately simulated observed soil moisture dynamics but improvements could be made. Modeling efficiency and R^2 values were 0.84 and 0.85 (Table 1.4), indicating the model strongly replicate within-season variability in soil moisture (Figure 1.1).

Table 1.4. Model performance statistics comparing simulated and observed for crop yields and soil moisture under rainfed conditions for multiple locations, management practices, and growing conditions in Maine.

Statistics		Potato		Barley	
	Soil Moisture	Atlantic	Russet Burbank	Newdale	Robust
Coefficient of determination (R^2)	0.85	0.78	0.61	0.90	0.89
Slope (m)	0.9813	0.965	1.020	0.930	1.081
nRMSE	12.43	13.29	12.26	10.74	13.25
Modeling Efficiency (EF)	0.84	0.76	0.60	0.79	0.84
Index of Agreement (d)	0.93	0.94	0.90	0.96	0.96

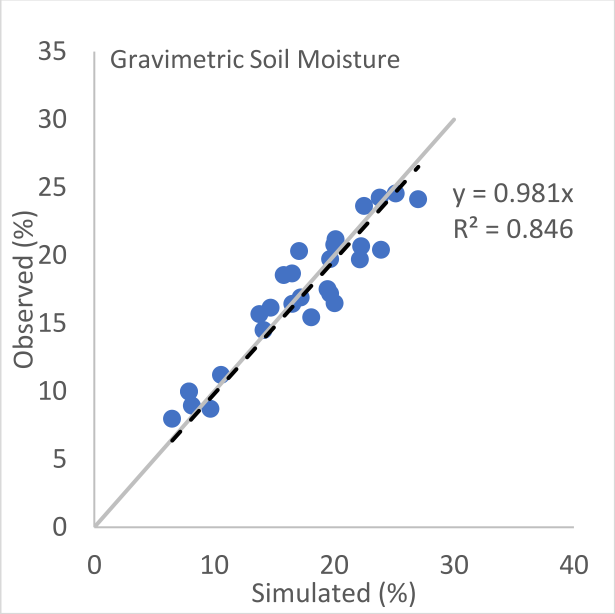

Figure 1.1. Simulated and observed soil moisture (0-20 cm) in Robust barley (2003-2005) and Atlantic potato (2017) throughout the growing season in Presque Isle, Maine

SUBSTOR-Potato successfully predicted rainfed tuber yield for potato varieties Atlantic and Russet Burbank under various growing conditions and management practices in Maine (Figures 1.2a and 1.2b). The nRMSE's were 13.3% for Atlantic and 12.3% for Russet Burbank (Table 1.4), which are below or within the range of nRMSE's from other similar potato modeling studies. Adavi et al. (2018), Kleinwechter et al. (2016), Raymundo et al. (2017), and Tubiello et al. (2002) reported relative nRMSE's of 2.18, 28.1, 21.4, and 15 to 25%, respectively. The relatively high modeling efficiency and index of agreement values further reinforced the model's accuracy in predicting tuber yields for both varieties. The R^2 with the intercept set to zero was 0.78 and 0.61 for Atlantic and Russet Burbank (Figure 1.2a and b).

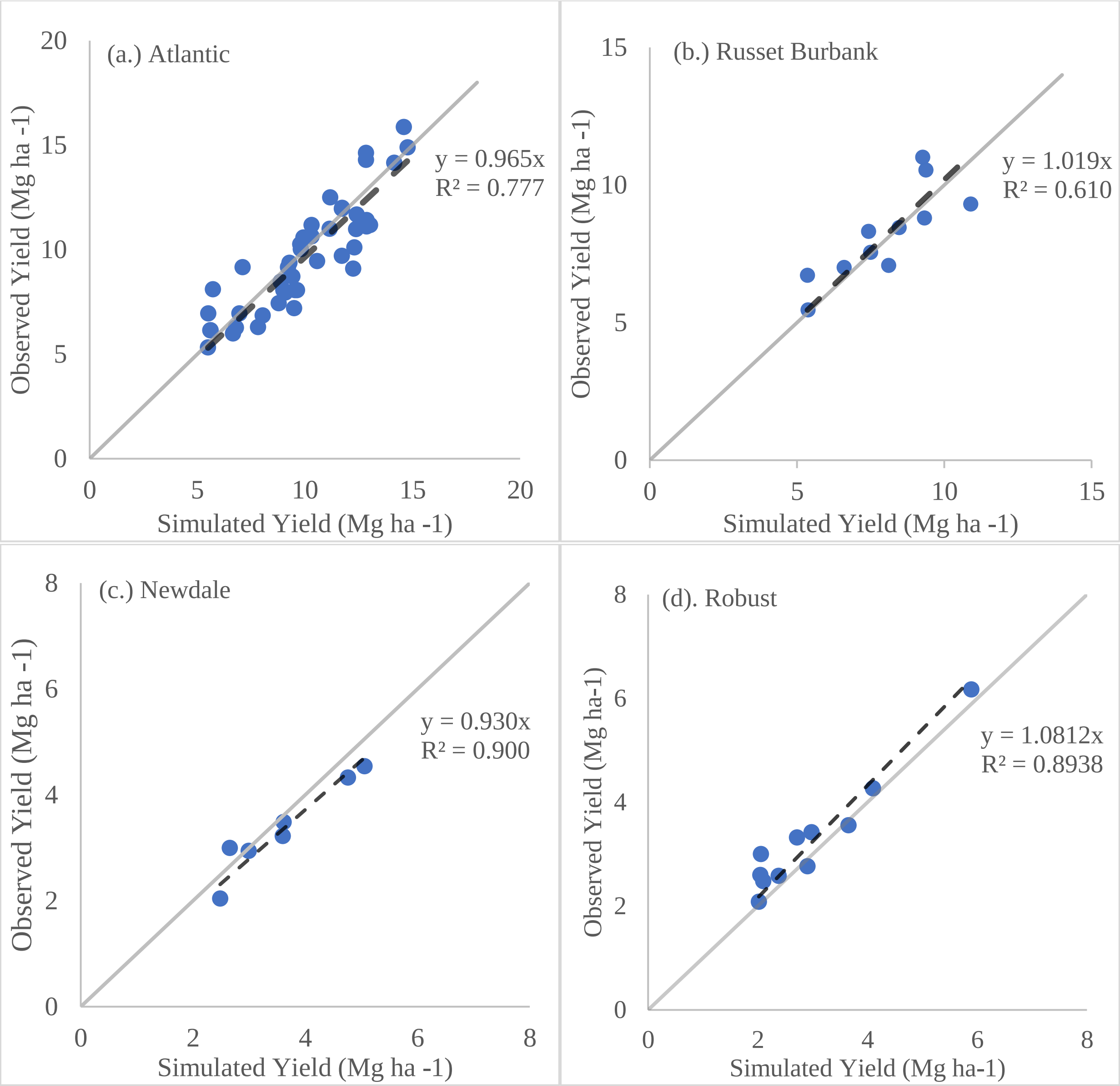

Figure 1.2. Comparison of simulated and observed yields for potato and barley (Mg ha $^{-1}$). Potato tuber varieties include Atlantic (a) and Russet Burbank (b) and barley grain varieties Newdale (c) and Robust (d). All varieties were grown under rainfed conditions in multiple locations statewide varying in management practices and environmental conditions.

The CERES-Barley model also performed well following calibration (Figure 1.2c and d). There was close agreement between predicted and observed yields for Robust, with an nRMSE of 13.3% and an R^2 of 0.89, and for Newdale, with an nRMSE of 10.7% and an R^2 of 0.90 (Table 1.4). These model performance values are similar to those reported by Hlavinka et al. (2010) and Trnka et al. (2004) in their modeling studies where CERES-Barley was also calibrated under various field conditions and management practices in central Europe.

1.4.2 Weather Changes

Average, T_{min} and T_{max} daily temperature and precipitation were compared among the generated weather scenarios and the baseline period, 1989-2018. For both locations, average daily temperature for in-season months (April to Sept.) increased on average by 1.7 and 2.2°C for RCP 6.0 and 8.5, respectively (Table 1.5). There was little variation in the average temperature change between months with the exception that the change in average daily temperature for August under RCP 6.0 was only 1.1°C and the change for June under RCP 8.5 was 3.2°C. Under RCP 6.0 and 8.5 both the T_{min} and T_{max} showed the greatest deviation from the baseline weather in the months of April, May and September. T_{min} exhibited a greater increase than T_{max} across all in-season months with the greatest rise occurring in April by as much as 52% and 77% for RCP 6.0 and 8.5, respectively. Asymmetric changes in temperature were in agreement with Brown et al. (2010) who documented non-uniform changes in the seasonal temperature distributions with greater warming in minimum daily temperatures than maximum for the Northeast. Total in-season precipitation increased with generated climate scenarios by 142 mm and 213 mm for RCP 6.0 and 8.5, respectively. Month-to-month differences in average precipitation fluctuated more than temperature with an 8 mm and 13 mm increase in precipitation from April to June and as much as a 2 mm and 4 mm decrease in precipitation in September for RCP 6.0 and 8.5. All months increased in precipitation with the exception of September. This observed overall shift in the Northeast towards a warmer and wetter climate has been reported by numerous other regional studies (Frumhoff et al., 2007; Brown et al., 2010; Douglas and Fairbank, 2010; Wolfe et al., 2018).

Table 1.5. Monthly temperature and precipitation for current and future weather scenarios at two locations, Presque Isle (PI) and St. Agatha (SA), Maine.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Average Daily Temperature							°C						
PI	1989-2018 Historical	-11.6	-10.0	-4.4	3.3	11.1	16.1	18.8	18.3	13.3	6.6	0.0	-7.2
	2050-2079 RCP 6.0	-8.8	-8.3	-2.2	5.0	12.7	17.7	20.5	19.4	15.0	8.3	1.6	-5.5
	2050-2079 RCP 8.5	-7.7	-7.2	-1.1	5.5	13.3	18.3	21.1	20.5	16.1	9.4	2.7	-4.4
SA	1989-2018 Historical	-12.7	-11.6	-5.5	2.2	10.0	15.5	18.3	17.7	12.7	6.1	-0.5	-8.3
	2050-2079 RCP 6.0	-10.0	-9.4	-3.8	3.8	11.6	16.6	20.4	19.4	14.4	7.7	1.1	-6.1
	2050-2079 RCP 8.5	-8.8	- 8.8	-2.7	4.4	12.7	17.7	15.0	20.0	15.5	8.8	1.6	-5.5
Minimum Daily Temperature							°C						
PI	1989-2018 Historical	-16.6	-15.7	-9.4	-1.6	5.1	10.1	13.1	12.1	7.5	1.9	-3.8	-11.7
	2050-2079 RCP 6.0	-13.8	-13.5	-7.3	0.0	6.7	11.7	14.7	13.6	9.3	3.6	-2.0	-9.5
	2050-2079 RCP 8.5	-12.4	-12.3	-6.2	0.8	7.5	12.4	15.4	14.4	10.2	4.4	-1.2	-8.4
SA	1989-2018 Historical	-17.9	-17.4	-10.8	-2.3	4.7	9.9	13.0	12.3	7.5	1.5	-4.4	-12.5
	2050-2079 RCP 6.0	-15.0	-15.1	-8.7	-0.6	6.3	11.5	14.6	13.8	9.3	3.2	-2.6	-10.3
	2050-2079 RCP 8.5	-13.6	-14.0	-7.6	0.2	7.2	12.3	15.3	14.5	10.2	4.0	-1.7	-9.2
Maximum Daily Temperature							°C						
PI	1989-2018 Historical	-6.3	-4.7	1.0	8.6	17.1	22.0	24.8	24.1	19.4	11.6	3.8	-3.0
	2050-2079 RCP 6.0	-4.0	-2.9	2.6	10.1	18.5	23.3	26.5	25.7	21.3	13.4	5.4	-1.2
	2050-2079 RCP 8.5	-2.8	-2.0	3.5	10.9	19.2	23.9	27.3	26.5	22.2	14.3	6.2	-0.3
SA	1989-2018 Historical	-7.6	-6.0	-0.3	6.9	15.8	20.9	23.5	23.0	18.3	10.5	3.0	-4.1
	2050-2079 RCP 6.0	-5.3	-4.2	1.3	8.4	17.2	22.2	25.2	24.6	20.2	12.3	4.6	-2.3
	2050-2079 RCP 8.5	-4.1	-3.3	2.1	9.2	17.9	22.8	26.0	25.3	21.1	13.2	5.4	-1.4
Total In-Season Precipitation							mm						
PI	1989-2018 Historical	72	60	69	73	90	101	109	95	88	101	86	93
	2050-2079 RCP 6.0	82	71	73	81	98	109	112	99	87	112	93	103
	2050-2079 RCP 8.5	87	76	75	84	101	113	114	102	86	117	96	109
SA	1989-2018 Historical	74	61	69	77	88	111	111	98	96	108	86	92
	2050-2079 RCP 6.0	85	72	73	85	96	120	113	101	94	120	93	103
	2050-2079 RCP 8.5	90	77	76	89	101	124	115	103	93	126	96	108

Warmer temperatures leading to an increase in the number of frost-free days is already apparent as Maine's average growing season length is 12 to 14 days longer than in 1930 (EPA, 2016). This trend was observed with generated future weather, where the first fall frost was an average of 13 to 18 days later for RCP 6.0 and 8.5 (data not shown). When combined with an earlier spring thaw, also predicted by the generated weather, the growing season lengthened by 20 to 27 days per year for both RCP's, respectively.

