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Potential benefits of climate change for potatoes in the United States

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Abstract

Potatoes are a mainstay of human diets and 4 million metric tons are produced annually in the United States. Simulations of future crop production show that climate change is likely to reduce the yields of the major grain crops around the world, but the impacts on potato production have yet to be determined. A model ensemble consisting of five process-based and one statistical model was used to estimate the impact of climate change on fully irrigated, well-fertilized potato crop across the USA under the RCP 8.5 scenario of high emissions. Results indicate that increasing temperature will reduce potato yields, but this will be mostly compensated by elevated atmospheric CO_2. Yields are predicted to decline with climate change in the current highest-yielding areas, which might experience the highest rises in growing season temperature during short hot summers. Simulated yields increase slightly elsewhere in the southern regions of the USA. Planting potatoes earlier as adaptation to avoid hot summers might improve yields in most regions. Water use by the potato crop is predicted to decline despite higher temperatures, due to a shorter growing season and increased water use efficiency under elevated atmospheric CO_2. With higher yields in many regions, crop uptake for (nitrogen + phosphorus + potassium) NPK fertilizer will increase, despite the reduced concentration of nutrients in potatoes due to a growth stimulus from elevated atmospheric CO_2. With earlier planting, by 2050 water use will decline by 11.7%, NPK fertilizer uptake will increase by 10.4%, and yields of slightly less nutritious potatoes will increase by 14.9% nationally.

1. Introduction

Potato (*Solanum tuberosum*) is the most important vegetable crop worldwide, ranking after only wheat and rice in terms of food crop production and consumption [1]. Potatoes have been described as 'perfect' for human nutrition as they are an excellent source of carbohydrate, and many vitamins and minerals [2]. The United States produces 4 million metric tons of potatoes (dry tuber weight) per year, equivalent to 62 kg per capita [3], the most of any vegetable. Potato crops are cultivated in the different soil and climatic conditions across most of the country. With ongoing global warming, it is crucial to estimate how the changing climate will impact the growth, development and yield of this key crop. Compared to cereal crops such as wheat, maize, and rice [4–7], there is little information related to climate change effects on potatoes, whether on the production or the related water and nutrient use. Additional knowledge gaps include the impact of increasing CO_2 concentration on crop growth/quality and adaptation measures to future climate scenarios.

Process-based crop models have been widely used to assess possible climate change impacts and the effects of proposed adaptation strategies [8]. These models encapsulate biologically meaningful relationships between climate, soil, growth, development, and biomass partitioning. The relationships included in the design and parameter implementation of any specific model tend to reflect the study context and objectives of the individual model developers. This inevitably leads to inconsistencies between study results even when the same driving inputs of static soil properties, defined forcing climate scenarios, and fixed management regimens are used [4]. When modeling climate change impacts, the uncertainty arising from crop models has been found to exceed the combinations of uncertainties from other sources [9, 10], and tends to increase in warming scenarios. With such a large uncertainty, the results obtained from any given crop model could bias any conclusions about crop responses to changing climate. To compensate for such inconsistencies, the multi-model ensemble technique, demonstrated for projects such as Agricultural Model Intercomparison and Improvement Project (AgMIP) and Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) [11, 12], uses the ensemble median values which are closer to the observed values the more models are considered, thus reducing uncertainty [4–6, 13]. Recently, multi-method ensembles have been extended to include field-controlled experiments with crop models and statistical models to limit the uncertainty arising from the independent methods [14, 15]. By using the multi-model approach, this study aimed to explore [1]. How will future climate change impact on US potato yield, crop water requirement and nutrient uptake [2], what is the spatial pattern of yield changes across climate zones in the US and [3] whether earlier planting will mitigate some of the negative impacts of climate change on yield?

2. Methods and materials

Crop Reporting Districts (CRDs) from the most recent US Department of Agriculture (USDA) AgCensus (www.nass.usda.gov/Publications/AgCensus/2012/) datasets were selected to represent the planting area for the main fruit and vegetable crops in the USA, including potatoes. We included the CRDs necessary to capture 80% of the total production area for the fruit and vegetable crops, resulting in a list of 31 CRDs. The counties having the highest target crop production area within each of these CRDs were then selected for the crop modeling, adding one more county (St Johns, Florida), to better represent potato production in that state [16].

