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Predicting the response of a potato-grain production system to climate change for a humid continental climate using DSSAT

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ABSTRACT

Climate change presents both challenges and opportunities for crop production. This study evaluated the vulnerability of potato *(Solanum tuberosum* L.*)* and barley (*Hordeum vulgare* L.) to climate change for 2050 to 2079 in Maine, U.S.A., and the potential of changing variety and planting date as climate adaptation strategies. The DSSAT model v4.7 was calibrated and evaluated for contrasting varieties of potato (Atlantic, a mid-season variety, and Russet Burbank, a late-season variety) and barley (Robust, a 6-row feed variety, and Newdale, a 2-row malting variety) using 99 field experiments conducted in Maine. The model accurately simulated observed final yield for each variety with modeling efficiencies (EF) ranging from 0.60 to 0.84 and coefficients of determination (r^2) above 0.98. Climate change simulations compared crop yield across multiple planting dates for one baseline period (1989-2018) and four future climate scenarios (two emissions scenarios, RCP 6.0 and 8.5, with and without elevated CO_2). In the absence of elevated CO_2, yield of the potato variety Atlantic, and both barley varieties declined by 6 to 27% under elevated temperature and precipitation, but increased by 5% for the potato variety Russet Burbank. However, under future climate conditions and elevated CO_2, yield of all potato and barley varieties increased or were unchanged. Optimal planting date for each variety was consistent across climate scenarios. These results suggest that climate change may favor longer-season varieties such as Russet Burbank, but adjusting planting date may not be an effective climate change adaptation strategy in this region. Elevated CO_2 boosted crop growth and development across all varieties for a humid continental climate and for the time period studied. The models used do not address climate change's possible effects on crop quality or losses due to plant diseases and pests.

1. Introduction

Adapting to climate change is the new imperative for agriculture. Measurable changes in weather patterns have already occurred in many regions of the world and are projected to intensify in the future. Within the United States, the Northeast region has witnessed a 1.1°C rise in annual mean temperature and a 10% increase in annual total precipitation between 1895 and 2011 (Kunkel et al., 2013), accompanied by a 71% increase in the frequency of extreme rainfall events (≥5 mm of precipitation in 24 hours) since the mid-1900s (Wolfe et al., 2018). Warming has been most pronounced for the winter minimum and summer nighttime temperatures, while precipitation has increased most during the winter and spring months, and these trends are expected to continue in the future (Wolfe et al., 2018). By some projections, the Northeast is expected to warm faster than other U.S. regions, and 50% faster than the global average (Karmalkar and Bradley, 2017).

Climate change presents both opportunities and challenges for agriculture in the U.S. Northeast. Concurrent with rising temperatures, the first fall frost is occurring later and the onset of spring is advancing, which has increased the number of frost free days and the length of the growing season (Brown et al., 2010; Wolfe et al., 2018). However, an increase in temperature also could reduce crop yield, by shortening

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phenological phases (Eyshi Rezaei et al., 2017; Worthington and Hutchinson, 2005) and reducing the available soil moisture through increased evapotranspiration (ET[1]) (Anderson et al., 2010; Williams et al., 2016), as well as affect crop quality (Hatfield et al., 2011; Worthington and Hutchinson, 2005). In addition, an increase in heavy rains could delay planting, cause physical damage to the crop, degrade fields, and increase potential disease pressure (Hatfield et al., 2011; Wolfe et al., 2018). Rising CO_2 concentration (a driving force of climate change) has been documented to positively impact plant biomass accumulation and yield (Donnelly et al., 2001; Finnan et al., 2005; Frumhoff et al., 2007; Pendall et al., 2003; Trnka et al., 2004) further reinforcing the complexity of the potential impact of climate change on crop production systems.

In the U.S., the potato industry is economically vital to a number of northern states including Maine (NASS, 2019). Potato has an inherently shallow root system (Opena and Porter, 1999) with often dry, aerated soils due to intensive cultivation (Grandy et al., 2002; Mallory and Porter, 2007). Thus, potato is highly sensitive to changes in weather and particularly susceptible to drought stress. The industry standard production practice is to rotate potato with cereal grains such as barley, both malt and feed types, to reduce pest pressure and improve soil health (Grandy et al., 2002; Halloran et al., 2005).

At the global level, the yield for potato is predicted to drop in response to climate change, by up to 6% by 2055 and 26% by 2085 (Raymundo et al., 2018). In general, predicted yield increases due to elevated CO_2 are offset by reductions due to higher temperatures and reduced precipitation, with net impacts depending on the region (Fleisher et al., 2017). For northern climates, studies in the Northwest U.S. (Stöckle et al., 2010) and Europe (Supit et al., 2012) suggest that potato yield will remain the same or improve with climate change and elevated CO_2 over the coming decades but rising temperatures will offset the positive effect of CO_2 by the end of the century. In contrast, Raymundo et al. (2018) predicted earlier and more substantial reductions in potato tuber yield for the Northwest and Northeast U.S., of 5 to 49% by mid-century for RCP8.5. Few studies exist on the potential impact of climate change on barley, but, as with other small grain crops, higher temperature can significantly impact grain yield by hastening crop development (Hakala et al., 2012; Rötter et al., 2012; Tubiello et al., 2002). In Ireland, barley showed less sensitivity to climate change than potato (Holden et al., 2003).

Farmer adaptation to climate change occurs at the regional level, emphasizing the importance of region-specific climate impact and adaptation studies. Two of the simplest potential adaptation strategies for farmers to adopt are changing varieties and planting dates, yet studies of these strategies for potato and barley are scarce. Hakala et al. (2012) found considerable diversity among 22 barley varieties in the response to planting delays and higher late-season temperatures. For potato, Adavi et al. (2018) found earlier-maturing varieties to be better adapted under climate change in Iran, yet Tubiello et al. (2002) did not find variety to be an effective adaptation strategy for rainfed U.S. sites.