1.4.3 Crop Response to Climate Change

Location had minimal effect on crop response to climate change for both potato and barley (Table 1.6). However, there were preexisting site differences in crop yields which were reflected in the simulations. Observed differences in yield between Presque Isle and St. Agatha were likely a result of site-specific soil fertility, daily weather dynamics and management. Across all five climate scenarios (including the baseline), both potato varieties and barley varieties yielded higher on average for the St. Agatha location, consistent with site-specific yield differences observed in the field.

Potato varieties had varying responses to changes in climate. For Atlantic, average tuber yield decreased significantly under weather scenarios RCP 6.0 and 8.5, by 18% and 27%, respectively, in Presque Isle, and by 13% and 20%, respectively, in St. Agatha (Table 1.6). With the addition of elevated CO_2, Atlantic potato yields increased by 6% with RCP 6.0 while remaining similar to the baseline for RCP 8.5 in St. Agatha. In Presque Isle, Atlantic potato yields remained similar to the baseline under RCP 6.0 and decreased by 5% with RCP 8.5. In contrast to Atlantic, Russet Burbank yields increased by 5% with a rise in temperature and precipitation under RCP 6.0 in Presque Isle and RCP 8.5 in St. Agatha exhibiting a site-dependent response. Russet Burbank yielded significantly higher with elevated CO_2 under both climate scenarios by 15% to 18% at both locations (Table 1.6).

Table 1.6. Average simulated potato tuber yield (Mg ha^{-1}) and barley grain yield (Mg ha^{-1}) as affected by weather scenario and planting date in Presque Isle (PI) and St. Agatha (SA), Maine, with ANOVA results.

		Potato				Barley			
		Atlantic		Russet Burbank		Robust		Newdale	
Main effect averages		PI	SA	PI	SA	PI	SA	PI	SA
Weather scenario									
Historical		9.15 a	10.98 b	10.12 c	10.75 c	4.51 c	5.06 c	3.54 c	3.98 c
RCP 6.0		7.52 c	9.59 c	10.57 b	11.18 bc	4.21 d	4.76 d	3.32 d	3.76 d
RCP 8.5		6.73 d	8.81 d	10.39 bc	11.28 b	4.00 e	4.58 d	3.20 d	3.65 d
RCP 6.0 + CO_2		9.36 a	11.67 a	11.64 a	12.37 a	4.80 b	5.40 b	3.82 b	4.29 b
RCP 8.5 + CO_2		8.73 b	11.11 b	11.61 a	12.68 a	4.992 a	5.63 a	4.02 a	4.55 a
Planting date									
1		7.97 c	10.08 b	11.72 a	12.47 a	5.06 a	5.43 a	4.10 a	4.45 a
2		8.22 b	10.28 b	11.10 b	12.13 a	4.81 b	5.35 ab	3.81 b	4.27 b
3		8.28 b	10.64 a	10.51 c	11.56 b	4.63 c	5.21 b	3.58 c	4.03 c
4		8.72 a	10.73 a	10.14 d	10.44 c	4.26 d	4.92 c	3.34 d	3.86 d
5		-	-	-	-	3.75 e	4.51 d	3.08 e	3.63 e
Source of Variation	d.f.	ANOVA							
Year	29	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003
Weather scenario (WX)	4	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Planting date (PD)	3, 4	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
WX x PD	12, 16	0.7815	0.4185	0.7544	0.5926	0.6539	0.8846	0.0347	0.1383
C.V., %		10%	10%	9%	12%	11%	11%	10%	11%

Classified as a short-day, cool-season crop with preference to warm days and cool nights, potato performs surprisingly well in hot environments when evapotranspiration demands are met, as a result of accelerated respiration and increased photosynthetic rates (Sanders and Creamer, 1996). Changes in climate lead to faster accumulation of growing degree days, advancing maturity for Atlantic and ultimately shortening the growth and development period. In contrast, with delayed frost, the growing season for Russet Burbank lengthened with climate change, prolonging the potential for biomass accumulation (Table 1.3). For both potato varieties, the number of optimum days for vine growth (where air temperatures were between 17°C and 25°C) increased with climate change by 22% on average (Table 1.7). This favorable increase was also accompanied by a 74% increase in the average number of above-optimum days where atmospheric temperatures were unfavorably high (data not shown). Vine growth was favored by later planting dates for Atlantic potato and earlier planting dates for Russet Burbank, explaining some of the variety-specific differences in yield relative to planting. For root and tuber growth, the number of optimum days (where soil temperatures were between 15°C and 24°C) drastically decreased with climate change and later planting for both varieties and locations with a relative increase in the number of above optimal days (unfavorably high soil temperature). This observed decrease in optimal days for root and tuber growth with later planting may also be a function of growing season length.

Table 1.7. The number of optimal days for vine growth (RTFVINE†) and root and tuber growth (RTFSOIL‡) as affected by planting date and weather scenario for each potato variety and location.

	Presque Isle				St. Agatha			
Planting Dates &Weather	5.02	5.12	5.22	5.30	5.05	5.15	5.25	6.05
RTFVine†								
Atlantic								
1989-2018 Historical	46	48	50	51	48	49	50	50
2050-2079 RCP 6.0	57	59	59	60	60	62	62	63
2050-2079 RCP 8.5	56	59	60	62	63	64	65	67
Russet Burbank								
1989-2018 Historical	58	57	56	56	52	52	51	50
2050-2079 RCP 6.0	72	71	71	69	68	68	66	64
2050-2079 RCP 8.5	77	76	75	73	73	73	71	69
RTFSoil‡								
Atlantic								
1989-2018 Historical	108	103	98	96	119	113	111	114
2050-2079 RCP 6.0	97	92	86	84	105	100	95	93
2050-2079 RCP 8.5	92	88	83	80	101	95	90	87
Russet Burbank								
1989-2018 Historical	84	80	76	71	96	94	89	82
2050-2079 RCP 6.0	74	73	67	62	88	86	81	73
2050-2079 RCP 8.5	66	66	60	55	84	83	77	69

† RTFVine is a function used in SUBSTOR to calculate vine growth relative to optimal temperatures.
‡ RTFSoil is a function used in SUBSTOR to calculate root and tuber growth relative to optimal temperatures.

Haulms weight for potato followed a similar trend to the yields. Atlantic biomass decreased significantly from the baseline with elevated temperature and precipitation and increased with elevated CO_2, especially under RCP 6.0. Russet Burbank exhibited the greatest biomass accumulation under RCP 6.0 and 8.5 and elevated CO_2 with biomass under all four climate scenarios greater than the baseline (Table 1.8). Simulated leaf area index was analyzed at tuber initiation for a subset of years (2006-2010) for both varieties (data not shown). Here, leaf area at tuber initiation increased on average across both sites by 7 and 47% under RCP 8.5 for climate change without elevated CO_2 and with, respectively. Greater surface area at such a key stage may have buffered any nutrient or water-stress caused by climate change in the model (IBSNAT et al., 1993) , particularly with elevated CO_2. Increased temperature and precipitation had little effect on the maximum leaf area index (LAI) for Atlantic potato, while the maximum LAI for Russet Burbank increased significantly (Table 1.8). Both potato varieties increased in maximum leaf area with increased CO_2. The harvest index (HI) for Atlantic decreased with increasing climate change and elevated CO_2, while for Russet Burbank, the HI remained unchanged across all four climate scenarios (Table 1.8).

Evapotranspiration rates rise with increasing temperature, escalating water stress for the crop, while increasing CO_2 increases net photosynthesis and decreases transpiration rates as a result of partial stomatal closure counteracting the negative impacts of temperature (Donnelly et al., 2001; Trnka et al., 2004; Snyder et al., 2011). Total in-season evapotranspiration (ET) significantly increased with climate change for Russet Burbank and decreased for Atlantic (Table 1.8). Differences between varieties may be a function of season length as Atlantic matures with GDD ultimately experiencing a shorter growing season with climate change, while the growing season for Russet Burbank lengthens as the first fall frost is delayed. Extractable soil moisture at maturity was not affected by the four climate change scenarios suggesting increased precipitation may negate the impacts of increased temperature, in addition to CO_2.

Table 1.8. Crop response and influencing factors in response to weather and planting date for each variety of potato averaged between both locations, ANOVA results.

Main effect averages		Haulms Weight	HI at Maturity	LAI at Maturity	Total In-Season ET	Soil Water at Maturity
Atlantic Potato		Mg ha^{-1}	—— Index ——		—— mm ——	
Weather scenario						
Historical		11.30 c	0.89 a	2.76 b	316.8 a	1412 a
RCP 6.0		9.99 d	0.86 b	2.83 b	294.3 b	1399 a
RCP 8.5		9.27 e	0.85 b	2.84 b	286.3 c	1140 a
RCP 6.0 + CO_2		12.22 a	0.84 c	3.54 a	293.4 b	1405 a
RCP 8.5 + CO_2		11.75 b	0.83 c	3.66 a	284.9 c	1418 a
Planting Date						
1		10.53 c	0.85 b	2.98 b	309.7 a	1417 a
2		10.82 bc	0.85 b	3.15 ab	299.3 b	1404 a
3		11.06 ab	0.85 b	3.23 a	288.9 c	1406 a
4		11.23 a	0.86 a	3.16 ab	282.7 d	1409 a
Source of Variation	d.f.	ANOVA				
Year	29	0.0002	0.0003	0.0002	0.0002	0.0116
Weather scenario (WX)	4	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.9969
Planting date (PD)	3	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.9919
WX x PD	12	0.8742	1.0000	0.8471	0.9999	1.0000
C.V., %		16%	3%	18%	9%	38%
Russet Burbank Potato						
Weather scenario						
Historical		12.28 c	0.85 a	4.86 d	368.1 c	1483 a
RCP 6.0		12.73 b	0.85 a	5.06 cd	397.7 b	1552 a
RCP 8.5		12.78 b	0.85 a	5.17 c	409.6 a	1574 a
RCP 6.0 + CO_2		14.07 a	0.85 a	5.80 b	396.1 b	1569 a
RCP 8.5 + CO_2		14.31 a	0.85 a	6.08 a	406.9 a	1598 a
Planting Date						
1		13.95 a	0.87 a	5.12 b	426.1 a	1509 a
2		13.61 b	0.85 b	5.54 a	410.7 b	1571 a
3		13.07 c	0.84 c	5.53 a	386.4 c	1572 a
4		12.31 d	0.83 d	5.37 a	359.4 d	1569 a
Source of Variation	d.f.	ANOVA				
Year	29	0.0002	0.0002	0.0002	0.0002	0.0016
Weather scenario (WX)	4	< 0.0001	0.0366	< 0.0001	< 0.0001	0.1239
Planting date (PD)	3	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.3310
WX x PD	12	0.8278	0.1560	0.9294	0.2395	0.9998
C.V., %		12%	3%	17%	5%	32%

For barley, both varieties exhibited a similar response to changes in climate. Both Newdale and Robust performed best under the RCP 8.5 scenario with elevated CO_2, increasing yield by 11% and 14% at both locations, respectively (Table 1.6). Both varieties also exhibited a negative response to increased temperature and precipitation with RCP 6.0 and 8.5, decreasing yields by 7% and 11% for Robust in Presque Isle and 6% and 9% in St. Agatha and 6% and 9% for Newdale at both locations. Similar to potato, spring barley is a cool-season crop (Klink et al., 2014) sensitive to high temperatures and the timing and intensity of environmental stress (Hakala et al., 2012; Rötter et al., 2012). Increasing temperature has been observed in numerous studies to negatively impact the yield of grain crops through the shortening of phenological phases (Trnka et al., 2004; Asseng et al., 2015; Eyshi Rezaei et al., 2017; Marcinkowski and Piniewski, 2018). Average anthesis dates advanced by 4 to 6 days at both locations (data not shown), while average maturity dates advanced by 6 to 11 days with climate change regardless of CO_2 (Table 1.3).