A multi-model approach based on AgMIP protocols [11] was used to estimate potato yield, potato transpiration, and potato nutrient uptake (N, P, K) in all cropping areas of interest in the USA through the 2021–2050 period, referred to here as the 2030s, and the 2041–2070 period, referred to as the 2050s. The model ensemble includes the five process-based models SIMPLE [17], CropSyst [18, 19], LINTUL-POTATO-DSS [20], EPIC [21, 22] and DSSAT-SUBSTOR-Potato [23] and one statistical model [24]. These models had been widely calibrated with their individual observed potato data. The five processed-based models simulated explicitly the temperatures and CO_2 effects on crop growth and yield, and had been calibrated with individual observed potato data. For the statistical model, the temperature effects on yield were implied from the regression equations, while the CO_2 effects were introduced by a prescribed CO_2-induced yield increase, which is 10% yield increase per 100 ppm relative to 360 ppm for potatoes [25]. More detailed introductions to each model can be found in Gustafson *et al* [26]. The accumulated temperature requirement of a process model for the baseline was set for each county (assuming different maturity types for each county), assuming that canopy cover for potato is still about 80% at the harvest date. In the present study, the crop models were calibrated to field-experiment based corrected district yields from around the year 2000 [27] for potatoes [16]. The statistical models used monthly maximum and minimum temperatures during the growing season to predict county-level yield. All temperature predictors in the model were in quadratic form to account for a non-linear yield response. The model was trained using all available observed county-level yield data for 1981–2016 from the National Agricultural Statistics Service (NASS) of USDA (https://quickstats.nass.usda.gov), and historical monthly temperature data from Processes Research by Imaging Space Mission

(PRISM) (http://prism.oregonstate.edu/). Prior to model training, yield was converted to yield anomaly (by subtracting a quadratic yearly trend) to remove the long-term yield trend.

Crop and statistical model estimates used gridded downscaled (4 km × 4 km) daily weather data for a baseline period (1981–2010) and two bias-corrected future time slices (2021–2050 and 2041–2070) from the five global climate models (GCMs), GFDL-ESM2M, HadGEM2-ES365, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M, consistent with the InterSectoral Impact Model Intercomparison Project [28, 29] for RCP 8.5 [30]. The weather data files include daily maximum and minimum temperature, precipitation, solar radiation, maximum and minimum relative humidity, and wind speed. GCMs tend to predict solar fluxes up to 8% higher than baseline data depending on the USA location, so solar radiation data was adjusted to minimize change compared to baseline data.

No limitations on water or nitrogen were assumed in the modeled potato cropping systems. A possible adaptation to a warmer climate, an earlier planting date, was considered. Model outputs include biomass and yield (except statistical model for biomass). Accumulated crop transpiration data from sowing to harvest was from only one crop model, CropSyst, as some models did not simulate transpiration (e.g. the statistical model) or their transpiration routines were never tested. Nitrogen, phosphorus and potassium uptake were calculated based on simulated biomass and yield, using prescribed nutrient concentrations [31, 32] adjusted to account for nutrient dilution resulting from elevated atmospheric CO_2 concentrations [33]. The output of the statistical model did not include any nutrient data as biomass data was not integral to the model. More details are provided in the protocol by Zhao *et al* [16].

3. Results and discussion

To establish a baseline against which to consider the effects of atmospheric CO_2 concentration on potato, simulated yields for a historical period were correlated against records from 32 USA Department of Agriculture CRDs (figure 1). The model ensemble performed well within the yield range of 5.7–18.0 t ha^{-1} when compared with the bias-corrected records [27] (slope = 0.85, R^2 = 0.95) and variety trials at the field level (slope = 0.69, R^2 = 0.85). Yields simulated with the model ensemble were somewhat higher than the available county level statistics (slope = 0.89, R^2 = 0.92), which was expected because the models did not take account of any biotic or abiotic stresses. Measured changes in tuber yield under elevated atmospheric CO_2 concentrations in recent free-air concentration enrichment (FACE) experiments [25, 34, 35] were generally close to the ensemble calculations. Specifically, CO_2 concentration increases going from 56 ppm to 317 ppm above the baseline increased tuber yield by 10%–30%.

For the baseline, the observed potato yield shows considerable heterogeneity across the regions studied (figure 2(a)). The Pacific Northwest (PNW) is one of the highest-yielding areas producing dry tuber yields of 12–18 t ha^{-1}. The potato growing season in this region is the longest in the USA, starting in April or May and lasting for 140–150 d. Long seasons allow more time for crop plants to capture solar radiation (figure 2(b)) for photosynthesis and biomass production, but in the PNW this includes a short, but hot summer (figure 2(c)). Potatoes growing at relatively high latitudes might also experience warmer climates (4 °C–7 °C) by the middle of the 21st century (figure 2(d)). Warm southern regions, such as Florida and Texas, have a relative low tuber yield, with a growing season of only ∼110 d and 60%–70% of the total solar radiation absorbed in the PNW. However, the shorter growing season beginning in January avoids exposure to the hot summer. For these lower latitudes, less warming might be predicted by the middle of the 21st century compared with the PNW.

Thirty climate-crop modeling combinations were used to simulate potato yield under the RCP 8.5 scenario. The ensemble medians show that by the 2050s the combination of climate change and elevated CO_2 concentration might have a varying impact on dry tuber yield across CRDs ranging from −10.7% to 47.0% (figure 3(a)) in the absence of any adaptation strategies. The contrast between impacts on the north and south of the USA was noted. According to the simulations, the PNW and some locations in the mid-west regions might suffer a yield loss of 2.4%–10.7%, while California, Arizona, Texas and Florida might see yield gains of 10.3%–47.0%. A similar pattern was found for the 2030s (figure S1). Notably, the locations already benefiting from better potato yields during the 2030s might gain more in the 2050s and the converse is true for the locations predicted to experience losses. Plotting the absolute deviations from the ensemble of 30 climate-crop modeling combinations shows that over 50% of ensemble members have the same sign of yield changes as the ensemble median in ∼80% of locations, and some locations in the PNW and mid-west regions have the same sign among 80% of ensemble members (figures 3(b) and (d)). The national average absolute deviations of yield changes for the 2030s is 18.8%, increasing to 25.8% for the 2050s.