The Decision Support Systems for Agrotechnology Transfer (DSSAT) computer simulation platform has been widely used to investigate potential climate change impacts on crops (White et al. 2011) and adaptive management strategies (Jones et al., 2003; Tsuji et al., 1998). Within DSSAT, the Cropping System Model (CSM)-SUBSTOR-Potato model has been successfully calibrated for a range of field conditions and management practices around the world and used for climate change impact studies (Adavi et al., 2018; Daccache et al., 2011; Fleisher et al., 2017; Holden et al., 2003; Raymundo et al., 2018; Tubiello et al., 2002; Vashisht et al., 2015; Woli and Hoogenboom, 2018; Woli et al., 2016). Raymundo et al. (2017) found that the SUBSTOR model in DSSAT v4.5 underestimated the impact of high temperature and elevated CO_2 on crop growth. These limitations were addressed in DSSAT v4.7 by modifying the CO_2 and temperature response functions for photosynthesis and adding a temperature response function for leaf senescence (Raymundo et al. 2018). The CSM-CERES-Barley model within DSSAT also has been calibrated for a number of locations, although most studies have been implemented outside of the United States (Alexandrov and Eitzinger, 2005; Hlavinka et al., 2010; Holden et al., 2003; Rötter et al., 2012; Trnka et al., 2004).

The objectives of this study were to: 1) calibrate and evaluate the CSM-SUBSTOR-Potato and CSM-CERES-Barley models for two contrasting varieties each, for Maine; 2) simulate the responses of those potato and barley varieties to changes in climate anticipated for 2050 to 2079; and 3) evaluate adjusting planting date and variety as potential adaptation strategies.

2. Materials and methods

2.1. Study site and field experiments

Two potato varieties were used in this study: 'Atlantic', a mid-season, round-white variety, grown primarily for the chip industry, and 'Russet Burbank', a late-season variety used primarily for french-fries and baking (PAA, n.d.a; PAA, n.d.b). Russet Burbank is Maine's most commonly grown variety, accounting for over a third of total potato acreage annually (NASS, 2018), and Atlantic is the top publicly available variety grown for seed in the state (MEDACF, 2019). Due to their popularity, these varieties are commonly included in agronomic field trials in Maine. Field experimental data from the three major production areas in Maine were used for model calibration and evaluation (Table A1). For the variety Atlantic, tuber yield and accompanying crop management information were obtained from: 1) 41 potato variety trials conducted from 2007 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 (Porter et al., 2007-2018); 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). For the variety Russet Burbank, yield and accompanying crop management information were obtained from: 1) 11 potato variety trials conducted from 2007 to 2018 in Presque Isle and St. Agatha, Maine (Porter et al., 2007-2018); 2) three nitrogen rate trials conducted from 2015 to 2017 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. For all trials, experimental data used for this study were the treatment means from four replicates. Plot sizes were 6-8 m^2 for the variety trials, 46 m^2 for the nitrogen rate trials, 54 m^2 for the CRISPI trial, and 599 m^2 for the Maine Potato Ecosystem Project. In addition to these data, in 2017 and 2018, time-series growth and development data including above-ground and tuber biomass, soil moisture, and soil inorganic nitrogen were collected for both varieties according to DSSAT methods (Hoogenboom et al., 1999) from plots adjacent to the potato variety trials at all locations. Planting dates varied by year for all sites and experiments. All experiments were rainfed. Soil types at Presque Isle, St. Agatha, and Exeter locations are Caribou gravelly loam (Fine-loamy, isotic, frigid Typic Haplorthods), Thorndike channery silt loam (Loamy-skeletal, isotic, frigid Lithic Haplorthods), and Penobscot gravelly silt loam (Coarse-loamy, isotic, frigid Typic Dystrudepts), respectively.

Field experimental data for calibration and evaluation of the CSM-CERES-Barley model for varieties Newdale and Robust were obtained from: 1) barley variety trials that were conducted from 2015 to 2018 at

[1] Abbreviations: CSM, Cropping Systems Model; d, Wilmott index of agreement; DSSAT, Decision Support System for Agrotechnology Transfer; EF, modeling efficiency; ET, evapotranspiration; GDD, growing degree day; nRMSE, normalized root mean square error; LAI, leaf area index; RCP, representative concentration pathway; RTF, relative temperature factor; SLPF, soil fertility factory; T_{min}, daily minimum temperature; T_{max}, daily maximum temperature.

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 (Mallory and Molloy, 2016-2019), 2) an additional set of plots established in Old Town in 2017 and 2018 to track barley growth and development, 3) for Newdale only, a planting date trial conducted in 2017 in Old Town, and 4) for Robust only, the Maine Potato Ecosystem Project mentioned above, for the years 1993 through 1997 and from 2003 through 2005. Detailed soil moisture, soil nitrogen, and plant nitrogen data from the Maine Potato Ecosystem Project from 2003 to 2005 were used for initial soil evaluation and the calibration of the barley variety Robust. Barley growth and development time-series data (above-ground barley biomass, growth stages, soil moisture, and soil inorganic nitrogen) were collected in accordance with DSSAT methods (Hoogenboom et al., 1999) for both varieties from the 2015, 2017, and 2018 variety trials, the 2017 and 2018 growth and development plots, and for Newdale from a 2017 planting date trial. Barley experimental data were the treatment means from four replicates. Plot size was 7 m^2 for the barley variety and planting date trials, and 16 m^2 for the growth and development plots.

2.2. The DSSAT model

The DSSAT Cropping System Model v4.7 (Hoogenboom, Porter, Boote et al., 2019; Hoogenboom, Porter, Sheila et al., 2019) was used to simulate yield under current and future climate conditions in Maine. DSSAT consists of component modules 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 (Hoogenboom et al. 2012). The latest version of the DSSAT model can be requested from the DSSAT web portal (www.dssat.net).

CSM-SUBSTOR-Potato is the crop model used by DSSAT to simulate the phenological development, biomass accumulation, and biomass partitioning of potato, and has been described in detail in IBSNAT (1993) and Singh et al. (1998). Briefly, the CSM-SUBSTOR-Potato model is a process-based model that simulates growth and development on a daily basis using the minimum data inputs stated above. Potato growth and development are simulated for five separate phenological phases (pre-planting, planting to sprout germination, sprout germination to emergence, emergence to tuber initiation, and tuber initiation to maturity), and are controlled by five variety-specific coefficients (Table 1) related to leaf area expansion rate (G2), potential tuber growth rate (G3), tuber growth suppression (PD), photoperiod effects on tuber initiation (P2), and the upper critical temperature above which tuber initiation is inhibited (TC). The model uses trapezoidal functions with ranges from zero to one to simulate the effects of temperature on daily leaf and vine growth (RTFVine), root and tuber growth (RTFSoil), photosynthesis (PRFT), and tuber initiation (RTFTI). RTFVine and PRFT are based on the mean daily air temperature, RTFSoil is based on modeled surface soil temperature (0-20 cm), and RTFTI is based on a weighted mean air temperature (T_{min}*0.75 + T_{max}*0.25) to reflect the stronger influence of daily minimum temperature than of daily mean or maximum. RTFVine and RTFSoil have the same base temperature (2°C) and upper critical temperature above which growth ceases (35°C), but different temperature optimum ranges (17°C to 24°C for RTFVine and 15°C to 23°C for RTFSoil). For PRFT, base and critical temperatures are 3°C and 42°C, respectively, and the temperature is optimal between 15°C and 30°C. For tuber initiation, which is based on both RTFTI and the TC cultivar coefficient, the base temperature is 4°C, the critical upper temperature is TC + 8°C, and the temperature is optimal when the weighted mean temperature is above 10°C and below TC. Tuber initiation is influenced also by a relative daylength factor (RDLFTI) that decreases relative to the P2 cultivar coefficient at a photoperiod or day length above 12 hours, such that early varieties are less sensitive than late varieties to an increase in the photoperiod. Rates of photosynthesis, phenological development, and biomass accumulation are modified by drought stress factors that are based on the relationship between potential root water uptake and potential transpiration, and by nitrogen deficit factors related to critical nitrogen concentrations for the maximum and the minimum rates at which these processes stop. CO_2 concentration affects daily potential photosynthesis and tuber growth (Raymundo et al. 2017).