Total above-ground biomass also decreased significantly for Newdale and Robust barley under climate pressures in the absence of elevated CO_2, with RCP 8.5 having a greater impact on Newdale as compared with Robust (Table 1.9). Above-ground biomass significantly increased above the original baseline with the addition of CO_2. Climate change and elevated CO_2 had a positive effect on the HI of both varieties increasing the grain yield relative to grain biomass (Table 1.9). Maximum LAI remained the same for Newdale with rising temperature and precipitation and decreased by 6% to 10% for Robust. With the addition of elevated CO_2 Newdale increased the maximum LAI by 13% to 16% and Robust exhibited a slight increase, although not significant, further reinforcing the positive impact of CO_2 on growth and biomass accumulation (Table 1.9).

Table 1.9. Crop response and influencing factors in response to weather and planting date for each variety of barley averaged between both locations, ANOVA results.

Main effect averages		AG Biomass Weight†	HI at Maturity	LAI at Maturity	Total In-Season ET	Soil Water at Maturity
Newdale Barley		Mg ha^{-1}	—— Index ——		—— mm ——	
Weather scenario						
Historical		7.01 c	0.53 ab	2.34 b	196 a	1503 a
RCP 6.0		6.64 d	0.53 b	2.51 b	189 bc	1519 a
RCP 8.5		6.45 e	0.53 b	2.47 b	186 c	1524 a
RCP 6.0 + CO_2		7.52 b	0.54 a	2.65 a	190 b	1516 a
RCP 8.5 + CO_2		7.94 a	0.54 a	2.72 a	187 bc	1520 a
Planting Date						
1		7.92 a	0.54 a	3.09 a	204 a	1516 a
2		7.55 b	0.53 ab	2.81 b	196 b	1525 a
3		7.15 c	0.53 b	2.57 c	189 c	1524 a
4		6.66 d	0.54 ab	2.31 d	182 d	1515 a
5		6.27 e	0.53 ab	2.11 e	177 e	1501 a
Source of Variation	d.f.	ANOVA				
Year	29	0.0003	0.0005	0.0003	0.0003	0.0400
Weather scenario (WX)	4	< 0.0001	0.0116	< 0.0001	< 0.0001	0.9860
Planting date (PD)	4	< 0.0001	0.0052	< 0.0001	0.3879	0.9936
WX x PD	16	0.0616	0.3380	0.0345	0.6446	1.0000
C.V., %		11%	7%	18%	5%	36%
Robust Barley						
Weather scenario						
Historical		8.98 c	0.53 ab	2.76 a	273.2 a	1475 a
RCP 6.0		8.49 d	0.53 bc	2.60 b	264.7 b	1479 a
RCP 8.5		8.23 d	0.52 c	2.48 b	260.8 c	1486 a
RCP 6.0 + CO_2		9.40 b	0.54 a	2.84 a	265.0 b	1475 a
RCP 8.5 + CO_2		9.78 a	0.54 a	2.89 a	261.6 bc	1479 a
Planting Date						
1		9.34 a	0.55 a	3.09 a	96.8 b	1490 a
2		9.20 a	0.55 ab	2.89 b	99.0 ab	1487 a
3		9.10 a	0.53 b	2.78 b	101.1 a	1469 a
4		8.82 b	0.52 c	2.55 c	100.1 a	1474 a
5		8.44 c	0.50 d	2.28 d	96.9 b	1474 a
Source of Variation	d.f.	ANOVA				
Year	29	0.0003	0.0003	0.0003	0.0003	0.0185
Weather scenario (WX)	4	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.9995
Planting date (PD)	4	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.9902
WX x PD	16	0.9925	0.4190	0.9490	1.0000	1.0000
C.V., %		13%	10%	21%	6%	38%

† Total above ground biomass for barley.

Evapotranspiration significantly decreased across all four climate change scenarios for both varieties. In the presence of elevated temperature and precipitation alone this may be a function of a shorter growing period (Table 1.3) and reduced biomass and yield (Table 1.9) leading to less water use overall. However, much like Atlantic, reduced evapotranspiration in conjunction with increased leaf area and biomass under elevated CO_2 may be a result of increased water use efficiency in response to elevated CO_2, caused by partial closure of the stomata and a reduction in plant transpiration (Donnelly et al., 2001; Trnka et al., 2004).

With the addition of elevated CO_2, both potato and barley varieties yielded significantly higher than both the baseline and generated weather scenarios without CO_2, suggesting CO_2 counteracted the negative impacts of increased temperature and precipitation. This is in agreement with Ingvordsen et al. (2015) who found that elevated CO_2 buffered the negative impact of temperature on barley yields in a controlled greenhouse experiment in Denmark. Donnelly et al. (2001) demonstrated an increase in both above-ground and below-ground biomass with elevated CO_2 in a controlled field experiment in the UK, such that tuber yields increased by 40%. In a modeling study using CERES-Barley, Trnka et al. (2004) also found that elevated CO_2 had a greater impact on spring barley yields than increased temperature and precipitation, subsequently increasing yields by 13% to 52%.

1.4.4 Crop Response to Planting Date

There was no significant interaction between planting date and weather scenario, with the exception of Newdale barley in Presque Isle (Figure 1.3), indicating that crop response to planting dates for all other varieties were not impacted by climate change. All varieties exhibited varying responses to changes in planting date. Planting date significantly affected the yields of both potato and barley varieties across both locations (Table 1.6). Atlantic potato yield increased by 6% to 9% when comparing the first and last planting dates. In agreement with Atlantic’s response to planting date, Adavi et al., (2018) found delayed planting to be a successful adaptation strategy in buffering the negative impacts of climate change on early- and mid-season maturing varieties. In contrast, Russet Burbank exhibited a significant decrease in yield with later planting, by 13% to 16%, suggesting the late-season variety will continue to perform best with the earliest possible planting and longest growing season.

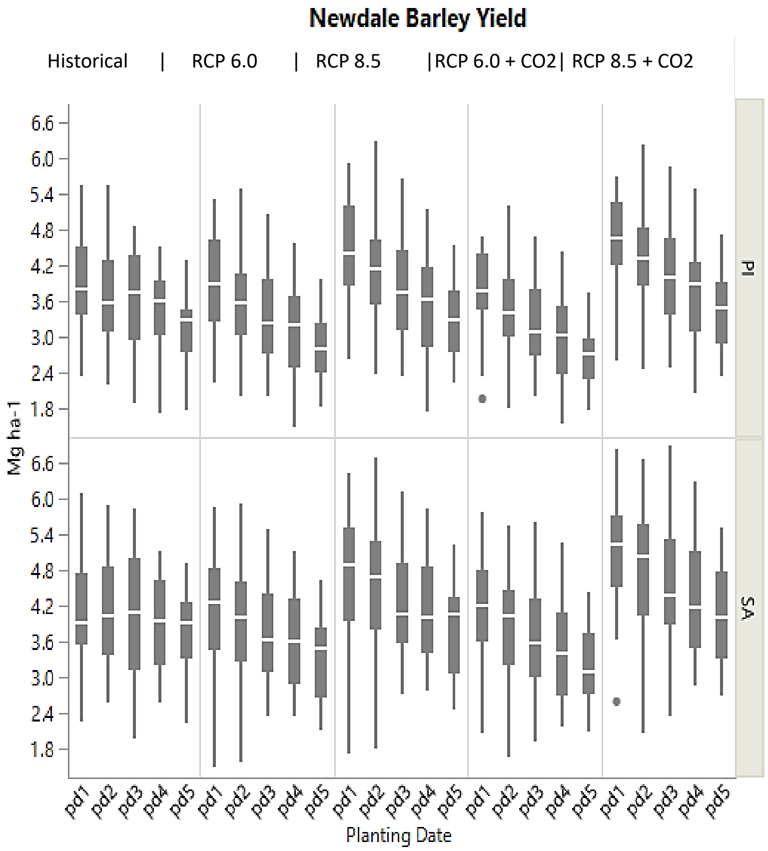

Figure 1.3. Simulated Newdale barley grain dry yield (Mg ha^{-1}) as affected by planting date and climate scenario.

Russet Burbank potato benefited from the earliest possible planting date with the greatest HI and Haulms weight, while the 2nd and 3rd planting dates resulted in higher maximum LAI at the expense of tuber yield (Table 1.8). Atlantic potato differed in response, with the latest possible planting date yielding highest and having the greatest HI. Both barley varieties performed better with the earliest possible planting in both biomass accumulation and yield. Newdale and Robust barley yields decreased significantly with later planting, by 17% and 26%, between the first and last planting dates (Table 1.6). Both varieties experienced a decrease in total biomass, HI and maximum LAI with delayed planting (Table 1.9) implying warmer temperatures may advance grain maturity at the expense of biomass accumulation and yield (Asseng et al., 2015). Later planting, however, had a greater negative impact on the total biomass and maximum leaf area for Newdale when compared to Robust, while the HI of Robust was more sensitive to later planting than Newdale. Variety-specific responses to changes in planting date suggest both varieties of barley and Russet Burbank potato perform better with a longer development period while the timing of in-season weather patterns are more critical for Atlantic. Additionally, the sensitivity of barley to changes in planting date may be linked to the yield-reducing effects of the timing of environmental stress relative to key stages in development (Hakala et al., 2012; Rötter et al., 2012).

1.4.5 Crop Response to Weather Variability

Simulation results presented thus far do not address the increased variability in weather that is anticipated with climate change. Within the 30-year time-period, the two subset 13-year periods exhibited considerable differences in weather (Table 1.10). In the later time-period (2006-2018) average in-season rainfall was 11% greater with more than double the amount of in-season variability. Within the later time-period, year-to-year variability in seasonal rainfall was much greater than the day-to-day variation in rainfall, suggesting changes in weather variability may occur on a greater scale. Interestingly, the incidence of heavy rain greater than 25 mm only occurred 12% more frequently in the later time period than the earlier, while the more extreme >50 mm events occurred 300% more frequently in the later time period. Daily average temperature was 5% greater in the later time-period than the earlier period, with the incidence of T_{max} exceeding 29°C occurring 32% more frequently and the occurrence of days when T_{max} exceeded 34°C when there had been none previously. Unlike precipitation, year-to-year variation in temperature was similar between the two time periods, as was day-to-day variation in temperature. Crop yields in response to greater variability in weather compared to a more stable baseline were not significantly different across all planting dates and weather scenarios, with the exception of Russet Burbank which significantly decreased by 8% with greater variability in weather (data not shown). Additionally, there were no significant differences in the variability of crop yields for all four varieties (Table 1.11).

Table 1.10. Weather characteristics of two 13-year periods representing ‘more stable’ (1992-2004) and ‘more variable’ (2006-2018) weather in Presque Isle, Maine.

	Year-to-year variability									Day-to-day variability	
Time Period	Seasonal rainfall (May-Aug)		Incidence of heavy rain events		Days between rain events†	Daily average temperature (T_{avg})		Incidence of high temperatures‡		CV of daily T_{avg}	CV of daily rainfall
	Mean	CV	>25 mm	>50 mm		Mean	CV	>29°C	>34°C		
	cm	%	—— days ——			°C	%	— days —		—— % ——	
1992- 2004	38.2	11	2.6	0.2	10.4	15.6	5%	7.2	0.0	6.47	4.59
2006-2018	42.3	30	2.9	0.6	9.2	16.4	4%	9.5	0.2	7.45	5.98

† A significant rain event was considered as a daily rainfall exceeding 10 mm.

