CLIMATE CHANGE IN A SEMI-ARID ENVIRONMENT: EFFECTS ON CROP ROTATION WITH DAIRY MANURE APPLICATIONS

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HIGHLIGHTS

- Spring wheat yields increase with high temperatures and the minimal impact of increased CO_2.
- At high temperatures and increased CO2, spring barley yields increase; yields decrease at only high temperatures.
- Potato and sugarbeet yields decrease with climate change.
- Climate change had little impact in soil nitrogen processes.

ABSTRACT. *Agricultural crops grown in the irrigated semi-arid region of southern Idaho account for almost two-thirds of the median household income in the region. The impacts of climate change on cropping systems and the availability of water for irrigation would be a serious challenge for the state's economic dependence on agriculture. The objective of the study was to simulate the future impact of climate change on a crop rotation of spring wheat-potato-spring barley-sugarbeet grown in the semi-arid region of southern Idaho using conventional management practices and a high dairy manure application. The Root Zone Water Quality Model (RZWQM2) simulations used bias-corrected and spatially disaggregated projections from the World Climate Research Program's coupled model inter-comparison project phase 5 to generate 40 GCM projections for the time from 2071-2099. The 28-yr scenarios were designed to simulate the impact of temperature and CO_2 regimes on crop production, soil nitrogen mineralization, nitrogen seepage, deep seepage of water, and nitrous oxide emissions. Data from a field experiment in southern Idaho with conventional fertilizer practices and annual applications of 52 Mg ha^{-1} dairy manure with a crop rotation of spring wheat-potato-spring barley-sugarbeet were used in the RZWQM2 simulations. Results were compared to a baseline scenario of conventional management practices, historical weather data, and ambient CO_2. Spring wheat yield increased by 22% and 16% for manure and fertilizer treatments, respectively, compared to the baseline scenario. Using the same comparison, potato tuber yield decreased by 65% and 60% in the manure and fertilizer treatments, respectively, for the highest temperature and CO2 increase scenarios. Spring barley produced a 33% higher yield with increased temperature and CO2. However, yield decreased when temperature increased, but CO2 remained unchanged. Sugarbeet yields decreased by 16% and 18% for manure and fertilizer treatments, respectively, compared to the baseline scenario. Nitrogen mineralization, N seepage from the profile, and nitrous oxide emissions were strongly influenced by the manure applications, and there was little simulated impact of climate change on these processes. These simulation results indicate that genetic enhancements or alternative management will be needed to maintain potato and sugar beet production levels in semi-arid areas, while spring barley and wheat yields may increase, assuming adequate irrigation water supplies are available.*

Keywords. *Nitrogen Mineralization, Potato, RZWQM2, Spring Barley, Spring Wheat, Sugarbeet.*

Climate change is an ongoing process where ecosystems and communities are being impacted today. Global temperatures rose about 1.1°C from 1901 to 2020; however, climate change refers to more than an increase in temperature, it also includes changes in weather patterns (IPCC, 2021). All aspects of water, energy, wildlife, agriculture, ecosystems, and human health are experiencing the effects of climate change (NOAA, 2023). Changes to water resources are especially

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important in the western United States, where snowpack is an important source of freshwater because little precipitation occurs in the summer months. As temperatures warm, there is less snow overall, and snow begins to melt earlier in the year; consequently, the snowpack may not be a reliable source of water for the entire warm and dry growing season. Higher air temperatures cause plants to transpire more, and as a result, farmers must use more irrigation water. At the same time, droughts are becoming more common, particularly in the western United States (NOAA, 2023).