Table 1
Cultivar coefficients for the varieties used to assess the effects of climate change on potato and barley in Maine.

Codes	Definitions	Cultivar coefficients	
Potato		Atlantic	Russet Burbank
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
Barley		Newdale	Robust
P1V	Days at optimum vernalizing temperature	0	0
P1D	Photoperiod response (% reduction in the developmental rate per 10-h drop in 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

CSM-CERES-Barley is the model in DSSAT that simulates growth, development, and yield for barley. It is described in detail by Jones et al. (2003) and Ritchie et al. (1998). Similar to CSM-SUBSTOR-Potato, the model simulates growth, development, and senescence in separate phenological phases (emergence, vegetative growth, anthesis, grain filling) with rates dependent on the accumulation of growing degree days (GDD) calculated using trapezoidal functions with a minimum base temperature, maximum critical temperature, and optimal temperature ranges. Growth and development rates are modified by water and nitrogen availability, CO_2 concentrations, and variety-specific coefficients (Table 1) related to vernalization sensitivity (P1V), photoperiod sensitivity (P1D), grain filling duration (P5), kernel number (G1), kernel filling rate (G2), potential stem and spike weight (G3), and the rate of leaf appearance (PHINT).

2.3. Model inputs

2.3.1. Soil

Soil files in DSSAT were developed for each experiment using site-specific soil characterization by depth, experiment-specific top-soil traits, and soil data obtained from NRCS (NRCS, 2018). The soil profile was characterized every 20 cm to a depth of 80 cm, where 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 for each year and experiment establishing year-to-year field-specific soil differences. Where measurements could not be obtained for deeper layers in the profile, region-specific soil data from the National Cooperative Soil Survey (NCSS; https://ncsslabdatamart.sc.egov.usda.gov/) were used.

2.3.2. Weather

For the Presque Isle site, daily total precipitation and daily maximum (T_{max}) and minimum (T_{min}) temperatures were acquired from the National Climatic Data Center (https://www.ncdc.noaa.gov/) through the National Oceanic and Atmosphere Administration (NOAA). Consistent data were not available from NOAA within a 25 km radius of the other sites (Exeter, St. Agatha, and Old Town). Therefore, weather data were obtained from the PRISM Climate Group, which provides interpolated measures at a 4 km x 4 km resolution (Oregon State University, http://prism.oregonstate.edu, created 15 Jan 2019). For all sites, solar radiation data was obtained from The Prediction of Worldwide Energy Resources (POWER) dataset from the National Aeronautics and Space Administration (https://power.larc.nasa.gov/).

2.3.3. Other inputs

Simulation options and methods within the model remained in their default states with the exception of CO_2 and the 'method of soil organic matter', where the Keeling-Curve (Keeling and Keeling, 2017) and the CENTURY model (Gijsman et al., 2002) were applied. The Keeling-Curve accounts for the accumulation of CO_2 over time as measured at the Mauna Loa Observatory in Hawaii, rather than a fixed value. The CENTURY-based soil module is recognized for its ability to simulate nitrogen, soil organic carbon, residue dynamics and soil-water processes, with a sub-module for each (Gijsman et al. 2002; Raymundo et al. 2017). Initial soil nitrogen concentrations by depth were estimated using field data from Zebarth et al. (2003) for the top layer (0-20 cm) and soil-specific percent changes among depths based on data from the NCSS. Other initial field conditions, including crop residue amounts and characteristics, were estimated using field measurements. Passive, or stable, carbon within the soil profile was estimated at 65% based on data collected in the Maine Potato Ecosystem Project (Mallory and Griffin, 2007).

2.4. The climate model

DSSAT-Perturb (CLIMsystems Limited, Version 1.0, https://www.climsystems.com/dssat-perturb/), used to generate future weather data, is an add-on tool based onClimSystems, https://www.climsystems.com/) 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). To generate a single climate scenario from an ensemble of multiple GCMs, DSSAT-Perturb uses the median value of the selected GCMs (Yin et al., 2013). For this study, the three GCMs selected (GFDL-CM3, GISS-E2, and HadGEM2-ES) were recommended by the Maine State Climatologist based in large part on their performance simulating historic weather data for the Northeast (S. Birkel, personal communication, May 24, 2018). Future weather for the years 2050 to 2079 was generated for Presque and St. Agatha by perturbing site-specific historical weather for the years 1989 to 2018 using the ensemble median of the three GCMs. For each location, weather was generated for two Representative Concentration Pathways (RCPs), the intermediate scenario RCP 6.5 and the high greenhouse gas (GHG) emissions scenario RCP 8.0 (IPCC, 2014). The resulting future climate scenarios represent the population of 30 years of predicted weather from 2050 to 2079, with a mean and a single CO_2 concentration relative to the RCP.

2.5. Model calibration and evaluation

Prior to calibrating the variety-specific parameters, soil model performance was evaluated using time-series soil moisture data for the barley variety Robust from the Maine Potato Ecosystem Project from 2003 to 2005. The barley data were used to evaluate soil dynamics as the inherently high spatial variability of potato made it difficult to measure and compare observed soil moisture with the model. A soil fertility factor (SLPF) was calibrated for each site to account for site-specific differences related to the effects of soil nutrients other than nitrogen (Bao et al., 2015; Romero et al., 2012). The SLPF was estimated using the final yield data from random years of variety-specific experiments, which were then excluded from future calibration. The SLPF was identified by the lowest normalized Root Mean Square Error (nRMSE) between observed and simulated yields within a fertility range of 0.75 and 1.0. Resulting SLPFs were: 0.83, 0.96, 1.0, and 0.94 for the Maine Potato Ecosystem Project, and variety and nitrogen rate trials in Presque Isle, St. Agatha, and Exeter, respectively.