‡ Days when maximum daily temperature exceeded 29 or 34°C.

Table 1.11. Crop yields (Mg ha $^{-1}$) and coefficient of variations (CV) of crop yield for two 13-year periods representing ‘more stable’ and ‘more variable’ weather in Presque Isle, Maine.

	Atlantic		Russet Burbank		Newdale		Robust	
	1992-2004	2006-2018	1992-2004	2006-2018	1992-2004	2006-2018	1992-2004	2006-2018
Average yield (Mg ha^{-1})								
Historical	10.14	10.06	10.36	10.03	3.62	3.88	4.94	5.07
RCP 6.0	8.29	8.06	11.09	10.26	3.37	3.77	4.59	4.48
RCP 8.5	7.65	7.28	10.94	10.09	3.31	3.69	4.21	4.11
RCP 6.0 + CO_2	10.43	10.00	12.11	10.93	3.92	4.37	5.29	5.03
RCP 8.5 + CO_2	9.93	9.47	12.08	10.90	4.17	4.64	5.30	5.03
CV of yield (%)								
Historical	22	20	22	19	27	27	25	16
RCP 6.0	23	25	23	21	27	24	26	21
RCP 8.5	24	26	25	22	27	27	25	21
RCP 6.0 + CO_2	21	25	17	19	26	23	25	20
RCP 8.5 + CO_2	21	28	18	19	26	27	27	22

1.5 Conclusions

The negative responses of Atlantic potato and both barley varieties to climate change appear to result from increased temperatures causing a decrease in overall days to maturity and the length of phenological phases. In contrast, the long-season Russet Burbank potato exhibited a positive response to climate change, likely resulting from an increase in growing-season length. All four varieties exhibited a positive response to climate change with elevated CO_2, such that CO_2 counteracted the degree to which increased temperature negatively impacted yields. For the most part, planting date effects were consistent across weather scenarios with later planting being optimal for Atlantic potato and earlier planting for Russet Burbank and both varieties of barley. Atlantic potato may be the most vulnerable of the four varieties studied.

While factors such as crop quality, pest and disease pressures are beyond the limitations of the model, they should be taken into consideration when examining potential climate change impacts (Frumhoff et al., 2007; Rötter et al., 2012). Changes in planting date did not prove to be an effective management strategy for the majority of crops evaluated in this study, however, other management strategies including changes in plant densities, irrigation, improved soil health or the altering of crop rotations may increase crop resiliency (White et al., 2011; Zheng et al., 2017). These adaptive management strategies should be further investigated for potato and barley systems in Maine.

CHAPTER 2: INVESTIGATING SOIL HEALTH AS A CLIMATE RESILIENCE STRATEGY FOR POTATO AND GRAIN IN MAINE USING THE DSSAT CROP MODEL

2.1 Chapter Abstract

Climate change will heighten both risk and opportunity for Maine agriculture. Current crop management practices may need to adapt in order to sustain specific crops crucial to Maine's economy. A cropping systems trial conducted from 1992-2008 in Presque Isle, Maine demonstrated that soil health improvement resulting from repeated additions of manure increased potato yield stability compared with a nonamended fertilizer-based treatment. Yield in the organically amended system was less influenced by adverse growing conditions, particularly low rainfall. The objective of this study was to assess the yield stabilizing effects of improved soil health versus irrigation under different weather scenarios using the SUBSTOR-Potato and CERES-Barley models in the Decision Support System for Agrotechnology Transfer (DSSAT). Experimental field data from the Maine Potato Ecosystem Project conducted from 1992 to 2008 in Presque Isle were used to evaluate model performance over two contrasting soil management systems and varying soil organic matter levels. Crop yield was simulated for five distinct weather scenarios: the last 30-year period 1989-2018, and four generated weather scenarios (two emissions scenarios, RCP 6.0 and 8.5, with and without elevated CO_2) for the future 30-year period 2050-2079. SUBSTOR-Potato predicted dry tuber yield well for the Atlantic cultivar using the original cultivar coefficients for both amended and nonamended soil management practices. CERES-Barley also performed well in the simulation of Robust barley yield under the two soil management practices following calibration. Irrigation performed best under projected climate pressures; however, this may not be a sustainable or viable option for Maine farmers as it is costly and increases N leaching. Increased soil health in the amended system was a close second to irrigation resulting in a 25% and 32% increase in average yield for potato and barley, respectively, compared to the nonamended treatment. Although there was no significant interaction between adaptive management strategies and climate change, there were strong treatment differences among management strategies and weather scenarios. The exceptional performance of the amended system is attributed to enhanced soil organic matter (SOM), increased water

holding capacity (WHC) of the soil and increased photosynthetic rate and water use efficiency (WUE) and in the crop.

2.2 Introduction

Adaptation and preparation in attempt to increase resilience in cropping systems and maintain current yields is critical as changes in climate are already taking place. Cropping system management has the potential to buffer unfavorable weather, such as low precipitation and increase resilience within local cropping systems (Mallory and Porter 2007). Adaptive management can include changes in planting dates or densities, irrigation, improved soil health or the altering of crop rotations (White et al., 2011; Williams et al., 2016; Zheng et al., 2017). Temperature, precipitation and CO_2 concentrations are all anticipated to rise with climate change (IPCC, 2014; Fernandez et al., 2015). As described in Chapter 1, the anticipated rise in Maine's average temperature is much greater than the anticipated increase in average precipitation. As a result, Anderson et al. (2010) notes that increased evaporation relative to projected precipitation amounts will likely lead to a decrease in soil moisture across the Northeast. Increased soil moisture deficits during the growing season caused by climate change could consequently increase the need for supplemental irrigation in place of rainfed regimes (Daccache et al., 2011).

A 13-year study conducted by Mallory and Porter (2007) comparing the long-term effects of compost and manure amendments on potato production in Maine found the amended soil management system increased overall yield stability relative to the nonamended fertilizer-based system. The greatest variability observed between the yields of the amended and nonamended system occurred in conjunction with the poorest growing conditions, suggesting yield-limiting factors were buffered in the amended system. Here, the greatest yield limiting factor was precipitation. Improved soil health through increased soil organic matter (SOM) has been documented to enhance the soil structure, water holding capacity (WHC) and nutrient availability of the soil (Grandy et al., 2002; Mallory and Porter, 2007; Williams et al., 2016). Yu et al. (2017), demonstrated that long-term organic amendments and the presence of organic acids can increase mineral formation and availability resulting in the retention and further binding of carbon, leading to carbon stable SOM. Precipitation was the most yield-limiting factor in the study by Mallory and Porter (2007), thus, implying that improved soil health could act as an alternative management strategy for achieving the effects of supplemental irrigation (Porter et al., 1999).

Crop models allow for the exploration of risk reduction strategies in agriculture, as various management techniques can be evaluated relative to changes in weather for a specific crop and region. The DSSAT model has been used to evaluate the potential of soil health, and irrigation as potential management strategies in response to climate around the world (Snapp and Fortuna, 2003; Booltink and Verhagen, 1997; Holden and Brereton, 2006; Daccache et al., 2011; Rosenzweig et al., 2014; Rabia et al., 2016; Nouri et al., 2017). Within DSSAT, the CENTURY soil model is known for its ability to simulate nitrogen, soil organic carbon, residue dynamics and soil-water processes (Gijsman et al., 2002; Li et al., 2015; Raymundo et al., 2017). To best capture soil organic carbon's (SOC) chemical and physical properties, as well as mechanisms in stabilization and decomposition, SOC is divided into discrete carbon pools for modeling purposes (Basso et al., 2014). Defining these pools enhances the model's simulation of field and management-specific soil dynamics, leading to a more accurate prediction of crop yield.

Few studies have used the DSSAT model to evaluate amended soil management systems as a climate resilience strategy. Irrigation, however, has been tested under various climate change scenarios for a variety of locations using the model (Tubiello et al., 2002; Holden and Brereton, 2006; Daccache et al., 2011; Vashisht et al., 2015; Attia et al., 2016; Rabia et al., 2016). Daccache et al. (2011) used the SUBSTOR-potato model (within DSSAT) to simulate future irrigation needs and resulting tuber yields in England. In the absence of nutrient and water limiting conditions, tuber yields were predicted to increase with climate change, however, average irrigation requirements also increased as a result of greater evapotranspiration. Holden and Brereton (2006) looked at irrigation as a climate adaptation strategy for spring barley and potato in Ireland and found that potato will likely require irrigation with future changes in climate, while barley was not as sensitive. As heavier soils can lead to run-off and increased pollution with supplemental irrigation, Holden and Brereton (2006) caution the use of irrigation with specific soil types as an effective and efficient management strategy. The impacts of projected changes in climate on the yields and development of potato and barley in Maine have been evaluated in Chapter 1. The present study aims to: 1) calibrate and evaluate SUBSTOR-Potato and CERES-Barley models for crop performance in an amended soil system in Maine and, 2) assess the yield enhancing and stabilizing effects of improved soil health versus irrigation under changes in climate anticipated for 2050-2079.

2.3 Materials and Methods

2.3.1 Study Site and Field Experiments

The potato variety Atlantic and barley variety Robust were simulated using the SUBSTOR-Potato and CERES-Barley models, respectively. Tuber yields and accompanying crop management information for Atlantic potato in both an amended and nonamended system were obtained from the MPEP, 1992 to 2008 in Presque Isle, Maine (Alford et al., 1996; Gallandt et al., 1998; Mallory and Porter, 2007; Mallory et al., 2010). Experimental grain yield for Robust barley came from two sources: 1) the Maine Potato Ecosystem Project, 1992-2005 for the nonamended and 1998-2005 for the amended in Presque Isle, Maine; and 2) 4 years of variety trials with 2 years (2015 and 2016) of manure-based soil amendments, and 2 years (2017 and 2018) with fertilizer-based management in Old Town, Maine. Time-series soil moisture from Robust barley under amended management practices from 2003-2005 in the MPEP were used to alter and evaluate soil files for the amended treatment. Time-series soil data for the nonamended system from the same trial and time period are evaluated in Chapter 1.

2.3.2 The Century Soil Model

Long-term organic amendments applications (such as manure), alter the organic carbon and nitrogen fractions within the soil (Sharifi et al., 2008), thus, the chemical and textural composition of the soil was the greatest treatment difference between the amended and nonamended systems. DSSAT offers two soil models, CERES and CENTURY. For this study, the CENTURY soil model was used. Differences in stable carbon between the amended and nonamended systems were estimated using data collected during the Maine Potato Ecosystem Project. Stable carbon was estimated to be 50% and 65% of the total SOC for the amended and nonamended systems, respectively (Table 2.1).

Table 2.1. Crop management practices and initial soil characteristics used in simulations of potato and barley grown using nonamended and amended soil management.

Management									Initial Soil Conditions (0-20cm)			
				Fertilizer	Manure							
	Soil Management Treatment	Previous Crop	Seeding Rate	Urea N	Application Rate, Fresh wt.	Total N	NH_4	Method to Determine Harvest Date†	Total Residue	Nitrogen (NO3)	Organic Carbon	Stable Carbon
			# m^{-2}	kg ha^{-1}	—— kg ha^{-1} ——				kg ha^{-1}	ppm	—— % ——	
Potato												
	Nonamended	Barley	4.31	191	-	-	-	GDD	1930	10.5	1.86	1.20
	Amended	Barley	4.31	-	24,224	330	21	GDD	1930	14.2	3.26	1.63
Barley												
	Nonamended	Potato	400	79	-	-	-	Maturity	929	10.5	1.86	1.20
	Amended	Potato	400	-	14,055	210	21	Maturity	929	14.2	3.26	1.63

† Harvest date was set for the potato variety Atlantic at 1385 cumulating growing degree days (GDD) after planting. For Robust barley, the harvest date was at crop maturity as determined by the CERES-Barley model.