Idaho's climate varies from the dry rangelands of southern Idaho to the temperate forests of the northern panhandle. Warming trends in Idaho are like those of the northwestern United States, with a long-term warming of 1°C since 1895, and since 1950, Idaho's snowpack has been decreasing in most locations (Abatzoglou et al., 2021). As the climate warms, snowpack melts earlier, and flows of fresh water in rivers and streams increase during late winter and early spring but decrease during the summer. Rising temperatures increase the rate of evaporation and transpiration from soils, plants, and surface water, resulting in less water draining into streams. While the impact on some streams may be negligible, in other streams, the flow of water during summer may be 50% less by mid-century than it is today (EPA, 2016). Tree ring analysis of old forest trees can assist in understanding past climate conditions (Abatzoglou et al., 2021). The tree ring analyses from Abatzoflou et al. (2021) indicate that over the past *ca.* 1000 years, the Idaho region experienced droughts that were more prolonged and severe compared to measured weather data from 1905-2019. A prolonged and severe drought that occurred during the 12th century (*ca.* 1130-1200) appears to be the longest and most severe drought over the past *ca.* 1000 years and exceeds the drought that happened during the Dust Bowl of the 1920s-1940s (Abatzoglou et al., 2021). The 12th century drought highlights the magnitude and duration of drought potential in Idaho, and it would create major problems for water resource managers should it occur again in the present time (Abatzoglou et al., 2021). The combination of natural climate variability in the 21st century with shifting weather patterns imposed by climate change would likely yield significant changes in climate and meteorological extremes in Idaho. These changes could challenge the state's economic and cultural dependence on snow, water resources, forests, agriculture, and outdoor recreation (Abatzoglou et al., 2021).

Recent research (Bento et al., 2021) indicates climate change may negatively affect wheat and barley crops situated in regions where temperatures and precipitation are already ideal for its growth and where small changes in weather may negatively impact crop yield. On the other hand, expected warming in colder regions may be beneficial for wheat and barley growth, particularly in early winter, where higher temperatures may increase cereal development (Bento et al., 2021). Idaho's Eastern Snake Plain Aquifer (ESPA) region covers most of southern Idaho and contributes substantially to agricultural production in the state, producing potatoes, sugarbeet, barley, wheat, and other crops. These crops are grown in rotation of three or more crops, and farmers think the ability to grow cash crops (primarily potato and sugarbeet) in diverse rotations gives them an advantage over farmers in other regions. Also, the diversity of crops can result in improved pest management (Spangler et al., 2022). Income from agricultural activities in southern Idaho accounts for almost two-thirds of the median household income in the region (Watson and Ringwood, 2016). Since 2013, Idaho has led the nation in annual barley production, producing about a third of the national total barley production (Ellis, 2020). Wheat is grown in 42 of 44 Idaho counties, and about half of the wheat produced in the state is processed domestically while the other half is exported to other countries (Hatzenbuehler et al., 2021). Although the increased photosynthetic effects of increased temperatures and CO_2 may potentially produce higher yields for some plants, it may not be as large for grains because of their relatively smaller leaves, and under dry conditions, heat stress on wheat plants can cause reductions in grain fill (Hatzenbuehler et al., 2021).

Potato is the most important non-grain crop in the world and the third most important food crop after rice and wheat, and they are often the main source of income and food security in developing countries (Lutaladio and Castaldi, 2009; Raymundo et al., 2018). The global climate change impact simulations suggested small reductions of potato yields by 2055, but up to a 26% potato yield decline towards the end of the century for the scenario where CO_2 and temperature increases are the most extreme (Raymundo et al., 2018). Estimates by Rajagopalan et al. (2018) showed that increased CO_2 levels would have a positive effect on potato yield; however, increases in temperatures are expected to have a negative effect on irrigated potato yields in the Pacific Northwest, with the overall effect of increased CO_2 and temperatures expected to be negative (Hatzenbuehler et al., 2021). Potatoes are a heavy water using crop, and hot, dry summers would cause increased soil and plant evapotranspiration, resulting in an increase in demand for soil moisture supplied by irrigation. Even small deviations from optimal soil moisture, either too little or too much, during the growing season can have substantial effects on potato yields (Hatzenbuehler et al., 2021).