Initial simulations were conducted to gauge how well the model performed for each variety. The model's ability to predict dry matter yield for the potato variety Atlantic resulted in no further calibration from the predetermined cultivar coefficients provided for Atlantic in DSSAT 4.7 (Table 1). The three other varieties required calibration. For Russet Burbank potato, cultivar coefficients were estimated using 2015-2017 growth and development data from the variety and nitrogen trials. The parameter estimation tool, GLUE (Generalized Likelihood Uncertainty Estimation) (He et al., 2010; Hoogenboom et al., 2019) was unsuccessful. Instead, coefficients were estimated using the Sensitivity Analysis tool in DSSAT followed by manual adjustments to minimize the nRMSE of simulated and observed yields. Growth parameters including leaf area expansion rate and tuber growth rate were adjusted first, followed by the parameters for tuber growth suppression and sensitivity to photoperiod and temperature. The baseline coefficients used in calibration were obtained from DSSAT 4.7. The resulting coefficients were within the ranges of values provided in DSSAT 4.7 for 26 potato varieties, and similar to values used for Russet Burbank in other studies (IBSNAT, 1993; Vashisht et al., 2015; Woli et al., 2016).

Cultivar coefficients for the barley variety Robust were estimated using GLUE and phenology, grain dry matter yield, and yield component data from 2003, 2005 (Presque Isle), and 2017 (Old Town). Parameter estimation was run over 6,000 iterations and the resulting coefficients were further adjusted using the Sensitivity Analysis tool (Table 1). 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), and the 'G3' coefficient, which was adjusted to the value measured in Old Town in 2017. Lowering the 'G2' coefficient closer to measured values reduced fit and were not adopted due to concerns that measured values may have underestimated the variety's potential. Cultivar coefficients for the barley variety Newdale were calibrated 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 mean of measured values. The estimated coefficients for both barley varieties were well within the minimum and maximum values provided in DSSAT 4.7 for barley.

Model evaluation was conducted using 44 experiments over 21 years for Atlantic potato, 11 experiments over 7 years for Russet Burbank potato, 7 experiments over 2 years for Newdale barley, and 11 experiments over 11 years for Robust barley, and excluded any experiments used in calibration. Model performance was evaluated by comparing simulated and observed final yield data using the following statistics: coefficient of determination (r^2) with the 1:1 line forced through the origin, normalized Root Mean Square Error (nRMSE), modeling efficiency (EF), and Willmott index of agreement (d) (Willmott, 1981; Yang et al. 2014). Perfect agreement of simulated values with observed values would lead to r^2, EF, and d values of 1 and a nRMSE of 0.

2.6. Simulation of future climate scenarios 2050-2079

Simulations were conducted annually for 30 years for the four crop varieties, two locations (Presque Isle and St. Agatha), and five climate change scenarios. The climate change scenarios included historical weather conditions for the period 1989 to 2018 and four future 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 for RCP 6.0 and 638 ppm for RCP 8.5).

A set of standard production conditions for each crop, variety, and location were used across all simulated climate scenarios, and included initial soil and crop residue conditions, initial crop residue, and crop management practices. These standard conditions were based on the most common conditions and management practices used for the field experiments described above. Seeding rates and fertilizer rates are congruent with current standard industry practices in Maine. For potato, the prior crop was barley with an estimated 1930 kg ha^{-1} of crop residue. Seeding rates were 4.31 and 2.72 seed pieces m^{-2} for potato varieties Atlantic and Russet Burbank, respectively, with fertilizer rates of 191 and 197 kg nitrogen ha^{-1} in Presque Isle and St. Agatha, respectively. For barley, the prior crop was potato with an estimated 929 kg ha^{-1} of crop residue. Seeding rates were 400 live seeds m^{-2} for both varieties, with a fertilizer rate of 79 kg nitrogen ha^{-1} at both locations. For both crops, initial soil conditions (0-20 cm) were 2.09 and 2.38% organic carbon, and 1.35 and 1.55% stable carbon in Presque Isle and St. Agatha, respectively, and 10.5 mg kg^{-1} nitrate for both locations.

The planting date scenarios included four dates spaced 10 days apart, starting 2 May, for potato, and five dates spaced 10 days apart, starting 12 April, for barley. The CSM-SUBSTOR-Potato model does not estimate crop maturity, thus, the harvest date for potato had to be estimated based on variety-specific phenological responses to environmental cues. For the variety Atlantic, which matures with GDD, the harvest date for each year of each climate scenario was calculated by using the mean cumulative GDD between planting and harvest observed in the field experiments (1365 GDD). In contrast, Russet Burbank, being a late-season variety, will typically grow until the first fall frost or period of drought in Maine (G.A. Porter, personal communication, 15 Nov 2017). Thus, harvest date was calculated for each year of each climate scenario using the mean number of days from planting to first frost ($< 0°C$) observed in the above field trials, with a maximum growing period set at 150 days (G.A. Porter, personal communication, 15 Nov 2017). The 150-day maximum growing period is supported by data from Maine for the length of time between the earliest typical planting date and the latest typical harvest date recorded for Maine (NASS, 2010), and corresponds to the number of days needed to achieve maximum yields for this variety (PAA, n.d.b). The CSM-CERES-Barley model predicts physiological and harvest maturity for the barley varieties Robust and Newdale as a function of phenological cultivar coefficients and environmental conditions. The mean number of days to harvest for each variety, climate scenario, and planting date is presented in Table 2.

The model outputs evaluated for potato were tuber dry matter yield, haulm weight, leaf area index (LAI), and total and mean daily ET. The number of optimum days and above-optimum days for potato vine growth and root and tuber growth were calculated for the different climate and planting date scenarios using the temperature response functions described above for RTFVINE and RTFSOIL. Model output data for barley were grain dry matter yield, above-ground dry matter, LAI, and ET.

2.7. Statistical analysis

Simulation results were analyzed using two-way ANOVA in JMP (JMP®, Version 14.3). The model included year (as a blocking factor), and planting date, climate scenario, and their interaction. The interaction was included to investigate the effect of planting date on crop response to climate change. Due to a lack of homogeneity of variances that could not be resolved with data transformation, analyses were conducted separately by site and variety. Mean separation was conducted using Tukey's HSD procedure in JMP.