Earlier planting is a possible management adaptation strategy to compensate for deleterious responses to heat duration and intensity that was considered in the next simulation. Compared with scenarios with no adaptation, planting potatoes 14 d earlier at all sites during the 2050s converted the simulated negative yield changes to positive in 6 of 10 CRDs in the PNW and mid-west (figure 3(c)). For the 2030s,

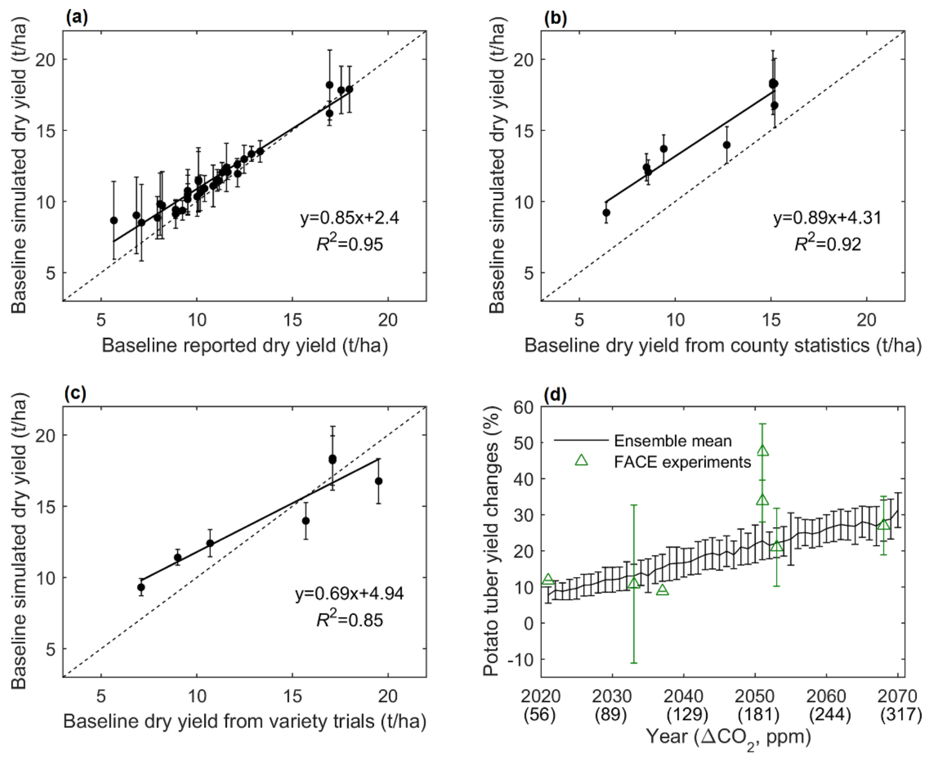

Figure 1. (a) Simulated versus reported baselines for dry matter yield of potatoes grown in the USA and the effect of CO_2 concentration. Simulations are the ensemble means ± standard errors. Potato yields for year 2000 reported by Monfreda *et al* [27] were increased by 3.6 t ha^{-1} to reflect the improved yield potential in more recent years shown in several variety trials. Extremely low reported yields for two counties (Fresno and Yolo, CA) were replaced with nearby variety trial yields. The reported data were used for calibration of SIMPLE, CropSyst and SUBSTOR models. The same simulation results are compared to observations from county statistics (b) and variety trials (c). (d) Observed and simulated CO_2 concentration effect on potato yield (dry tuber). For each year labeled on the *x*-axis, the CO_2 changes relative to the baseline are given in brackets. Observations are from recent FACE experiments [25, 34, 35], including an outlier (+47.6% yield) [34]. Simulations are the ensemble means ± standard errors. The EPIC model runs with constant CO_2 concentration for 2030s and 2050s, so the results were two points included in the ensemble mean.

planting 7 d earlier was allowed in the simulation, which made 5 of 8 CRDs in these regions go from yield loss to yield gain. For the latter CRDs, the simulated adaptation measures increase yield by an average of 2.3%–6.3%. In CRDs where yield might already benefit from climate change alone, earlier planting had little significant effect, with average increases of 0.7%–2.4%. One exception is the region of Monterey in California, which shows an unexpected yield decrease of 20.5% and 35.1% if the earlier planting was applied. This region has a relatively low temperature (14.1 °C mean, 19.6 °C maximum) during the potato growing season (Figures 2(c) and (4)), so colder periods during an earlier season might restrict the daily growth and biomass accumulation. In the plots of absolute deviations from the ensemble of 30 climate-crop modeling combinations (figures 3(d) and S1), for most locations over 50% of ensemble results agree on the sign of yield changes, and as many as 80% for some mid-west locations, similar to the non-adaptation scenarios shown in figure 2(b).