Compared with other crops, sugarbeet is relatively tolerant to hot, dry, and mildly saline conditions, possibly because the wild populations of sugarbeet, *Beta vulgaris subsp. Maritima,* thrive in habitats characterized by such harsh conditions (Ober and Rahabi, 2010). However, there is evidence that in many areas, the growing conditions for sugarbeet are becoming more challenging because of increased water demand in sugarbeet growing regions such as Europe (Supit et al., 2010; Shrestha et al., 2010). However, warmer springs that extend the growing season and increased yields due to atmospheric CO2 fertilization can offset some of the negative effects on sugarbeet (Jaggard et al., 2007; Jaggard et al., 2010). Climate change and global warming are expected to happen for at least the next 100 years, and the magnitude of the impact on agricultural production will be determined by the commitment of humankind (Gornall et al., 2010).

Information on the impact of climate change on soil nitrogen mineralization is more limited. Liu et al. (2017) provide empirical evidence that nitrogen varies among different ecosystems and regions on a global scale. Their results indicate soil nitrogen availability under global warming scenarios is expected to increase in colder regions compared to warmer regions. Keller et al. (2004) studied nitrogen mineralization in peat soils, and their results suggest that even short-term changes in climate can affect mineralization.

Simulation models have been used to study the potential impact of climate change on crop production for several years (White et al., 2011). Crop models integrate the nonlinear dynamics of soil, weather, and crop management to estimate crop growth and production under a wide range of conditions (Jones et al., 2003) and can help analyze the effect of abiotic stresses during the crop growing cycle or to explore management strategies to improve yields under specific environments (Haverkort and Top, 2011). Most studies on the impacts of climate change using crop models have focused on grain crops (White et al., 2011). The Root Zone Water Quality Model (RZWQM2) used in this study has previously been used to simulate the impact of climate change on soybean (Ma et al., 2021), and Malone et al. (2020) investigated drainage nitrogen loads with winter rye. Jiang et al. (2020) used RZWQM2 to study nitrogen losses to tile drainage in soybean and corn in Canada. Their model simulations indicated climate change in their region would increase mineralization and denitrification and result in greater nitrogen loss to tile drainage (Jiang et al., 2020). Wang et al. (2016) used RZWQM2 in an Iowa study to simulate the impact of different management practices on corn production and nitrogen losses to mitigate the impact of climate change. Tubers and roots crops have received little attention, particularly in model testing and model improvement for simulating climate change effects (Raymundo et al., 2018). There is also little information about the impact of climate change on soil nitrogen mineralization in irrigated, semi-arid environments. Therefore, this study was conducted to determine the response of crops grown in rotation, especially potato and sugarbeet, and soil nitrogen processes to future climate change projections.

The goal of this study was to simulate the future impact of climate change using RZWQM2 and a crop rotation of spring wheat, potato, spring barley, and sugarbeet grown in the semi-arid irrigated region of southern Idaho using conventional fertilizer practices and a high dairy manure application. Possible management practices to lessen the impact of climate change were also simulated. RZWQM2 simulations used 40 general circulation models (GCMs) and centered on the last three decades of the 21st century from 2071-2099. RZWQM2 scenarios were designed to simulate the impact of two high temperature plus CO_2 regimes (RCP4.5 and RCP8.5), two high temperature regimes associated with RCP4.5 and RCP8.5 with ambient CO_2 (410 ppm), and historical temperature with two climate change CO_2 regimes associated with RCP4.5 and RCP8.5. Investigating the impact of different temperature and CO_2 regimes will provide information to scientists on approaches to reduce the impact of climate change.