3. Results and discussion

3.1. Model evaluation

The CSM model adequately simulated observed soil moisture dynamics with r^2, m, nRMSE, ER, and d values of 0.85, 0.98, 12.43, 0.84, and 0.93 respectively, indicating the model strongly replicated within-season variability in soil moisture for both potato and grain (Figure A1). CSM-SUBSTOR-Potato successfully predicted rainfed tuber yield for the potato varieties Atlantic and Russet Burbank for various environmental conditions and management practices in Maine (Fig. 1a and 1b). The nRMSE for Atlantic (13.3%) and Russet Burbank (12.3%) are below or within the range of nRMSEs from other similar potato modeling studies (Table 3). Adavi et al. (2018), Kleinwechter et al. (2016), Raymundo et al. (2017), and Tubiello et al. (2002) reported relative nRMSEs of 2.18, 28.1, 21.4, and 15 to 25%, respectively. The relatively high EF and d values further reinforced that the model accurately predicted tuber yield for both varieties. The r^2 values with the intercept set to zero were 0.985 and 0.986 for Atlantic and Russet Burbank, respectively.

CSM-CERES-Barley model also performed well following calibration (Fig. 1c and 1d). There was a close agreement between simulated and

Table 2
Days to harvest as a function of planting date and climate scenario for potato varieties Atlantic and Russet Burbank, and barley varieties Newdale and Robust, at two locations in Maine.

	Days to Harvest									
	Presque Isle					St. Agatha				
Potato planting dates	May 2	May 12	May 22	May 30	–	May 5	May 15	May 25	June 5	–
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	April 12	April 22	May 2	May 12	May 22	April 12	April 22	May 2	May 12	May 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

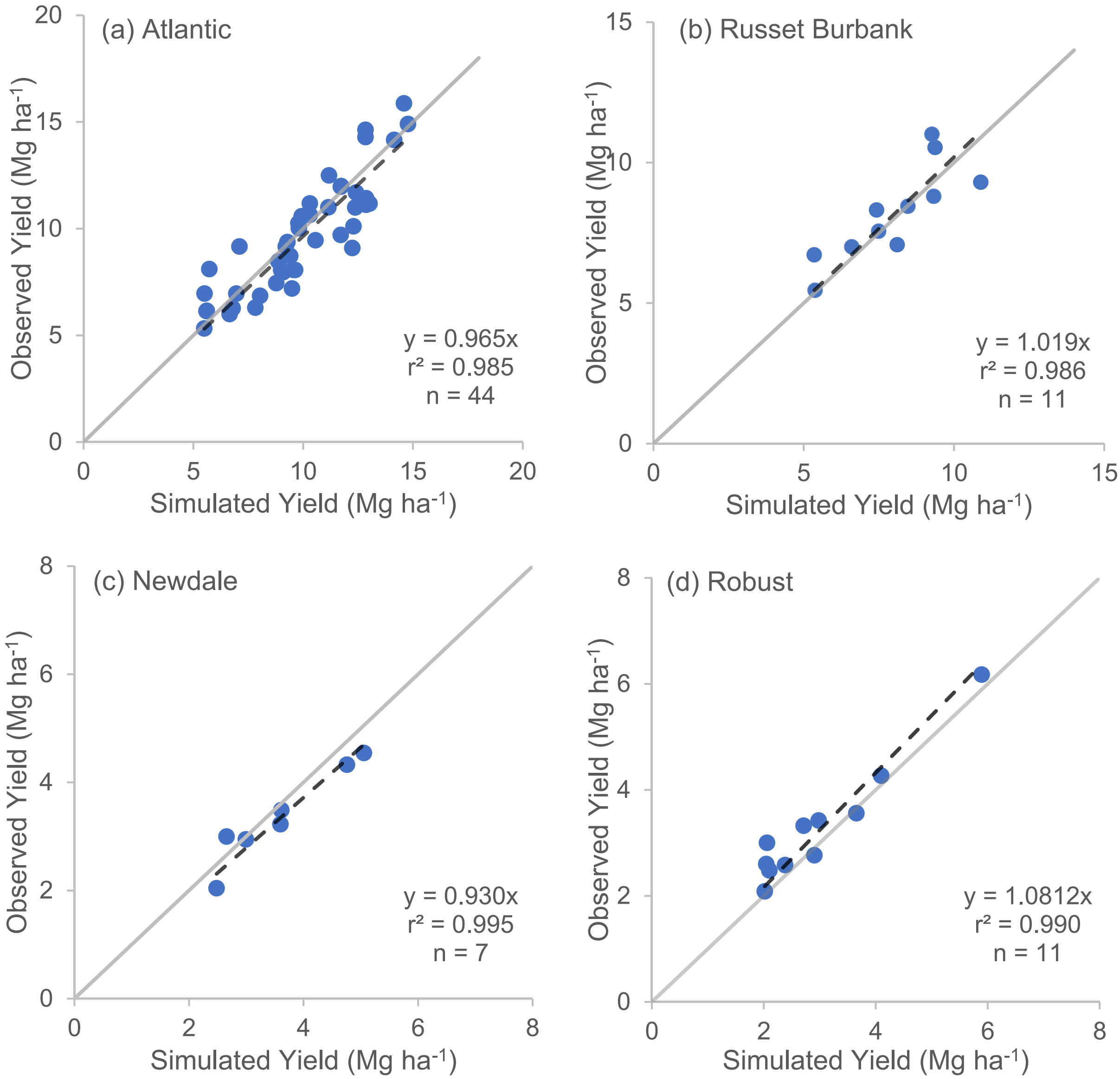

Fig. 1. Comparison of simulated and observed yield (dry weight) for potato varieties Atlantic (a) and Russet Burbank (b), and barley varieties Newdale (c) and Robust (d), all grown under rainfed conditions in Maine. Dots are individual field trials, dashed lines are the linear fit of the trial data, and solid lines show a 1:1 relationship between observed and simulated.

Table 3
Model performance statistics comparing simulated and observed potato and barley yield under rainfed conditions for multiple locations, management practices, and growing conditions in Maine.