2.3.3 Calibration and Evaluation of the Soil Managements Systems in DSSAT

Evaluation of the nonamended soil dynamics was performed for the nonamended fertilizer-based management in Chapter 1. Further calibration of the drainage and soil fertility was necessary for the amended system, as well as, the soil fertility of the MPEP-specific nonamended system. Time-series soil moisture data for Robust barley in the amended system were used to compare simulated dynamics to the dynamics observed in the field. Initial evaluations of the model revealed consistent over-simulation by the model when compared to the observed values. DSSAT calculates the drained upper and lower limits and saturated water content from input values for chemical and textural soil characteristics by depth. Calibration of the amended soil files was performed by uniformly decreasing the drained upper and lower limits and saturated water content of the soil file for Robust barley (2003) until time-series simulated and observed values produced the lowest nRMSE. This resulted in an additional 12% decrease in the model's calculation of each of the three parameters for each amended soil file (Table 2.2). Soil files for the amended system were adjusted prior to calibration of the soil fertility factor (SLPF) and any evaluation. Subsequent simulations of the soil dynamics were evaluated using deviation statistics for Robust barley 2004 and 2005. Calibration of the SLPF was performed for both soil management practices using the methodology from Chapter 1, with a resulting nRMSE of 0.95 and 1.0 for to the amended system and 0.83 and 1.0 for the nonamended system for Presque Isle and Old Town, respectively.

Table 2.2. Soil characteristics generated by the model as a function of textural and chemical composition with calibration of the soil drainage for the amended soil management treatment.

Soil Management	Soil Layer Depth cm	LL† cm3 cm3	DUL† cm3 cm3	SAT† cm3 cm3	Bulk Density g cm3
Nonamended	0-20	0.110	0.215	0.313	1.25
	20-40	0.115	0.220	0.313	1.30
	40-60	0.075	0.144	0.243	1.45
	60-90	0.032	0.071	0.146	1.45
	90-200	0.034	0.074	0.146	1.45
Amended	0-20	0.121	0.235	0.304	1.12
	20-40	0.140	0.266	0.342	1.13
	40-60	0.081	0.155	0.255	1.41
	60-90	0.033	0.075	0.151	1.44
	90-200	0.037	0.079	0.152	1.43

† LL is the drained lower limit, DUL is the drained upper limit and SAT is the saturated water content of the soil, calculated within DSSAT-SBuild as a function of the textural and chemical composition of the soil.

Atlantic potato and Robust barley used the genetic coefficients previously calibrated and evaluated in Chapter 1. The model's ability to predict for each crop in the amended system were further evaluated using 9 experiments for Atlantic potato and 8 experiments for Robust barley. Deviation statistics used in evaluation were: the coefficient of determination (R^2), normalized Root Mean Square Error (nRMSE), modeling efficiency (EF), and Willmott index of agreement (d) (Willmott, 1981).

2.3.4 Simulations and Statistical Analysis

Adaptive management treatments, including nonamended and amended soil conditions and nonamended with added irrigation under present weather, and four future weather scenarios were simulated using DSSAT. Weather scenarios generated and described in Chapter 1 included: historical weather (1989-2018) and four predicted weather scenarios for 2050-2079 based on RCP 6.0 and 8.5, using current atmospheric CO_2 concentrations and using estimated future CO_2 concentrations relative to each emissions scenario (527 ppm and 638 ppm for RCP 6.0 and 8.5, respectively). Simulations of the nonamended fertilizer-based treatment used standard management data, described in Chapter 1. The amended system used similar crop-specific management with adjustments made to the amended soil file including existing soil N, SOC fractions and manure-based amendments (in place of inorganic fertilizer) (Table 2.1). Both the amended and nonamended treatments were rainfed. Irrigation was also applied to the nonamended irrigation treatment on an 'as needed' basis to a maximum field capacity (FC) of 70% via the sprinkler method, with an efficiency fraction of 75%. Here, DSSAT determines when irrigation is needed when field capacity falls below 50% of the maximum. Planting dates were May 22 for potato and May 2 for barley.

Analyses were performed by crop. A REML mixed effects model in JMP (JMP®, Version *14.3*) was used to compare management treatment, weather scenario and their interaction as fixed effects, and replicates (years) as a random effect. Unequal variance in yield between adaptive management strategies and weather scenarios were evaluated using the Levene's test in JMP.

2.4 Results and Discussion

2.4.1 Model Evaluation

Soil moisture dynamics were sufficiently predicted by the DSSAT model for the amended system (Table 2.3). Calibration of the soil files for amended resulted in a lower nRMSE than the nonamended system (Table 1.4) but with less of an overall ‘fit’, as exhibited by the statistics (R^2, d and EF). However, compared to the soil moisture evaluation for the nonamended system this may be a result of fewer experimental data for the amended soil system (Figures 1.1 and 2.1).

Table 2.3. Model performance statistics comparing simulated and observed for crop yields and soil moisture under rainfed conditions for nonamended and amended soil management for potato and amended soil management for barley in Maine.

Statistics		Potato	Potato	Barley	Barley
	Soil Moisture	Nonamended	Amended	Nonamended	Amended
Coefficient of determination (R^2)	0.576	0.706	0.766	0.893	0.904
Slope (m)	0.972	1.020	1.036	1.081	1.065
nRMSE (%)	9.37	8.67	7.47	13.5	12.15
Modeling efficiency (EF)	0.53	0.69	0.70	0.84	0.87
Index of agreement (d)	0.88	0.93	0.92	0.96	0.96

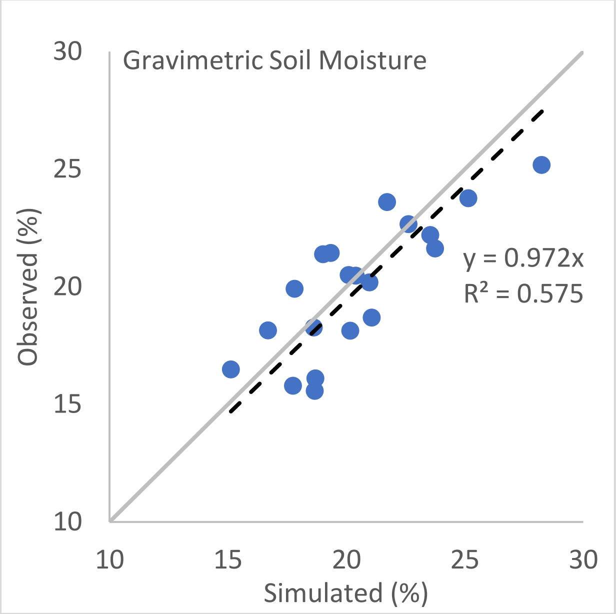

Figure 2.1. Simulated and observed soil moisture (0-20 cm) at various dates in two years of amended Robust barley with manure applications (‘2004’ and ‘2005’) and one year without manure applied (‘2004 No N’) also in the amended system, in Presque Isle, Maine.

The SUBSTOR-potato and CERES-barley models both exhibited satisfactory agreement between simulated and observed yields in the amended and nonamended system. The model adequately predicted the potato tuber yield from the MPEP in the nonamended fertilizer-based system with an nRMSE of 8.67% and index of agreement of 0.93 (Table 2.3) well within range of the model evaluations for Atlantic potato in a nonamended system presented in Chapter 1 (Table 1.4). The model evaluation of Atlantic potato in the nonamended system using data exclusively from the MPEP resulted in a lower R^2 (0.71) and modeling efficiency (0.69) than evaluations in Chapter 1 (Figure 2.2a). This discrepancy is likely a result of fewer evaluation experiments. Few studies have evaluated the DSSAT model for organic manure-based amendments. The model’s ability to simulate for potato and barley growth in an amended system in Maine were also well within range of the nonamended evaluation (Table 1.4 and 2.3). Comparing simulated and observed tuber yields for Atlantic resulted in an nRMSE of 7.47%, with a modelling efficiency of 0.70 and Willmott index of agreement of 0.92. The R^2 of Atlantic potato yield in the amended system was also in agreement with that of the nonamended system with a fit of 0.77 with the intercept set to zero (Table 2.3, Figure 2.2b). The impacts of the amended and nonamended soil management treatments on tuber yield, and the year-to-year variability of those yields were also adequately predicted by the model (Figure 2.3) and in agreement with Mallory and Porter (2007).

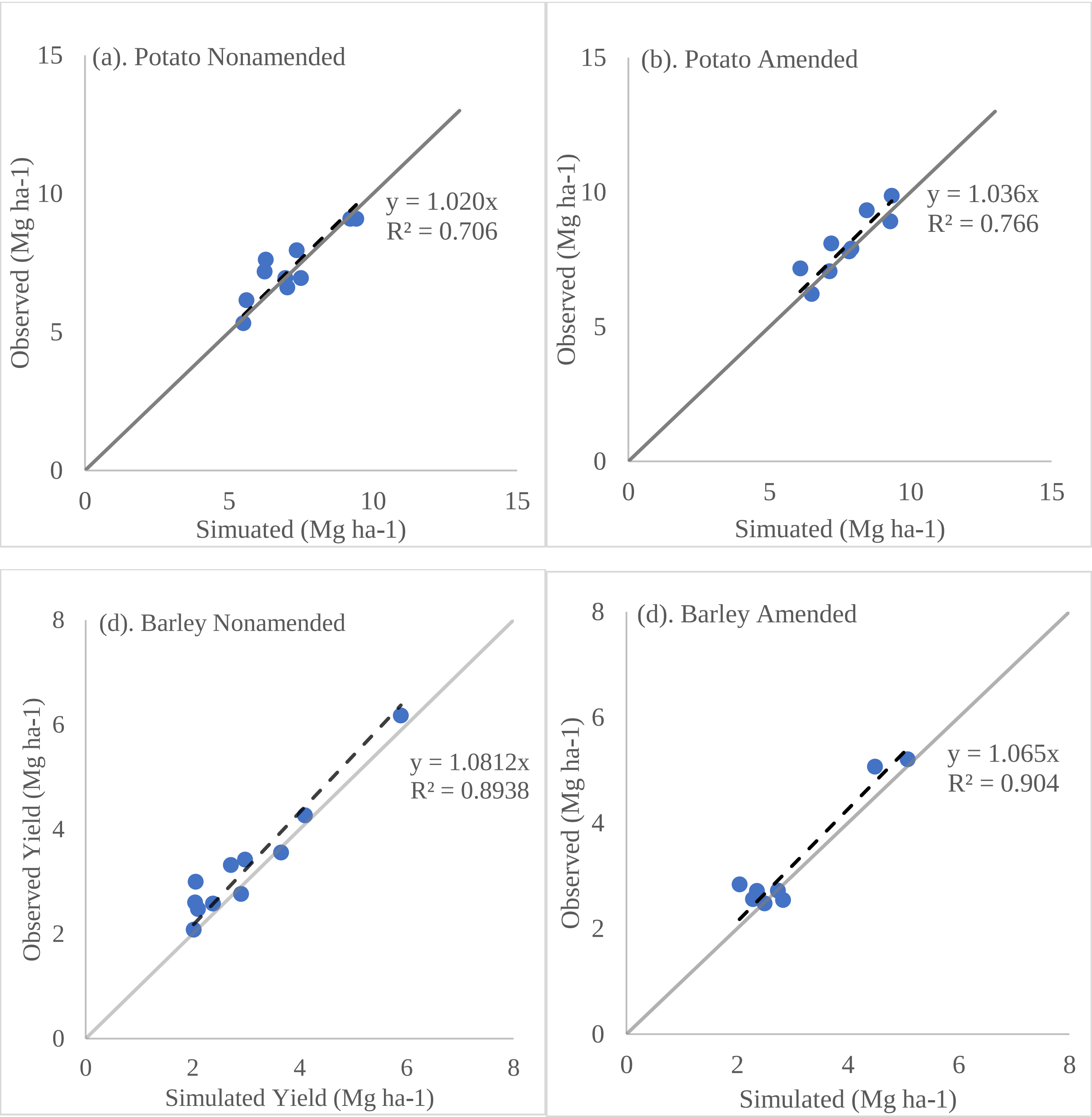

Figure 2.2. Comparison of simulated and observed potato tuber dry yield (Mg ha-1) for Atlantic nonamended (a) and amended (b) and Robust barley grain yield (Mg ha-1) for nonamened (c) and amended (d). All varieties were grown under rainfed conditions across multiple locations statewide varying in management practices.