To gain insight into how regional variations in yield changes related to climate conditions, we performed a linear regression of yield changes for the 2030s against the baseline temperature during the potato growing season (figure 4). This regression analysis shows that yield changes are negatively correlated with the baseline growing-season mean temperature ($R^2 = 0.70$, $P < 0.001$) and growing-season maximum temperature ($R^2 = 0.62$, $P < 0.001$). Different degrees of warming predicted in the specific regions could bias the correlations, so we added the specific warming applied at each site to the baseline, then verified that the linear relationship became stronger ($R^2 = 0.72$–0.80, $P < 0.001$). Locations with a cool growing season will see considerable yield gains under future climate change, while the opposite is true for the hot locations. The linear fit of yield changes against mean growing-season temperature crosses zero at the mean temperature of 19.9 °C, the maximum of 27.7 °C, and minimum of 13.2 °C, indicating the optimal temperatures that are relevant at the spatial scale. For example, currently a total of 13 of the 32 CRDs have growing-season temperatures around this temperature threshold. Extrapolating space for time leads us to speculate that in regions where growing-season temperature may surpass this threshold in the future, yield loss might result. This can also be seen from the large negative correlations

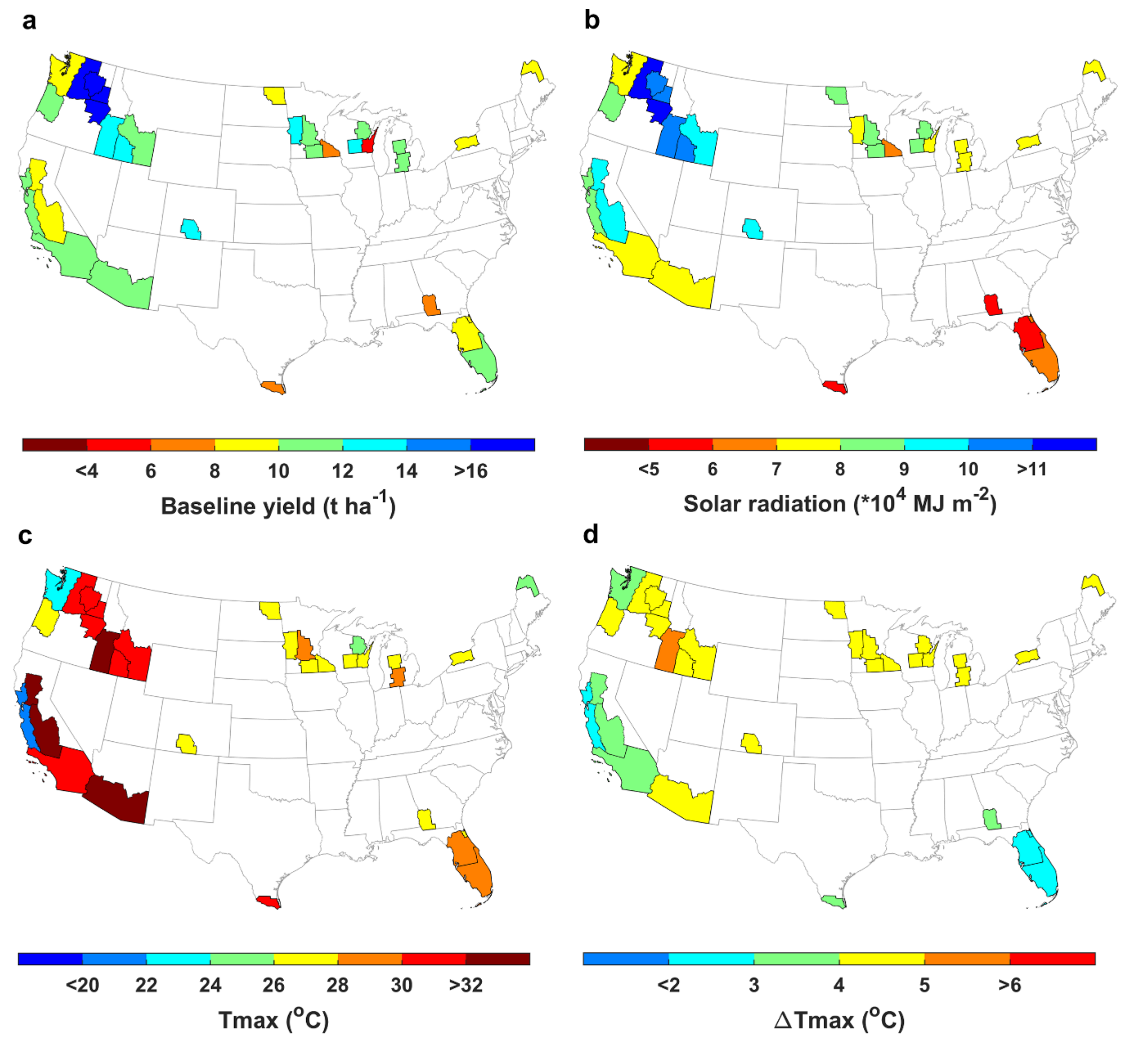

Figure 2. (a) Potato tuber dry matter yield for the baseline period (1981–2010) for the USA CRDs (shaded areas) selected for modeling. The potato yields from Monfreda *et al* [27] for year 2000 were increased by 3.6 t ha^{-1} to reflect yield potential attained in more recent years, based on yields from several variety trials compared with the year 2000 data. Extremely low reported yields for two counties (Fresno and Yolo, CA) were replaced with nearby variety trial yields. (b) Cumulative solar radiation from potato planting to harvest during the baseline period. (c) Maximum temperature for the hottest month during the potato growing season from planting to harvest ($T_{\max}$) for the baseline period. (d) Predicted changes in $T_{\max}$ for the 2050s (2041–2070) relative to the baseline $T_{\max}$.

between yield changes and growing-season temperature during the 2050s period compared to the 2030s.

The amount of water needed for potato farming is a crucial factor. Using just the CropSyst model, we found that under full irrigation, transpiration from potato crops might diminish at almost all CRD sites during the 2050s, with 10%–20% reduction in some northern regions of the USA and less than 10% in other places (figure 5(a)). This pattern is similar for the 2030s period, but less pronounced (figure S2), a sign of better water use efficiency. A small change in precipitation was predicted in the recent Intergovernmental Panel on Climate Change (IPCC) report [36], so the net irrigation demand for potato crops might be less in the future time range studied. Earlier planting did not change the pattern of transpiration reduction much, except in three northern California locations (figure 5(c)). Although higher temperature should accelerate crop transpiration through increasing vapor pressure deficit, this effect is counteracted by shortened growing seasons and by the elevated atmospheric CO_2 concentration that tends to reduce stomatal conductance and thus transpiration.

We also estimated how nutrient uptake by potato crops changes in the climate scenarios (figures 5(b) and (d)) using all five crop models. The estimated ensemble median of crop uptake for NPK (nitrogen + phosphorus + potassium) fertilizer per hectare might increase in 66% and 72% of the CRDs during the 2030s and 2050s (figures 5 and S2), except for portions of the PNW and mid-west. Earlier planting further increases the total uptake in 69% and 81% of regions during the 2030s and 2050s, respectively, by between 1.0% and 17.2%. Across the CRDs studied, the simulated response of nutrient uptake is similar to the yield response, even though certain nutrients might be less concentrated in potatoes due to the effects of elevated atmospheric CO_2.