Statistic[†]	Potato Atlantic	Russet Burbank	Barley Newdale	Robust
r^2	0.985	0.986	0.995	0.990
m	0.96	1.02	0.93	1.08
nRMSE	13.29	12.26	10.74	13.25
EF	0.76	0.60	0.79	0.84
d	0.94	0.90	0.96	0.96

[†] r^2, coefficient of determination; m, slope; nRMSE, normalized root means square error; EF, modeling efficiency; d, index of agreement.

observed yield for the variety Newdale, with an nRMSE of 10.7% and an r^2 of 0.995, and for the variety Robust, with an nRMSE of 13.3% and an r^2 of 0.990 (Table 3). These model performance values are similar to those reported by Hlavinka et al. (2010) and Trnka et al. (2004) who calibrated CSM-CERES-Barley for various management practices under field conditions in Central Europe

3.2. Climate change

Daily mean temperature, T_{min}, T_{max}, and precipitation were compared among the generated climate scenarios and the baseline period (1989-2018). For both locations, the growing season mean temperature (April to September) increased by 1.7°C for RCP 6.0 and 2.2°C for RCP 8.5 (Table A2). Each climate scenario followed a trend similar to the baseline climate trend with little variation in the mean temperature change among months. Comparing future climate to the baseline climate, RCP 6.0 and 8.5 both showed the greatest deviation for the months of April, May, and September in both T_{min} and T_{max}. T_{min} exhibited a greater increase than T_{max} across all in-season months with the greatest increase for April by as much as 1.7°C and 2.5°C for RCP 6.0 and RCP 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 daily minimum temperature than daily maximum temperature for the northeastern United States.

Total in-season precipitation increased for the future climate scenarios by 142 mm for RCP 6.0 and 213 mm for RCP 8.5 (Table A2). Month-to-month differences in mean precipitation fluctuated more than temperature with 8 mm and 13 mm increases in precipitation from April to June and as much as 2 mm and 4 mm decreases in precipitation in September for RCP 6.0 and 8.5, respectively. All months had an increase in precipitation except for September. This observed overall shift in the northeastern United States towards a warmer and wetter climate is consistent with what has been reported by others (Brown et al., 2010; Douglas and Fairbank, 2010; Fernandez et al., 2020; Frumhoff et al., 2007; Wolfe et al., 2018).

Warmer temperatures leading to an increase in the number of frost-free days is already apparent as Maine's average growing season length was 15.7 days longer in 2018 than in 1950 (Fernandez et al., 2020). This trend was observed with future climate scenarios, where the first fall frost was an average of 13 days later than the baseline for RCP 6.0 and 18 days later for RCP 8.5 (data not shown). When combined with an earlier spring thaw, also predicted by the future climate scenarios, the growing season lengthened by 20 to 27 days per year for both RCPs.

3.3. *Crop response to climate change*

Location had a minimal effect on crop response to climate change for both potato and barley (Tables 4 and 6). Simulated crop yield for both crops was higher in St. Agatha than in Presque Isle across all five climate scenarios, consistent with the yield differences that were observed in the field due to differences in soil fertility, daily weather dynamics, and management.

3.3.1. *Potato*

The two potato varieties showed contrasting responses to changes in climate. Mean tuber yield for the variety Atlantic decreased significantly under climate 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 4). With the addition of elevated CO_2, the yield for Atlantic remained similar to the baseline under RCP 6.0 and decreased by 5% for RCP 8.5 in Presque Isle, whereas in St. Agatha, potato yield increased by 6% for RCP 6.0 while remaining similar to the baseline for RCP 8.5. In contrast to Atlantic, Russet Burbank potato yield was unaffected (RCP 8.5 in Presque Isle and RCP 6.0 in St. Agatha) or increased by 5% (RCP 6.0 in Presque Isle and RCP 8.5 in St. Agatha) under constant CO_2, and yield increased significantly with elevated CO_2 at both locations, by 15% and 18% under RCP 6.0 and RCP 8.5, respectively. These results contrast with the 5 to 49% yield reductions predicted by Raymundo et al. (2018) for the Northeast U.S. for RCP8.5, but the results for Russet Burbank are congruent with the findings of Stöckle et al. (2010) and Supit et al. (2012) for the Northwest U.S. and Europe, respectively.

Classified as a short-day, cool-season crop with preference to warm days and cool nights, potato performs surprisingly well in hot environments when ET demands are met, as a result of accelerated respiration and increased photosynthetic rates (Rosen, 2010). Changes in climate led to faster accumulation of GDDs, advancing maturity for the variety Atlantic and ultimately shortening the growth and development period (Table 2). In contrast, with delayed frost, the growing season for the late-season Russet Burbank variety lengthened with climate change, prolonging the potential for biomass accumulation. For both potato varieties, the number of optimum days for vine growth, when air temperatures are between 17°C and 25°C, increased with climate change on average by 28% (Table A3). This favorable increase was also accompanied by a 74% increase in the mean number of above-optimum days where atmospheric temperatures were unfavorably high (data not shown). Higher temperatures also can negatively affect crop quality (e.g., internal defects, lower tuber starch levels, sugar ends and other fry color defects; Bethke et al., 2009) but could not be predicted with the CSM-SUBSTOR-Potato model. For root and tuber growth, the number of optimum days when the temperature of the surface soil (0-20 cm) is between 15°C and 24°C, drastically decreased with climate change for both varieties and locations (Table A3) with a relative increase in the number of days with unfavorably high soil temperature (data not shown).

Haulm weight for potato followed a similar trend to tuber yield (Table 5). Atlantic biomass decreased significantly from the baseline with elevated temperature and precipitation, but increased with elevated CO_2, especially under RCP 6.0. Russet Burbank exhibited the greatest biomass accumulation under RCP 6.0 and 8.5 with elevated CO_2, with biomass greater than the baseline for all four climate scenarios. Increased temperature and precipitation had little effect on the maximum LAI for Atlantic, while the maximum LAI for Russet Burbank increased significantly under RCP 8.5 (Table 5). Both potato varieties increased in maximum LAI with increased CO_2. Raymundo et al. (2017) noted that above-ground biomass, LAI, and root biomass are not as well

Table 4

Mean simulated potato tuber yield (dry weight) as affected by climate change scenario and planting date for Presque Isle (PI) and St. Agatha (SA), Maine, with ANOVA results. For each climate scenario and planting date combination, yield was simulated annually for 30 years. Climate scenario means are averaged over the planting date scenarios, and planting date means are averaged over the climate scenarios, because there was no significant interaction between these factors.