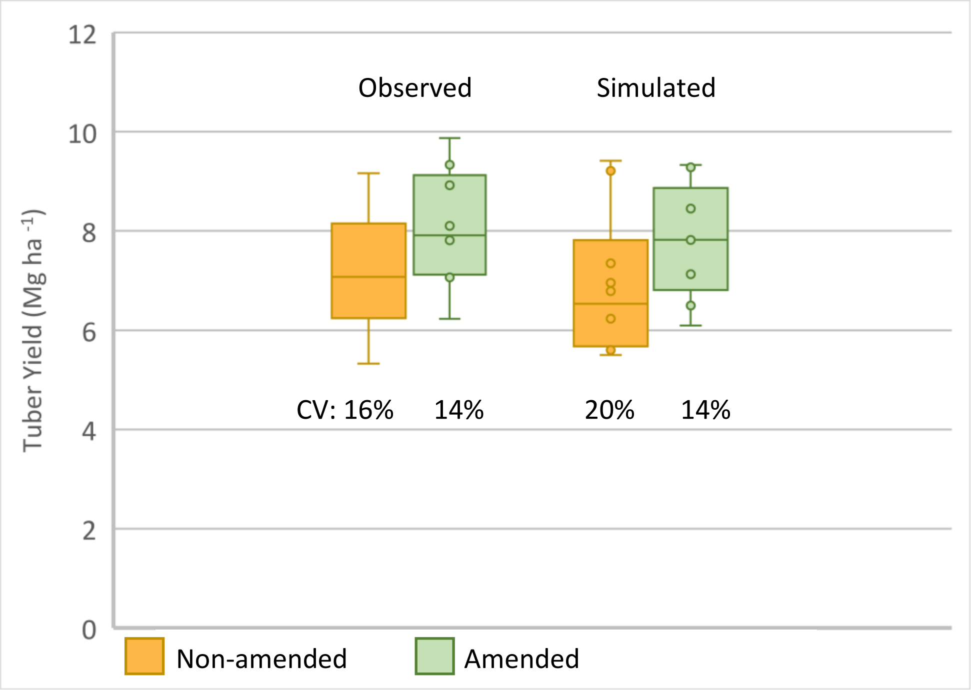

Figure 2.3. Box plots of total potato yields observed from 1997 to 2008 in nonamended and amended treatments of the MPEP and simulated yields for those treatments predicted by the SUBSTOR-Potato model.

Using data from MPEP and variety trials, the model adequately predicted the yields for Robust barley yield in a nonamended system (Table 2.3, Figure 2.2c) with and R^2 of 0.89 and modeling efficiency of 0.84, as described in Chapter 1. Simulation of Robust barley in the amended system yielded an nRMSE of 12.2%, with a modeling efficiency of 0.87 and Willmott index of agreement of 0.96 (Table 2.3, Figure 2.2d). The R^2 between simulated and observed was 0.90 with the intercept set to zero. These results are similar to other evaluations using the CERES model within DSSAT for manure-based fertility systems. Li et al. (2015), who looked at wheat in a manure-based amended system simulated over multiple years, reported an nRMSE between simulated and observed of 21.5% with a modeling efficiency of 0.46 and index of agreement of 0.89. Tovihoudji et al. (2019) found single-year simulations of maize perform well in a manure-based system with an nRMSE of 12%, a modeling efficiency of 0.70 and index of agreement of 0.96. Both studies presented a combined treatment R^2 of 0.81 and 0.91, respectively.

2.4.2 Crop Response to Adaptive Management

In this study, the standard nonamended treatment acts as the baseline in addition to the historical weather, when further evaluating the effects of long-term soil amendments or irrigation. There was no significant interaction between the adaptive management strategies and weather scenarios for either crop. However, there were strong treatment differences among the management strategies and among the weather scenarios within each strategy (Table 2.4). In comparing the main effects of management, potato performed best with applied irrigation across all five weather scenarios resulting in a 46% increase in yield from the basic nonamended management (Table 2.4). The amended system for potato also increased yields, yielding 25% higher than the nonamended system. Barley performed best with amended soil or irrigation with a respective increase in yield of 32% and 29% from the nonamended system. From these main treatment differences, it is clear that potato responded better to irrigation relative to barley, while the barley exhibited a stronger positive response to the amended soil. These results are in agreement with a field study conducted by Porter et al. (1999), who found irrigation had a greater impact on potato yields than amended soil management, however, both management strategies increased productivity. The model reproduced the effects of amended soil management on tuber yields, however, the year-to-year variation in yield (Table 2.6) of the amended system (36%) and nonamended system (38%) were much greater than that observed by Mallory and Porter (2007). Irrigation demonstrated the lowest year-to-year variation of all three treatments with a CV of 17% for both varieties.

Table 2.4. Average simulated potato tuber and grain yield (Mg ha^{-1}) as affected by soil management treatment (nonamended, amended, and nonamended with irrigation) and weather scenarios in Presque Isle, Maine, with ANOVA results.

		Potato			Barley		
Main effects		Nonamended	Amended	Irrigated	Nonamended	Amended	Irrigated
			Mg ha^{-1}			Mg ha^{-1}	
Adaptive Management†		7.019 C	8.749 B	10.270 A	3.821 B	5.039 A	4.942 A
Weather Scenarios‡							
Historical		7.314 b	9.704 ab	11.118 b	3.905 b	5.132 b	5.110 b
RCP 6.0		5.911 c	7.754 c	9.190 c	3.584 c	4.744 c	4.586 c
RCP 8.5		5.444 c	7.035 d	8.233 d	3.324 d	4.374 d	4.234 d
RCP 6.0 + CO_2		8.334 a	9.858 a	11.755 a	4.133 a	5.437 a	5.337 a
RCP 8.5 + CO_2		8.094 a	9.393 b	11.226 b	4.160 a	5.510 a	5.441 a
Source of variation	d.f.			ANOVA			
Year	29		0.0003			0.0003	
Management (M)	2		< 0.0001			< 0.0001	
Weather (WX)	4		< 0.0001			< 0.0001	
WX x M	8		0.5333			0.7432	
C.V., %			18%			12%	

† Uppercase means separation letters are to compare among adaptive management treatments (across all weather scenarios) within a crop.

‡ Lowercase means separation letters are to compare among simple effect means within each adaptive management treatment (column).

Total in-season evapotranspiration was greatest in the irrigated system for both crops, likely a function of increased crop productivity and water availability within the system (Table 2.5). Extractable soil water at maturity was also greatest under the irrigated treatment for potato, while for barley, both the amended and irrigated treatments were equally high. Nonsignificant differences in soil water at crop maturity between the irrigated and amended barley systems imply the WHC of the amended system may be greater than that of the nonamended and nonamended, irrigated systems. While the irrigated system presents higher yields, it also possesses the greatest projected N-leaching of all three treatments. Total estimated in-season N leached was 13% and 17% greater than the nonamended baseline system for potato and barley, respectively. The greatest difference occurred between the amended and irrigated, with the irrigated system leaching 42% and 51% more than amended for potato and barley, respectively. Irrigation is not only documented to be costly and increase nitrate leaching, such that the N leached leads to subsequent losses in groundwater quality (Vashisht et al., 2015), decreasing the practicality for Maine farmers.

Table 2.5. Total in-season evapotranspiration, total extractable soil water at maturity and total in-season nitrogen leached as affected by soil management practices (nonamended, amended, and nonamended with irrigation) and weather scenarios in Presque Isle, Maine, with ANOVA results.

		Total In-Season Evapotranspiration			Soil Water Content at Maturity			In-Season Nitrogen Leached		
Main effects		Nonamended	Amended	Irrigated	Nonamended	Amended	Irrigated	Nonamended	Amended	Irrigated
			mm			cm			kg ha^{-1}	
Potato										
Adaptive Management†		263.8 C	273.2 B	309.9 A	82.8 C	86.4 B	96.5 A	41.2 B	32.6 C	46.4 A
Weather Scenarios‡										
Historical		283.7 a	293.2 a	337.1 a	78.8 a	80.8 b	92.3 a	35.4 c	26.6 c	41.2 b
RCP 6.0		261.3 b	271.1 b	307.6 b	83.8 a	87.0 ab	96.6 a	41.0 b	32.3 b	46.5 a
RCP 8.5		256.9 c	266.6 cd	303.0 c	84.0 a	87.8 ab	97.4 a	44.0 a	35.5 a	48.5 a
RCP 6.0 + CO_2		261.3 b	270.0 bc	304.2 c	83.5 a	87.7 ab	97.9 a	41.1 b	32.7 b	46.6 b
RCP 8.5 + CO_2		256.0 c	265.2 d	297.5 d	83.8 a	88.9 a	98.4 a	44.4 a	36.1 a	49.2 a
Source of Variation	d.f.					ANOVA				
Year	29		0.0002			0.0002			0.0001	
Management (Mgmt)	2		< 0.0001			< 0.0001			< 0.0001	
Weather (WX)	4		< 0.0001			< 0.0001			< 0.0001	
WX x Mgmt	8		0.7724			0.9989			0.9951	
C.V., %			7%			12%			12%	
Barley										
Adaptive Management		250.3 C	262.0 B	306.7 A	88.0 B	90.8 A	93.1 A	34.6 B	26.8 C	40.6 A
Weather Scenarios										
Historical		258.9 a	270.7 a	319.1 a	85.9 a	88.3 b	92.0 a	29.6 c	21.4 c	35.2 c
RCP 6.0		249.9 bc	261.4 bc	306.7 b	87.1 a	90.1 ab	91.6 a	35.0 b	26.9 b	40.8 b
RCP 8.5		244.6 d	256.9 d	300.7 c	91.0 a	93.8 a	95.4 a	37.5 a	29.8 a	42.9 a
RCP 6.0 + CO_2		250.9 b	262.8 b	306.4 b	86.7 a	89.2 ab	92.0 a	34.4 b	26.6 b	40.8 b
RCP 8.5 + CO_2		247.2 cd	258.6 cd	300.6 c	89.5 a	92.7 a	94.9 a	36.7 a	29.4 a	43.6 a
Source of Variation	d.f.					ANOVA				
Year	29		0.0003			0.0002			0.0002	
Management (Mgmt)	2		< 0.0001			0.0005			< 0.0001	
Weather (WX)	4		< 0.0001			< 0.0001			< 0.0001	
WX x Mgmt	8		0.9928			0.9989			0.9931	
C.V., %			6%			9%			12%	

† Uppercase means separation letters are to compare among adaptive management treatments (across all weather scenarios) within a crop.

‡ Lowercase means separation letters are to compare among simple effect means within each adaptive management treatment (column).

2.4.3 Crop Response to Current and Future Weather per Management Strategy

The response of both crops to the nonamended management relative to weather were similar to the findings in Chapter 1, although there are slight statistical differences. Overall, final yield trends decreased from the baseline (1989-2018) with increased temperature and precipitation and increased to match or exceed the baseline yields with elevated CO_2 (Table 2.4). Both crops under nonamended management performed best under climate change with elevated CO_2, such that yields increased across both RCP's by a respective 7% and 12% for barley and potato. In the nonamended system, barley and potato were quite sensitive to climate change in the absence of elevated CO_2 experiencing an average 12% and 22% decrease in yield from current production under historical weather (Table 2.4). Lower yields overall in the nonamended system compared to Chapter 1 (Table 1.4) may be a result of differences in the SLPF adjusted for the yields of the MPEP, as well as a lower organic carbon input and initial N in the initial soil conditions.

Both crops exhibited variation in their response to the weather scenarios within the amended and irrigated treatments. Potato yields decreased in the amended system with climate change in the absence of elevated CO_2 by as much as 20% and 28% relative to historical weather for RCP 6.0 and 8.5, respectively (Table 2.4)Potato yield also decreased under irrigation with increased temperature and precipitation in the absence of elevated CO_2 for RCP 6.0 and 8.5 by a respective 17% and 26%. It should be noted, that while there is a significant decrease in potato yield in the amended and irrigated system, both treatments are significantly higher yielding than the nonamended treatment in all five weather scenarios as discussed in section 2.4.2.

The yield decrease with irrigation in particular is inconsistent with Sanders and Creamer (1996), who noted that potato performs well at high temperatures when water demands are met. Thus, suggesting the current irrigation approach used in the model (applied 'as needed' to 70% FC) may not meet crop demands with warmer temperatures, changes in the number of optimal growing days for the crop (Table 1.7) or that N is limiting with increased N leaching in the irrigated system (Table 2.5). Daccache et al. (2011), observed a comparable trend when simulating the irrigation needs of potato, where future crop demands required a 14% to 30% increase in irrigation to maintain normal production. This rise in irrigation requirements with climate change was attributed by Daccache et al. (2011) to increased evapotranspiration.