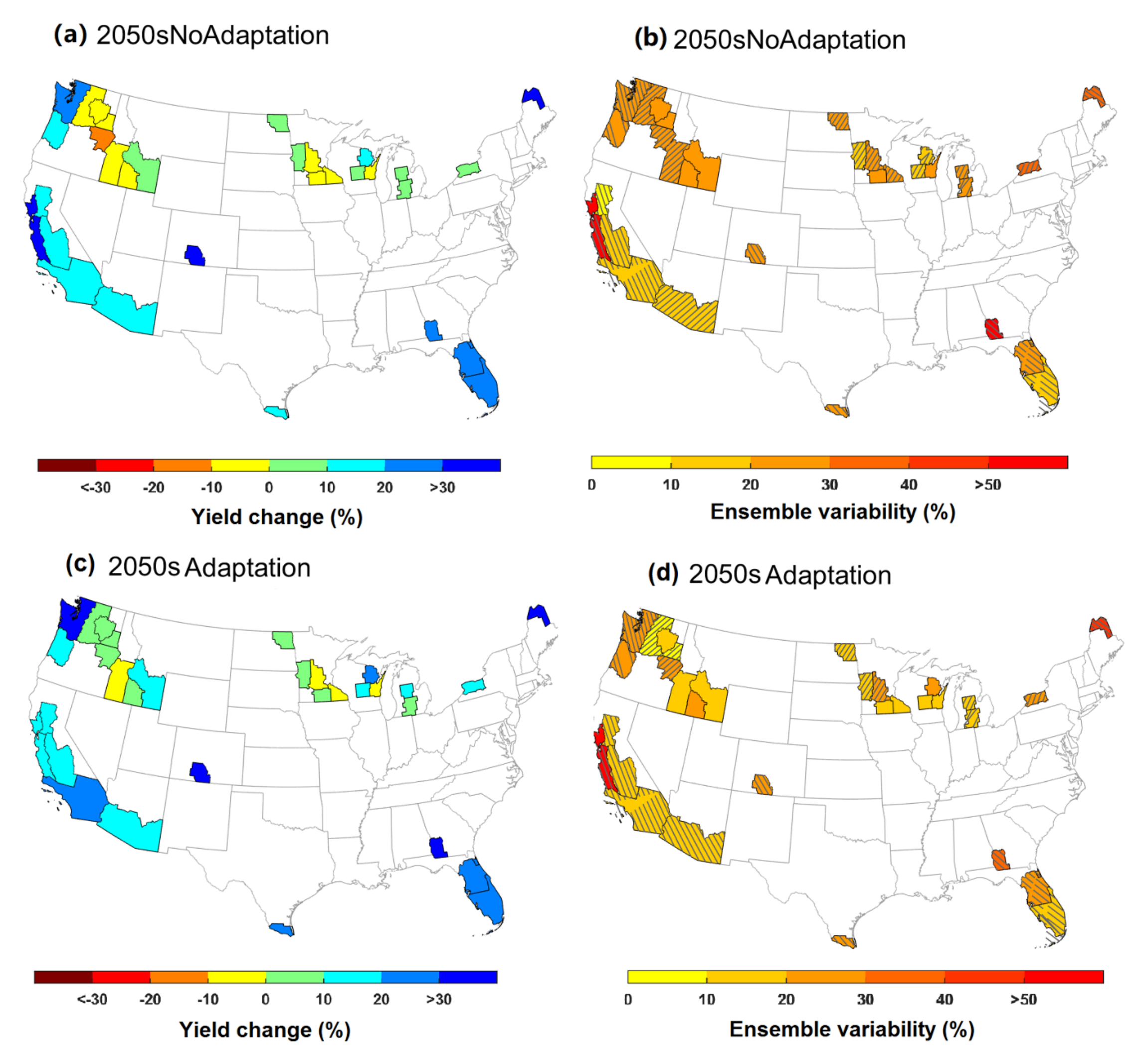

Figure 3. Simulated potato yield changes and variabilities for 32 USA CRDs in the 2050s compared to the baseline (1981–2010) under increasing atmospheric CO_2 concentrations (RCP 8.5) without (a), (c) or with (b), (d) adaptation. The maps show the ensemble median yield changes (%) and deviations from 5 crop models + 1 statistical model with 5 GCM simulations for each CRD. In (b) and (d), oblique line-shading indicates areas for which the sign of yield changes of over 80% (left-to-right) or over 50% (right-to-left) of model combination simulations is the same as the sign of median yield changes in (a) and (c) respectively.

The simulated results from the 32 CRDs were aggregated at a national scale. Without adaptive management, the production-weighted yield increases by 9.8 ± 3.8% in the future scenarios (figure 6). The contributions of climate change and elevated atmospheric CO_2 were separated, showing that tuber yield is reduced by 4.6 ± 3.5% due to climate change alone, but the elevated CO_2 fully offset this negative impact by independently increasing the yield by 14.3 ± 4.3%, similar to the findings for potatoes in the Europe [37, 38]. Relative to the non-adaptation scenario, yield will increase by an additional 2.0%–4.1% with earlier planting. The change in NPK uptake is similar but at a lower level, likely related to the plant nutrient concentration being slightly reduced when CO_2 is elevated. Potato transpiration will decline by 3.3 ± 0.7% and 8.9 ± 1.2% during the 2030s and 2050s, respectively. Earlier planting strategies might reduce crop transpiration, attributed more to the elevated atmospheric CO_2 concentrations than to climate change alone.