Main effect means†	df	Potato Atlantic PI	SA	Russet Burbank PI	SA	
	———— Mg ha^{-1}————					
Climate scenario						
	Historical		9.15 a	10.98 b	10.12 c	10.75 c
RCP 6.0		7.52 c	9.59 c	10.57 b	11.18 bc	
RCP 8.5		6.73 d	8.81 d	10.39 bc	11.28 b	
RCP 6.0 + CO_2		9.36 a	11.67 a	11.64 a	12.37 a	
RCP 8.5 + CO_2		8.73 b	11.11 b	11.61 a	12.68 a	
Planting date for PI, SA						
May 2, May 5		7.97 c	10.08 b	11.72 a	12.47 a	
May 12, May 15		8.22 b	10.28 b	11.10 b	12.13 a	
May 22, May 25		8.28 b	10.64 a	10.51 c	11.56 b	
May 30, June 5		8.72 a	10.73 a	10.14 d	10.44 c	
	ANOVA					
Source of variation						
Climate scenario (C)	4	<0.0001	<0.0001	<0.0001	<0.0001	
Planting date (P)	3	<0.0001	<0.0001	<0.0001	<0.0001	
C x P	12	0.7815	0.4185	0.7544	0.5926	
C.V., %		10%	10%	9%	12%	

† Within a column, means followed by a common letter are not significantly different (P<0.05), as determined by Tukeys HSD test.

Table 5
Potato haulm dry weight and maximum leaf area index (LAI), and total in-season evapotranspiration (ET) as affected by climate scenario and planting date for two varieties, averaged across two locations in Maine, with ANOVA results. For each climate scenario and planting date combination, the traits were simulated annually for 30 years. Climate scenario means are averaged over the planting date scenarios, and planting date means are averaged over the climate scenarios, because there was no significant interaction between these factors.

Main effect means[†]	df	Atlantic Haulm weight Mg ha^{-1}	LAI	ET mm	Russet Burbank Haulm weight Mg ha^{-1}	LAI	ET mm
Climate scenario							
Historical		11.30 c	2.76 b	317 a	12.28 c	4.86 d	368 c
RCP 6.0		9.99 d	2.83 b	294 b	12.73 b	5.06 cd	398 b
RCP 8.5		9.27 e	2.84 b	286 c	12.78 b	5.17 c	410 a
RCP 6.0 + CO_2		12.22 a	3.54 a	293 b	14.07 a	5.80 b	396 b
RCP 8.5 + CO_2		11.75 b	3.66 a	285 c	14.31 a	6.08 a	407 a
Planting date							
May 2		10.53 c	2.98 b	310 a	13.95 a	5.12 b	426 a
May 12		10.82 bc	3.15 ab	299 b	13.61 b	5.54 a	411 b
May 22		11.06 ab	3.23 a	289 c	13.07 c	5.53 a	386 c
May 30		11.23 a	3.16 ab	283 d	12.31 d	5.37 a	359 d
	ANOVA						
Source of variation							
Climate scenario (C)	4	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Planting date (P)	3	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
C x P	12	0.8742	0.8471	0.9999	0.8278	0.9294	0.2395
C.V., %		16%	18%	9%	12%	17%	5%

[†] Within a column, means followed by a common letter are not significantly different (P<0.05), as determined by Tukeys HSD test.

simulated as tuber yield, so it is possible that the simulated haulm and LAI values in Table 5 are over-estimations. However, we do not expect for the observed trends among treatments to be significantly affected.

Total in-season ET significantly decreased with climate change for the potato variety Atlantic, by up to 10% for RCP 8.5, both with and without CO_2, whereas total ET increased for the potato variety Russet Burbank, by up to 11% for both RCP 8.5 scenarios (Table 5). For Russet Burbank, mean daily ET (total ET divided by days to harvest, Table 2) was unchanged, indicating that the increase in total ET can be attributed to the increase in days to maturity under climate change for this variety. For Atlantic, however, mean daily ET increased, by over 8% for both RCP 8.5 scenarios, suggesting that the change in total ET is due to a physiological response to elevated temperatures not observed in Russet Burbank.

The positive yield response to elevated CO_2 observed for both potato varieties is not attributable to changes in ET, as others have proposed. For instance, in a controlled field experiment in the United Kingdom, Donnelly et al. (2001) attributed a 40% increase in tuber yield with elevated CO_2 to reduced plant transpiration and increased water use efficiency caused by CO_2-induced stomatal closure. In the present study, however, both total and mean ET were unaffected by CO_2.

Other modeling studies, by Stöckle et al. (2010) and Supit et al. (2012), also have found potato yield to remain the same or improve with climate change and elevated CO_2 over the coming decades, but they predicted that rising temperatures will offset the positive effect of CO_2 by the end of the century. As was noted earlier, these modeling results do not take into account possible effects of climate change on crop quality or losses due to plant diseases and pests.

3.3.2. Barley

For barley, both varieties exhibited a similar response to changes in climate. Robust and Newdale performed best under the RCP 8.5 scenario with elevated CO_2, increasing yield by 14% and 11%, respectively, for both locations (Table 6). Barley exhibited a negative response to RCP 6.0 and 8.5 at baseline CO_2 concentrations with yield decreasing, respectively, by 7% and 11% for Robust in Presque Isle, 6% and 9% for Robust 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 small grain crops through the shortening of phenological phases (Asseng et al., 2014; Eyshi Rezaei et al., 2017; Marcinkowski and Piniewski, 2018; Trnka et al., 2004). Mean anthesis dates advanced by 4 to 6 days at both locations (data not shown), while mean maturity dates advanced by 6 to 11 days under climate change (Table 2), regardless of CO_2 level.

Total above-ground biomass also decreased significantly for both barley varieties under climate pressures in the absence of elevated CO_2 (Table 7). Above-ground biomass significantly increased above the original baseline with the addition of CO_2. Maximum LAI remained the same for the variety Newdale with rising temperature and precipitation

Table 6
Mean simulated barley grain yield (dry weight) as affected by climate change scenario and planting date for Presque Isle (PI) and St. Agatha (SA), Maine, with ANOVA results. For each climate scenario and planting date combination, yield was simulated annually for 30 years. Climate scenario means are averaged over the planting date scenarios, and planting date means are averaged over the climate scenarios, because there was no significant interaction between these factors.