With the addition of CO_2, the amended treatment for Atlantic remained nonsignificant from the baseline weather scenarios, while the irrigated treatment remained unchanged under RCP 8.5 and significantly increased by 6% with RCP 6.0. This recovery in crop yield with the addition of elevated CO_2 and climate change has been attributed to increased net photosynthesis, decreased photorespiration and decreased transpiration (Donnelly et al., 2001), potentially resulting in increased water use efficiency (WUE) in the crop (Finnan et al., 2005), all due to a physiological response (the partial closure of the stomata) to increased atmospheric CO_2. This concept is further reinforced by a simultaneous decrease in evapotranspiration with climate change and elevated CO_2 from the baseline evapotranspiration (Table 2.5) relative to increased biomass and yield (data not shown). These findings are similar to the response mechanisms describe in Chapter 1. The extractable soil water at maturity relative to climate change for all three treatments was nonsignificant for the nonamended and irrigated treatment resembling the Chapter 1 results for the nonamended system. The amended system did exhibit higher extractable water content under RCP 8.5 with CO_2 relative to the baseline, likely resulting from increased precipitation with climate change in conjunction with enhances WHC of the soil (Table 1.5).

Barley yields decreased by 8% and 15% in the amended system, and 10% and 17% in the irrigated system with climate change in the absence of elevated CO_2 under RCP 6.0 and 8.5, respectively. The greater reduction in the irrigated yields compared to the amended system may reflect greater sensitivity of the barley to N leached (Table 2.5) relative to these management effects on potato. While the improved performance of barley in the amended system relative to the irrigated system may be associated with the 'yield stabilizing effect' of amended systems, similar to that observed by Mallory and Porter, (2007). Here, the enhanced yield stability in potato was attributed to enhanced soil chemical and physical characteristics like soil organic matter and aggregation. Total in-season evapotranspiration for barley significantly decreased from the historical weather with climate change by an average of 4% and

5% in amended and irrigated systems, respectively (Table 2.5). Extractable soil water at maturity and N-leaching remained relatively unchanged for both management systems, with the exception extractable soil water for amended under RCP 8.5 and N leaching for all three management scenarios also under RCP 8.5. Here, the observed changes in soil water content and N-leaching are likely a result of increased precipitation with the higher emissions scenario (Table 1.5).

The addition of elevated CO_2 with climate change improved barley yield in the amended and irrigated system above that of the baseline by a respective 7% and 5%. The simulated increase in barley yield in the irrigated system with climate change and elevated $CO_{2,}$ is likely a function of available water combined with increased crop productivity and potentially increased WUE. In the amended barley system, increased yields with elevated CO_2 close to that of the irrigated system, may be a result of increased WHC of the soil which retained any increased precipitation with climate change (Table 1.5) in conjunction with increased crop productivity and potentially increased WUE resulting from elevated atmospheric CO_2.

Variance in yield across all five weather scenarios was similar for both crops in the amended and nonamended systems, while variance in the irrigated system was almost half of the other two treatments (Table 2.6). Weather scenarios did not significantly impact the variance in yield for either crop (data not shown). When comparing the CV's of the amended and nonamended system, treatment differences did not reflect those observed in the MPEP where the amended system decreased variability in yield, as shown in Figure 2.3. Variability in yield with irrigation (17%) remained relatively low and consistent for both crops. This finding is within the range Daccache et al. (2011), who reported a 5 to 24% increase in the inter-annual variability in irrigated potato yield with climate change and Tubiello et al. (2002), who reported the simulated CV's for irrigated potato and grain systems to be between 10% to 30% and rainfed 10% to 50%.

Table 2.6. Coefficient of variation in yield exhibiting year-to-year yield variability relative to adaptive management and weather scenarios for Atlantic potato and Robust barley.

	Potato			Barley		
	Nonamended	Amended	Irrigated	Nonamended	Amended	Irrigated
		%			%	
CV	38%	36%	17%	27%	28%	17%
Levene Test						
F Ratio		21.9			22.2	
Prob > F		<0.0001			<0.0001	

2.5 Conclusions

This study illustrates the importance of soil health as a crop resilience strategy that would be equally effective in the future as it is now. Irrigation is also a feasible option in increasing system productivity and decreasing year-to-year yield variability. However, irrigation may not be the most viable option for Maine farmers based on cost, water availability, nitrogen losses and the increased potential for ground water pollution. Due to limitation in the model, disease and decay were not evaluated in this study, but have been observed to increase with increasing and consistent soil moisture (Porter et al., 1999). Tuber quality under such conditions could potentially depress the positive impacts of irrigation and amended soils on potato production and should be taken into consideration with the results of this study. Further analyses should be performed to explore the quantity and timing of supplemental irrigation application with projected changes in weather relative an optimized nonamended system.

REFERENCES

Adavi, Z., R. Moradi, A.H. Saeidnejad, M.R. Tadayon, and H. Mansouri. 2018. Assessment of potato response to climate change and adaptation strategies. Sci. Hortic. Amsterdam. 228:91–102. doi:10.1016/j.scienta.2017.10.017.

Alexandrov, V.A., and J. Eitzinger. 2005. The potential effect of climate change and elevated air carbon dioxide on agricultural crop production in Central and Southeastern Europe. J. Crop Improv. 13(2):291–331. doi:10.1300/j411v13n01_14.

Alford, A.R., F.A. Drummond, E.R. Gallandt, E. Groden, D.A. Lambert, M. Liebman, M.C. Marra, J.C. McBurnie, G.A. Porter, B. Salas. 1996. The ecology, economics, and management of potato cropping systems: A report of the first four years of the Maine Potato Ecosystem Project. Maine Agricultural & Forest Experiment Station Bulletin 843.

Anderson, B.T., K. Hayhoe, and X.Z. Liang. 2010. Anthropogenic-induced changes in twenty-first century summertime hydroclimatology of the Northeastern US. Clim. Change 99(3):403–423. doi:10.1007/s10584-009-9674-3.

Asseng, S., F. Ewert, P. Martre, R.P. Rötter, D.B. Lobell, et al. 2014. Rising temperatures reduce global wheat production. Nat. Clim. Chang. 5(2)143-147. doi:10.1038/nclimate2470.

Attia, A., N. Rajan, Q. Xue, S. Nair, A. Ibrahim, et al. 2016. Application of DSSAT-CERES-Wheat model to simulate winter wheat response to irrigation management in the Texas High Plains. Agric. Water Manag. 165:50–60. doi:10.1016/j.agwat.2015.11.002.

Bao, Y., G. Hoogenboom, R. McClendon, and P. Urich. 2015. Soybean production in 2025 and 2050 in the southeastern USA based on the SimCLIM and the CSM-CROPGRO-Soybean models. Clim. Res. 63(1):73–89. doi:10.3354/cr01281.

Basso, B., O. Gargiulo, K. Paustian, G.P. Robertson, C. Porter, et al. 2014. Erratum: Procedures for initializing organic carbon pools in the DSSAT-CENTURY model for agricultural systems. Soil Sci. Soc. Am. J. 78(4):1490. doi:10.2136/sssaj2010.0115er.

Booltink, H.W.G., and J. Verhagen. 1997. Using decision support systems to optimize barley management on spatial variable soil. Springer, Dordrecht. 6:219–233

Brown, P.J., R.S. Bradley, and F.T. Keimig. 2010. Changes in extreme climate indices for the Northeastern United States, 1870-2005. J. Clim. 23(24):6555–6572. doi:10.1175/2010JCLI3363.1.

Daccache, A., E.K. Weatherhead, M.A. Stalham, and J.W. Knox. 2011. Impacts of climate change on irrigated potato production in a humid climate. Agric. For. Meteorol. 151(12):1641–1653. doi:10.1016/j.agrformet.2011.06.018.

Dias, M.P.N.M., C.M. Navaratne, K.D.N. Weerasinghe, and R.H.A.N. Hettiarachchi. 2016. Application of DSSAT crop simulation model to identify the changes of rice growth and yield in Nilwala River Basin for mid-centuries under changing climatic conditions. Procedia Food Sci. 6:159–163. doi:10.1016/j.profoo.2016.02.039.

Donnelly, A., J. Craigon, C.R. Black, J.J. Colls, and G. Landon. 2001. Elevated CO2 increases biomass and tuber yield in potato even at high ozone concentrations. New Phytol. 149(2):265–274. doi:10.1046/j.1469-8137.2001.00015.x.

Douglas, E.M., and C.A. Fairbank. 2010. Is precipitation in northern New England becoming more extreme? statistical analysis of extreme rainfall in Massachusetts, New Hampshire, and Maine and updated estimates of the 100-year storm. J. Hydrol. Eng. 16(3):203–217. doi:10.1061/(asce)he.1943-5584.0000303.

Eitzinger, A., P. Läderach, B. Rodriguez, M. Fisher, S. Beebe, et al. 2016. Assessing high-impact spots of climate change: spatial yield simulations with Decision Support System for Agrotechnology Transfer (DSSAT) model. Mitig. Adapt. Strateg. Glob. Chang. 22(5):743-760. doi:10.1007/s11027-015-9696-2.

EPA. 2016. Climate change indicators in the United States 2016 Fourth Edition. EPA. 4:663–670. doi:10.1016/j.ajodo.2007.08.016.

Eyshi Rezaei, E., S. Siebert, and F. Ewert. 2017. Climate and management interaction cause diverse crop phenology trends. Agric. For. Meteorol. 233:55–70. doi:10.1016/j.agrformet.2016.11.003.

Fernandez, I.J., C.V. Schmitt, S.D. Birkel, E. Stancioff, A.J. Pershing, J.T. Kelley, J.A. Runge, G.L. Jacobson, and P.A. Mayewski. 2015. Maine’s climate future: 2015 Update. Orono, ME: University of Maine. 24pp. https://mco.umaine.edu/pubs/pdf/mcf-2015.pdf (accessed 3 June 2019)

Finnan, J.M., A. Donnelly, M.B. Jones, and J.I. Burke. 2005. The effect of elevated levels of carbon dioxide on potato crops. J. Crop Improv. 13:91–111. doi:10.1300/j411v13n01_06.

Fleisher, D.H., B. Condori, R. Quiroz, A. Alva, S. Asseng, et al. 2017. A potato model intercomparison across varying climates and productivity levels. Glob. Chang. Biol. 23(3)1258-1281. doi:10.1111/gcb.13411.

Frumhoff, P. C., McCarthy, J. J., Melillo, J. M., Moser, S. C., & Wuebbles, D. J. (2007). Confronting climate change in the US Northeast: science, impacts and solutions. synthesis report of the Northeast climate impacts assessment, 146. Retrieved from http://www.cabdirect.org/abstracts/20083177506.html

Gallandt, E.R., E.B. Mallory, A.R. Alford, F.A. Drummond, E. Groden, et al. 1998. Comparison of alternative pest and soil management strategies for Maine potato production systems. Am. J. Altern. Agric. 13(4):146–161. doi:10.1017/s0889189300007864.

Gijsman, A.J., G. Hoogenboom, W.J. Parton, and P.C. Kerridge. 2002. Modifying DSSAT crop models for low-input agricultural systems using a soil organic matter-residue module from CENTURY. Agron. J. 94(3):462–474.

Grandy, A.S., G.A. Porter, and M.S. Erich. 2002. Organic amendment and rotation crop effects on the recovery of soil organic matter and aggregation in potato cropping systems. Soil Sci. Soc. Am. J. 66(4):1311. doi:10.2136/sssaj2002.1311.

Hakala, K., L. Jauhiainen, S.J. Himanen, R. Rötter, T. Salo, et al. 2012. Sensitivity of barley varieties to weather in Finland. J. Agric. Sci. 150(2):145–160. doi:10.1017/S0021859611000694.

Halloran, J.M., T.S. Griffin, and C.W. Honeycutt. 2005. An economic analysis of potential rotation crops for Maine Potato cropping systems. Am. J. Potato Res. 82(2):155–162. doi:10.1007/BF02853653.

Hlavinka, P., M. Trnka, J. Eitzinger, V. Smutný, S. Thaler, et al. 2010. The performance of CERES-Barley and CERES-Wheat under various soil conditions and tillage practices in Central Europe. 61(1):5-7.