This study included simulations from five process-based and one statistical model forced by five GCM climate outputs, which means a total of 30 members were used to cover the possible uncertainties. Our results are robust as in most locations over 50% of ensemble members agree on what direction yield changes will take under climate change, and for some locations over 80% of members agree. The uncertainties arising from crop models were larger than those from climate inputs (not shown), as found in studies on other crops [9, 10]. The major difference between independent methods was that compared with process-based models, statistical models showed an opposite sign of yield response in the PNW region of the USA (figure S3). The regression relationships from the statistical model were based on historical data where temperatures are mostly cool

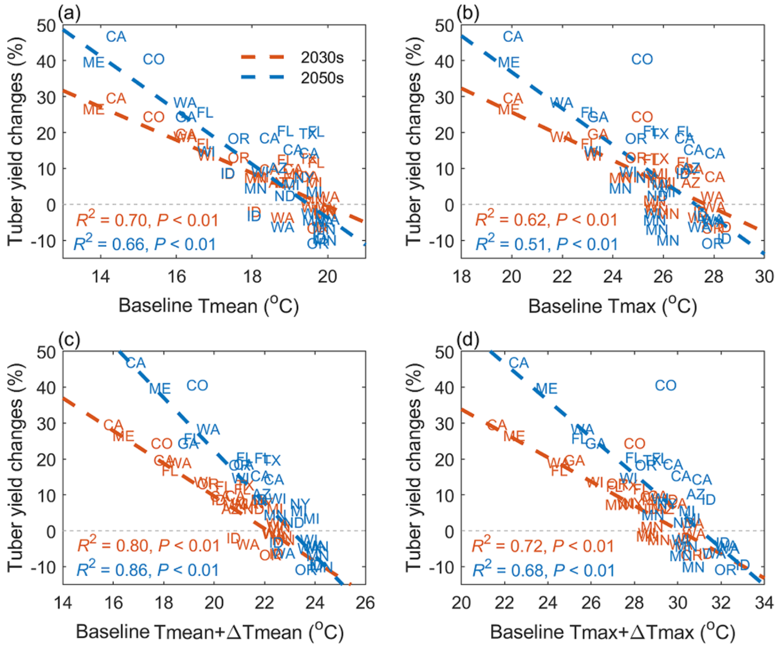

Figure 4. State-level detail of relationships between simulated tuber yield changes (%) and baseline growing-season temperature for the 2030s and 2050s under non-adaptation scenarios. Tuber yield changes are plotted against (a) baseline growing-season mean temperature, (b) baseline growing-season maximum temperature, (c) baseline growing-season mean temperature plus the future change in mean temperature, (d) baseline growing-season maximum temperature plus the future change in maximum temperature. For each graph, the two-letter names indicate the state of the individual CRD results roughly indicating the deviation from the median. The blue and red line shows the period of 2050s and 2030s, respectively.