MATERIALS AND METHODS

FIELD EXPERIMENT

A long-term study designed to evaluate the impacts of manure application rate and timing on nutrient cycling in a four-year crop rotation was used to calibrate and validate the RZWQM2. The field is located at the USDA ARS Northwest Irrigation and Soils Research farm near Kimberly, ID (Lat 42°33′, Long 114°21′, 1187m elevation). The soil is a Portneuf silt loam (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplacalcid). The historical average annual precipitation for the Kimberly area is 284 mm; therefore, all crops are irrigated during the growing season (U.S. Climate Data, 2022). This study was initiated in the fall of 2012 and consisted of a four-year rotation of spring wheat (2013)–potato (2014)–spring barley (2015)–sugarbeet (2016). The experimental design was a randomized complete block with four replications and individual plot sizes of 18.3 × 12.2 m. The study was sprinkler irrigated using a solid-set irrigation system, with all treatments receiving the same irrigation regime. The irrigation application for each crop was 41.06, 59.3, 46.14, and 72.64 cm for spring wheat, potato, spring barley, and sugarbeet, respectively. The fertilizer applications for spring wheat, potato, spring barley, and sugarbeet were 43.46, 263.2, 53.76, and 123.20 kg ha^{-1} Urea-N, respectively. The dry manure applied on the 52TA treatment was 55412, 70170, 55494, and 57622 kg ha^{-1} NH_4, and the corresponding NH_4 in the manure was 156.2, 199.07, 121.39, and 160.16 kg ha^{-1} for spring wheat, potato, spring barley, and sugarbeet, respectively. The field experiment was designed to maximize production, so the manure was amended with fertilizer for spring wheat (43.46 kg ha^{-1} Urea-N) and potato (218.4 kg ha^{-1} Urea-N). The irrigation regime, fertilizer, and manure applications were repeated seven times for each crop in the 28-yr scenario RZWQM2 simulations. The experimental field and laboratory methods are described in detail in Koehn et al. (2021).

RZWQM2 AND CLIMATE PROJECTIONS

The RZWQM2 consists of seven main components: water balance, heat and chemical transport, nutrient dynamics (carbon and nitrogen), plant growth, soil chemical processes, pesticide processes, and management practices (Ma et al., 2011). The RZWQM2 includes the DSSAT V4.0 crop growth models (Decision Support System for Agrotechnology Transfer) for plant growth and development. We used the DSSAT crop parameters for spring wheat (DSSAT cultivar = 990001 Spring High Lat), potatoes (DSSAT cultivar = IB0003 Russet Burbank), and spring barley (DSSAT cultivar = 97002 High Lat Spring) in this study. The HERMES growth model in RZWQM2 was used to model sugarbeet growth (Kersebaum, 2011). The calibrated parameters for all crops were published in Koehn et al. (2021). The previous study used 330 ppm CO_2 (RZWQM2 default value), which was updated for this study to 410 ppm CO_2 because it is the present atmospheric CO_2 concentration (https://www.climate.gov). The updated calibration and validation information using 410 ppm CO_2 is in table A1.