Holden, N.M., A.J. Brereton, R. Fealy, and J. Sweeney. 2003. Possible change in Irish climate and its impact on barley and potato yields. Agric. For. Meteorol. 116(4):181–196. doi:10.1016/S0168-1923(03)00002-9.

Holden, N.M., and A.J. Brereton. 2006. Adaptation of water and nitrogen management of spring barley and potato as a response to possible climate change in Ireland. Agric. Water Manag. 82(3):297–317. doi:10.1016/j.agwat.2005.07.026.

Hoogenboom, G., Wilkens, P. W., & Tsuji, G. Y. (1999). DSSAT version 3 vol 4. 4:1-300.

IBSNAT. 1993. Research Report Series 02. A simulation model for potato growth and development:.SUBSTOR - Potato Version 2.0. Dept. of Agronomy and Soil Science, College of Tropical Agriculture and Human Resources, Univ. of Hawaii, Honolulu, HI.

Ingvordsen, C.H., G. Backes, M. Foged Lyngkjaer, P. Peltonen-Sainio, J. Due Jensen, et al. 2015. Significant decrease in yield under future climate conditions: Stability and production of 138 spring barley accessions. Eur. J. Agron. 63:105–113. doi:10.1016/j.eja.2014.12.003.

IPCC. 2014. Climate Change 2014: Synthesis report. contribution of working groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change [core writing team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Jones, J.W., G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L.A. Hunt, P.W. Wilkens, U. Singh, A.J. Gijsman, J.T. Ritchie. 2003. The DSSAT cropping system model. European Journal of Agronomy. 18:235-265. doi:10.1016/S1161-0301(02)00107-7

Kassie, B.T., S. Asseng, C.H. Porter, and F.S. Royce. 2016. Performance of DSSAT-N wheat across a wide range of current and future growing conditions. Eur. J. Agron. 81:27–36. doi:10.1016/j.eja.2016.08.012.

Kleinwechter, U., M. Gastelo, J. Ritchie, G. Nelson, and S. Asseng. 2016. Simulating cultivar variations in potato yields for contrasting environments. Agric. Syst. 145:51-63. doi:10.1016/j.agsy.2016.02.011.

Klink, K., J.J. Wiersma, C.J. Crawford, and D.D. Stuthman. 2014. Impacts of temperature and precipitation variability in the Northern Plains of the United States and Canada on the productivity of spring barley and oat. Int. J. Climatol. 34(8):2805–2818. doi:10.1002/joc.3877.

Kropff, M.J., J. Bouma, and J.W. Jones. 2001. Systems approaches for the design of sustainable agro-ecosystems. Agric. Syst. 70(3):369–393. doi:10.1016/S0308-521X(01)00052-X.

Larkin, R.P., C.W. Honeycutt, T.S. Griffin, O.M. Olanya, Z. He, et al. 2017. Cumulative and residual effects of different potato cropping system management strategies on soilborne diseases and soil microbial communities over time. 66(3):437–449. doi:10.1111/ppa.12584.

Li, Z.T., J.Y. Yang, C.F. Drury, and G. Hoogenboom. 2015. Evaluation of the DSSAT-CSM for simulating yield and soil organic C and N of a long-term maize and wheat rotation experiment in the Loess Plateau of Northwestern China. Agric. Syst. 135:90–104. doi:10.1016/j.agsy.2014.12.006.

Maa, A., A. Khalil, M. Hassanien, and A. Abou-Hadid. 2010. Sensitivity of potato yield to climate change. J. Appl. Sci. Res. 6(6):751–755.

Maine Potato Board. 2016. A Review of the Industry 2016. Presque Isle, Maine.

Mallory, E.B., T.S. Griffin, and G.A. Porter. 2010. Seasonal nitrogen availability from current and past applications of manure. Nutr. Cycl. Agroecosystems 88(3):351–360. doi:10.1007/s10705-010-9361-9.

Mallory, E. B., & Porter, G. A. 2007. Potato yield stability under contrasting soil management strategies. In Agronomy Journal. 99:501–510. https://doi.org/10.2134/agronj2006.0105

Marcinkowski, P., and M. Piniewski. 2018. Effect of climate change on sowing and harvest dates of spring barley and maize in Poland. Int. Agrophys 32:265–271. doi:10.1515/intag-2017-0015.

Mereu, V., G. Carboni, A. Gallo, R. Cervigni, and D. Spano. 2015. Impact of climate change on staple food crop production in Nigeria. Clim. Change 132(2):321–336. doi:10.1007/s10584-015-1428-9.

Nouri, M., M. Homaee, M. Bannayan, and G. Hoogenboom. 2017. Towards shifting planting date as an adaptation practice for rainfed wheat response to climate change. Agric. Water Manag. 186:108–119. doi:10.1016/j.agwat.2017.03.004.NRCS. 2018. Web Soil Survey. Nat. Resour. Conserv. Serv. United States Dep. Agric. https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx (accessed: 2 Jul. 2019)

Opena, G.B., and G.A. Porter. 1994. (1999) Soil Management and Supplemental Irrigation Effects on Potato: II. Root Growth. Agronomy Journal. 91:426–431.

Pendall, E., S. Del Grosso, J.Y. King, D.R. LeCain, D.G. Milchunas, et al. 2003. Elevated atmospheric CO2 effects and soil water feedbacks on soil respiration components in a Colorado grassland. Global Biogeochem. Cycles 17(2):1-15. doi:10.1029/2001gb001821.

Porter, G.A., W.B. Bradbury, J.A. Sisson, G.B. Opena, and J.C. McBurnie. 1999. Soil management and supplemental irrigation effects on potato: I. soil properties, tuber yield, and quality. Agron. J. 91(3):416. doi:10.2134/agronj1999.00021962009100030010x.

Porter, G. A., Ocaya, P. C., Associate, R., Macfarline, B., & Plummer, B. 2017. 2017 Maine potato variety trials NE1231 regional trials and advanced breeding lines Exeter, Presque Isle, and St. Agatha, Maine. Retrieved from https://potatoes.ncsu.edu/NE1014reports/Maine%20Variety%20Trials%202017RPT%20posting.pdf

Raymundo, R., S. Asseng, R. Prassad, U. Kleinwechter, J. Concha, et al. 2017. Performance of the SUBSTOR-potato model across contrasting growing conditions. F. Crop. Res. 202:57–76. doi:10.1016/j.fcr.2016.04.012.

Rabia, M., H. Tarik, and D. Farida. 2016. Evaluation of DSSAT model for sprinkler irrigated potato: A case study of Northeast Algeria. African J. Agric. Res. 11(29):2589–2598. doi:10.5897/ajar2015.9828.

Romero, C.C., G. Hoogenboom, G.A. Baigorria, J. Koo, A.J. Gijsman, et al. 2012. Reanalysis of a global soil database for crop and environmental modeling. Environ. Model. Softw. 35:163–170. doi:10.1016/j.envsoft.2012.02.018.

Rosenzweig, C., J. Elliott, D. Deryng, A.C. Ruane, C. Müller, et al. 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proc. Natl. Acad. Sci. 111(9):3268–3273. doi:10.1073/pnas.1222463110.

Rötter, R.P., T. Palosuo, K.C. Kersebaum, C. Angulo, M. Bindi, et al. 2012. Simulation of spring barley yield in different climatic zones of Northern and Central Europe: A comparison of nine crop models. F. Crop. Res. 133:23-36. doi:10.1016/j.fcr.2012.03.016.

Sanders, D., and N.G. Creamer. 1996. Commercial potato production in Eastern North Carolina. NC State Univ. Hortic. Inf. Leafl. 57:1-85. www.ces.ncsu.edu/depts/hort/hil/hil-22.html.

Sharifi, M., B.J. Zebarth, D.L. Burton, C.A. Grant, and G.A. Porter. 2008. Organic amendment history and crop rotation effects on soil nitrogen mineralization potential and soil nitrogen supply in a potato cropping system. Agron. J. 100(6):1562. doi:10.2134/agronj2008.0053.

Sharma, L., S. Bali, J. Dwyer, A. Plant, A. Bhowmik, et al. 2017. A case study of improving yield prediction and sulfur deficiency detection using optical sensors and relationship of historical potato yield with weather data in maine. Sensors 17(5):1095. doi:10.3390/s17051095.

Snapp, S.S., and A.M. Fortuna. 2003. Predicting nitrogen availability in irrigated potato systems. Hort. Tech. 13(4):598-604

Snyder, R.L., R. Moratiel, Zhenwei Song, A. Swelam, I. Jomaa, et al. 2011. Evapotranspiration response to climate change. Acta Hortic. (922):91–98. doi:10.17660/ActaHortic.2011.922.11.

Šťastná, M., F. Toman, and J. Dufková. 2010. Usage of SUBSTOR model in potato yield prediction. Agric. Water Manag. 97(2):286-290. doi:10.1016/j.agwat.2009.09.015.Surjawan, I., M.P. Dougherty, M.E. Camire, and J.J. Jemison. 2004. Malting quality of maine-grown barley. https://digitalcommons.library.umaine.edu/cgi/viewcontent.cgi?article=1009&context=aes_miscreports.

Tovihoudji, P.G., P.B.I. Akponikpè, E.K. Agbossou, and C.L. Bielders. 2019. Using the DSSAT model to support decision making regarding fertilizer microdosing for maize production in the sub-humid region of Benin. Front. Environ. Sci. 7:13. doi:10.3389/fenvs.2019.00013.Trnka, M., M. Dubrovský, and Z. Žalud. 2004. Climate change impacts and adaptation strategies in spring barley production in the Czech Republic. Clim. Change 64(2):227–255. doi:10.1023/B:CLIM.0000024675.39030.96.

Tubiello, F.N., C. Rosenzweig, R.A. Goldberg, S. Jagtap, and J.W. Jones. 2002. Effects of climate change on US crop production: Simulation results using two different GCM scenarios. Part I: Wheat, potato, maize, and citrus. Clim. Res. 20(3):259-270. doi:10.3354/cr020259.

Vashisht, B.B., T. Nigon, D.J. Mulla, C. Rosen, H. Xu, et al. 2015. Adaptation of water and nitrogen management to future climates for sustaining potato yield in Minnesota: field and simulation study. Agric. Water Manag. 152:198–206. doi:10.1016/j.agwat.2015.01.011.

White, J.W., G. Hoogenboom, B.A. Kimball, and G.W. Wall. 2011. Methodologies for simulating impacts of climate change on crop production. F. Crop. Res. 124(3):357–368. doi:10.1016/j.fcr.2011.07.001.

Williams, A., M.C. Hunter, M. Kammerer, D.A. Kane, N.R. Jordan, et al. 2016. Soil water holding capacity mitigates downside risk and volatility in US rainfed maize: time to invest in soil organic matter? PLoS One 11(8):1-11. doi:10.1371/journal.pone.0160974.

Willmott, C.J. 1981. On the validation of models. Phys. Geogr. 2(2):184–194. doi:10.1080/02723646.1981.10642213.

Wolfe, D.W., A.T. DeGaetano, G.M. Peck, M. Carey, L.H. Ziska, et al. 2018. Unique challenges and opportunities for northeastern US crop production in a changing climate. Clim. Change 146(2):231–245. doi:10.1007/s10584-017-2109-7.

Worthington, C.M., and C.M. Hutchinson. 2005. Accumulated growing degree days as a model to determine key developmental stages and evaluate yield and quality of potato in Northeast Florida. Proc. Fla. State Hort. Soc. Proc. Fla. State Hort. Soc 118:98–101.

Yin, C., Clim. Yinpeng Li, and Clim. Peter Urich. 2013. SimCLIM 2013 data manual. www.climsystems.com (accesssed: 14 June 2019)

Zebarth, B.J., Y. Leclerc, G. Moreau, R. Gareau, and P.H. Milburn. 2003. Soil inorganic nitrogen content in commercial potato fields in New Brunswick. Can. J. Soil Sci. 83(4):425–429. doi:10.4141/s02-065.

Zheng, Z., H. Cai, L. Yu, and G. Hoogenboom. 2017. Application of the CSM–CERES–wheat model for yield prediction and planting date evaluation at Guanzhong plain in northwest China. Agron. J. 109(1):204–217. doi:10.2134/agronj2016.05.0289.

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