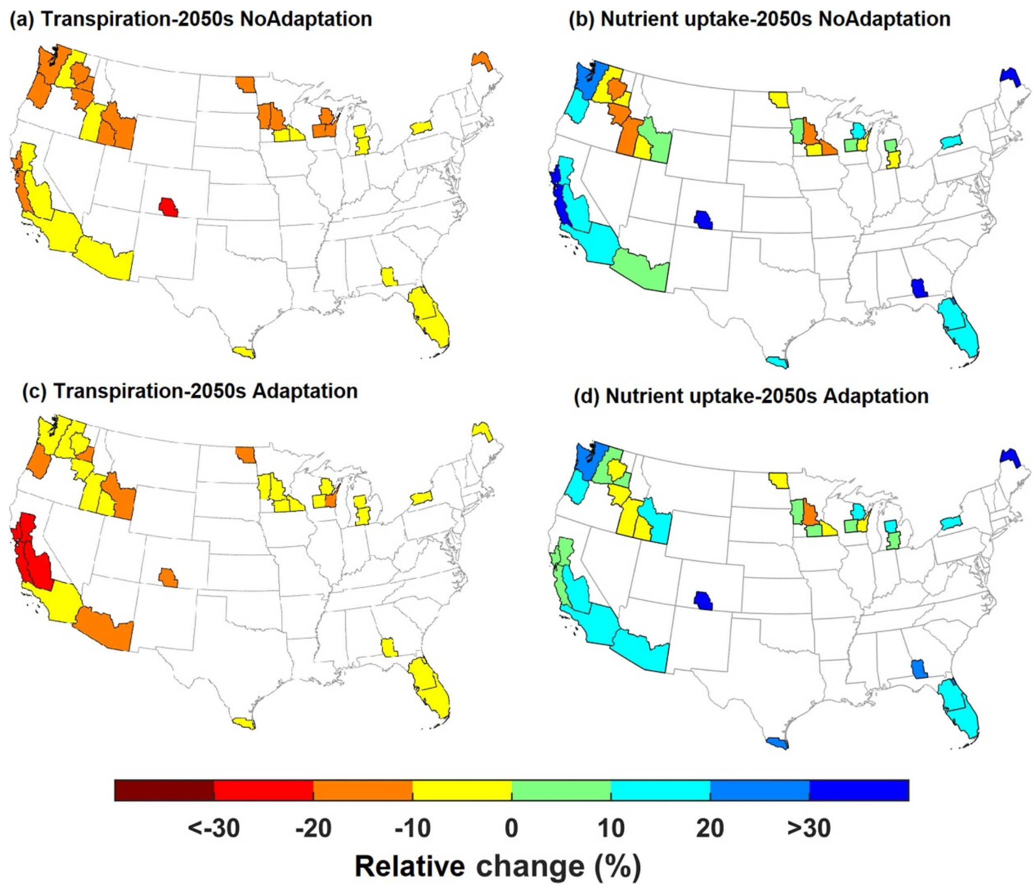

Figure 5. Simulated changes of USA potato crop transpiration and nutrient uptake (nitrogen, phosphorus and potassium) for the 2050s compared to the baseline (1981–2010) under increasing atmospheric CO_2 concentrations (RCP 8.5) without (a), (b) or with (c), (d) earlier planting adaptation. Transpiration maps (a), (c) show the ensemble median yield changes (%) from the CropSyst model with 5 GCM simulations for each CRD. The nutrient uptake maps (b, d) show the ensemble median yield changes (%) from 5 crop models each with 5 GCM simulations for each CRD.