Main effect means[†]	df	Barley Robust PI	SA	Newdale PI	SA
		Mg ha^{-1}			
Climate scenario					
Historical		4.51 c	5.06 c	3.54 c	3.98 c
RCP 6.0		4.21 d	4.76 d	3.32 d	3.76 d
RCP 8.5		4.00 e	4.58 d	3.20 d	3.65 d
RCP 6.0 + CO_2		4.80 b	5.40 b	3.82 b	4.29 b
RCP 8.5 + CO_2		4.99 a	5.63 a	4.02 a	4.55 a
Planting date					
April 12		5.06 a	5.43 a	4.10 a	4.45 a
April 22		4.81 b	5.35 ab	3.81 b	4.27 b
May 2		4.63 c	5.21 b	3.58 c	4.03 c
May 12		4.26 d	4.92 c	3.34 d	3.86 d
May 22		3.75 e	4.51 d	3.08 e	3.63 e
		ANOVA			
Source of variation					
Climate scenario (C)	4	<0.0001	<0.0001	<0.0001	<0.0001
Planting date (P)	4	<0.0001	<0.0001	<0.0001	<0.0001
C x P	16	0.6539	0.8846	0.0347	0.1383
C.V., %		11%	11%	10%	11%

[†] Within a column, means followed by a common letter are not significantly different (P<0.05), as determined by Tukeys HSD test.

Table 7
Barley above-ground biomass (dry weight) and maximum leaf area index (LAI), and total in-season evapotranspiration (ET) as affected by climate scenario and planting date for two varieties, averaged across two locations in Maine, with ANOVA results. For each climate scenario and planting date combination, the traits were simulated annually for 30 years. Climate scenario means are averaged over the planting date scenarios, and planting date means are averaged over the climate scenarios, because there was no significant interaction between these factors.

Main effect means[†]	df	Newdale Above-ground biomass Mg ha^{-1}	LAI	ET mm	Robust Above-ground biomass Mg ha^{-1}	LAI	ET mm
Climate scenario							
Historical		7.01 c	2.34 b	196 a	8.98 c	2.76 a	273 a
RCP 6.0		6.64 d	2.51 b	189 bc	8.49 d	2.60 b	265 b
RCP 8.5		6.45 e	2.47 b	186 c	8.23 d	2.48 b	261 c
RCP 6.0 + CO_2		7.52 b	2.65 a	190 b	9.40 b	2.84 a	265 b
RCP 8.5 + CO_2		7.94 a	2.72 a	187 bc	9.78 a	2.89 a	262 bc
Planting date							
April 12		7.92 a	3.09 a	204 a	9.34 a	3.09 a	97 b
April 22		7.55 b	2.81 b	196 b	9.20 a	2.89 b	99 ab
May 2		7.15 c	2.57 c	189 c	9.10 a	2.78 b	101 a
May 12		6.66 d	2.31 d	182 d	8.82 b	2.55 c	100 a
May 22		6.27 e	2.11 e	177 e	8.44 c	2.28 d	97 b
	ANOVA						
Source of variation							
Climate scenario (C)	4	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Planting date (P)	3	<0.0001	<0.0001	0.3879	<0.0001	<0.0001	<0.0001
C x P	12	0.0616	0.0345	0.6446	0.9925	0.9490	1.0000
C.V., %		11%	18%	5%	13%	21%	6%

[†] Within a column, means followed by a common letter are not significantly different ($P<0.05$), as determined by Tukeys HSD test.

and decreased by 6% to 10% for the variety Robust, whereas with the addition of elevated CO_2, maximum LAI increased by 13% to 16% for Newdale and remained the same for Robust, further reinforcing the positive impact of CO_2 on growth and biomass accumulation. Total ET decreased for both varieties across all four climate change scenarios by only 3 to 5% (Table 7), whereas mean daily ET was unchanged (Newdale RCP, both 6.0 scenarios) or increased by 5% (Robust, both RCP 6.0 scenarios) or 7% (both varieties, both RCP 8.5 scenarios). Similar to Atlantic potato, the reduction in total ET is a function, in part, of a shorter growing period (Table 2) leading to less water use overall. Accelerated photosynthesis with elevated CO_2 resulted in increased leaf area and biomass, thus, increasing crop yield, regardless of growing season length.

Physiologically, enhanced barley growth with elevated CO_2 is in agreement with Ingvordsen et al. (2015) who found elevated CO_2 to buffer the negative impact of temperature on barley yield in a controlled greenhouse experiment in Denmark. In a modeling study using CERES-Barley, Trnka et al. (2004) found that elevated CO_2 had a greater impact on spring barley yield than increased temperature and precipitation, subsequently increasing yield by 13% to 52%.

3.3.3. Planting date

There was no significant interaction between planting date and climate scenario (Tables 4 and 6), with the exception of the barley variety Newdale for Presque Isle (p-value 0.0347), indicating that, for the most part, crop response to climate change was not impacted by planting date. For the early-season potato variety Atlantic, delaying planting to the last date increased yields by 6% to 9% in Presque Isle and St. Agatha, respectively, as compared with the earliest planting across all climate scenarios (Table 4). Adavi et al., (2018) also found delayed planting to benefit early- and mid-season maturing potato varieties, but specifically under future climate conditions. In contrast, Russet Burbank exhibited a 15% reduction in yield on average with later planting at both locations. Potato haulm weight had a similar response as yield (Table 5). The number of optimum days for potato root and tuber growth decreased with later planting for both potato varieties, vine growth was favored by later planting dates for potato variety Atlantic and earlier planting dates for Russet Burbank (Table A3). Variety-specific responses to changes in planting date suggest that the late-season Russet Burbank variety will continue to perform best with the earliest possible planting to allow for a longer development period, while the timing of in-season weather patterns is more critical for the early-season Atlantic variety.

For barley, both varieties exhibited the same general trend of a decrease in yield with later planting (Table 6). However, in Presque Isle, climate change scenarios intensified the yield decline with delayed planting for the variety Newdale, whereas this interaction was not observed in St. Agatha or for the variety Robust (Table A4). The sensitivity of barley, and other small grains, to later planting dates can be attributed to shortening of phenological phases and days to maturity (Table 2) driven by changes in GDD accumulation and photoperiod (Aslam et al., 2017).

4. Conclusions

The results presented here suggest that climate change impacts on potato production in Maine for 2050 to 2079 may not be as severe as predicted by others. The positive yield response of the long-season variety to climate change with elevated CO_2 suggests that selecting potato varieties with indeterminate growth may be an effective adaptation strategy for the coming decades. The results did not support variety selection as an effective adaptation strategy for barley, although only two varieties were evaluated, nor did they indicate that altering planting dates would affect climate change response for either potato or barley for the period studied. Confidence in these projections could be increased by using multiple crop models and more climate models. Further investigations also should consider later time periods, as well as other management strategies that may increase crop resilience, such as irrigation, improved soil health, and altering crop rotations. Potential climate change impacts on crop quality, pest, and disease pressures, which are beyond the limitations of the models used here, should also be taken into consideration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2021.108452.

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