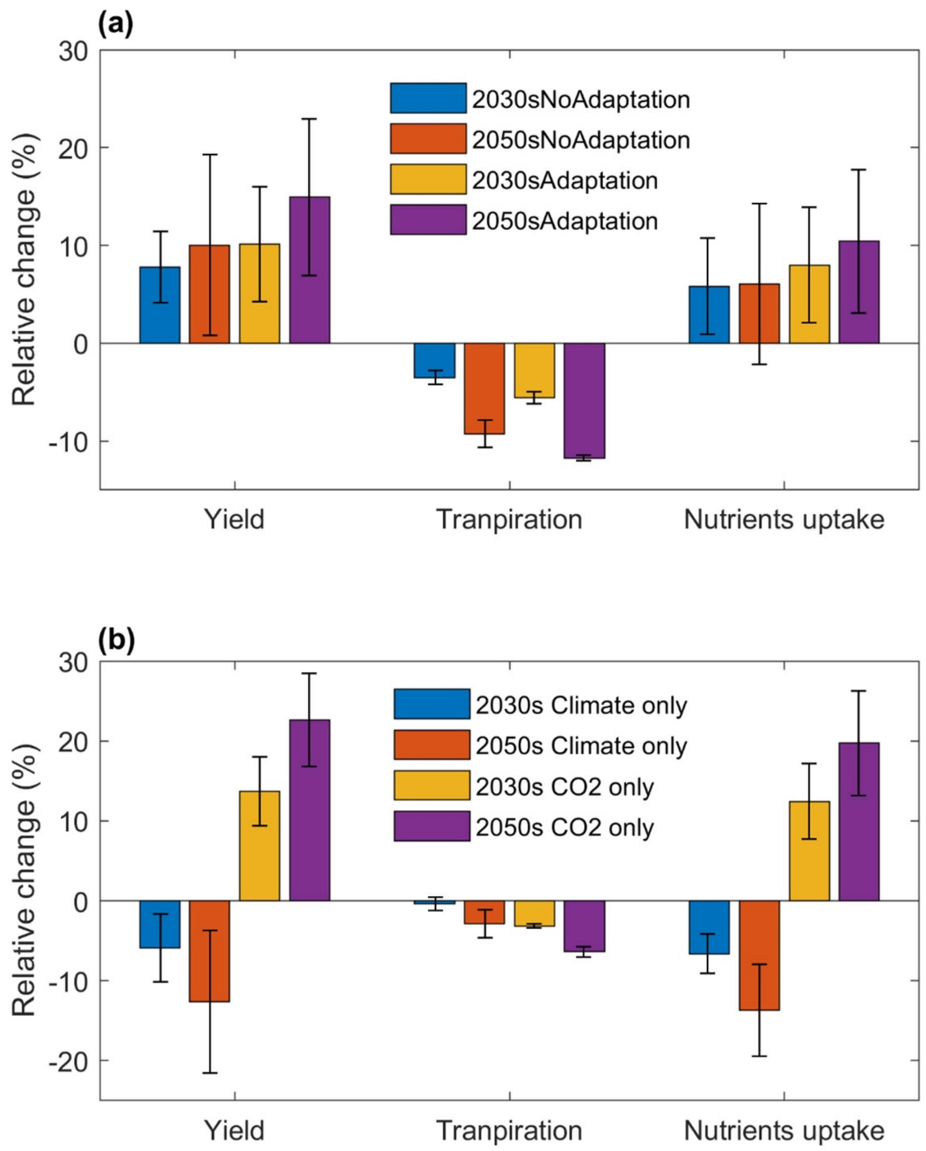

Figure 6. National scale simulated changes in potato yield, transpiration and nutrient uptake (nitrogen + phosphorus + potassium) for the 2030s and 2050s compared to the baseline period (1981–2010) without or with earlier planting adaptation (a) or only with changing climate or atmospheric CO_2 concentration (RCP 8.5) (b). The bars show changes in ensemble means (%) and the error bars show the standard deviations. The results are the average of each CRD result weighted by the corresponding current potato production across the USA.

or optimal for potato (figure 4). Extrapolating to a world over 2 °C warmer is unlikely to capture future heat stress on potatoes. In addition, the irrigation assumption in the process-based models did not include the irrigation cooling effects recently found by the statistical model [39], which might therefore overestimate the heat stress. Other sources of uncertainty originated from the individual process-based models. Although these models shared the same climatic data and simulation protocols for potato, the resulting large differences in magnitude should not be overlooked (figure S3). Differences in model design and parameterization influenced simulation of the potato crop response to environmental warming/heat. For instance, the SIMPLE and SUBSTOR models were newly developed to include a process with more severe leaf senescence and radiation use efficiency that was possibly more sensitive to warm environments [17, 23] compared to the CropSyst and LINTUL models, resulting in a larger estimated negative impact on PNW yields (figure S3).

Based on the model ensemble being more certain than individual models [40], USA potato production will generally benefit from the future climate change. Overall tuber yield will increase, and crop transpiration will decrease, with plants attaining higher water use efficiency. However, in Idaho and Washington, historically the most productive states for potato, the prolonged duration and intensity of heat spells predicted in future climate scenarios threatens yield loss if no adaptation measures are undertaken, even though this potential loss might be partially compensated by the effects of increasing CO_2. Shifting the growing season to avoid potential periods of heat intolerance could be an effective strategy. Another important aspect is that warming will shorten growing seasons and therefore limit how much solar radiation potatoes can capture for photosynthesis and biomass accumulation. In addition, the climate impact simulations were cultivar specific, not reflecting the huge cultivar diversity in potatoes with regard to the development rate (very early to very late cultivars), as well the response of crop quality parameters to rising CO_2 [33]. Consequently, cultivar change and crop breeding might be other potential adaptation options to the future climate scenarios.

Data availability statement

The data generated and/or analyzed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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Author contributions

C Z and S A designed the research; C Z performed the analysis; C Z wrote the draft and all authors contributed to interpreting the results and writing the paper.

Conflict of interest

The authors have no competing financial interests.

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