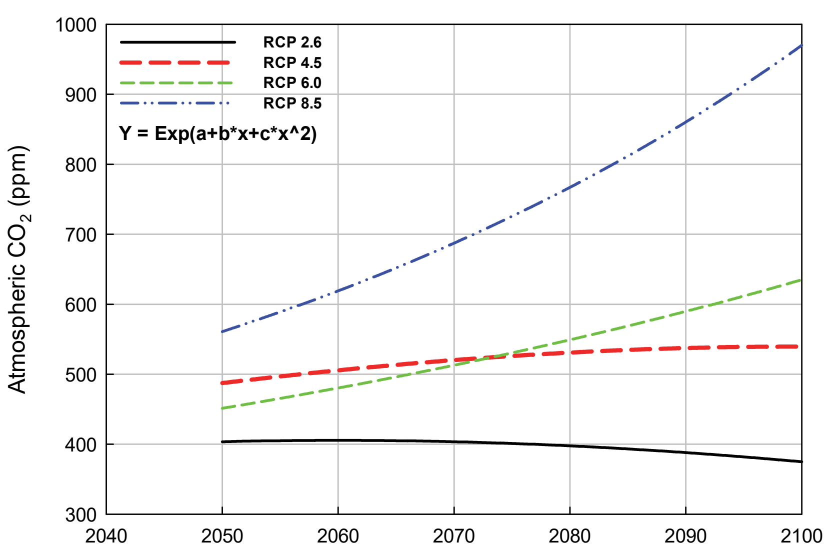
Bias-corrected and spatially disaggregated (BCSD) projections from the World Climate Research Program's (WCRP) coupled model inter-comparison project phase 5 (CMIP5) were obtained to generate 40 GCM projections (table 3 in Ma et al., 2021) for two commonly studied Representative Concentration Pathways (RCPs), RCP4.5 and RCP8.5 (Brekke et al., 2013; Pierce et al., 2015). Each projection included maximum and minimum air temperature and precipitation from 2071 through 2099, which were then superimposed onto the historical weather data of wind speed, relative humidity, and solar radiation from 1991 through 2019. By the end of 2100, atmospheric CO2 concentrations were projected to be 538 ppm under RCP4.5 and 936 ppm under RCP8.5 (Fu et al., 2016; IPCC, 2014; Meinshausen et al., 2011). The projected CO_2 concentration for each year was calculated using the equations in figure 1 for RCP4.5 (range = 520 to 539 ppm CO_2) and RCP8.5 (range = 688 to 947 ppm CO_2). The average daily minimum temperature, average daily maximum temperature, average annual precipitation, and the standard deviations for each variable for each GCM are presented in table A2 of the appendix. Less than 70 mm of precipitation occurs during the growing season (Abatzoglou et al., 2021), and irrigation provides most of the crop water needs; therefore, precipitation was not a focus in this study. Simulated GCMs for 1991-2019 were compared to historical weather data for 1991-2019 to evaluate if the simulated weather data from the GCMs was reasonable for the region. The simulated average annual precipitation for RCP4.5 and RCP8.5 was 23.16 cm, close to the actual average historical precipitation of 26.51 cm. The simulated average daily minimum temperature for RCP4.5 and RCP8.8 was 3.26 and 3.28°C, respectively, similar to the actual average historical daily minimum temperature of 2.96°C. The simulated average daily maximum temperature for RCP4.5 and RCP8.5 was 17.51 and 17.52°C, respectively, close to the actual average historical daily maximum temperature of 16.41°C. Therefore, the GCM projections are reasonable for the region.

Eight scenarios were constructed in this study: 1) Fert45 = Fertilizer treatment, RCP4.5 temperatures and CO_2 = 520 to 539 ppm, 2) 52TA45 = 52TA manure treatment, RCP4.5 temperatures and CO_2 = 520 to 539 ppm, 3) Fert85 = Fertilizer treatment, RCP8.5 temperatures and CO_2 = 688 to 947 ppm, 4) 52TA85 = 52TA manure treatment, RCP8.5 temperatures and CO_2 = 688 to 947 ppm, 5) FT45AMB = Fertilizer treatment, RCP4.5 temperatures and CO_2 = 410 ppm (present ambient CO_2), 6) 5245AMB = 52TA manure treatment, RCP4.5 temperatures, CO_2 = 410 ppm, 7) FT85AMB = Fertilizer treatment, RCP8.5 temperatures, CO2 = 410 ppm, and 8) 5285AMB, 52TA manure treatment, RCP8.5 temperatures, CO_2 = 410 ppm. The purpose of using the present ambient CO_2 concentration along with the GCM projected temperature was to investigate the influence of higher temperatures on crop performance without CO_2 effects. The total number of scenarios simulated for the 40 GCM projections was 320 (8 scenarios * 40 RCP projections). Six additional scenarios were simulated with historical weather data (1991-2019) where only the CO_2 concentration had changed, so the impact of higher CO_2 concentrations on the different crops could be investigated. The range of the annual average minimum, maximum temperature, and median precipitation for all 40 RCP4.5 and RCP8.5 climate projections, and historical climate is presented in table 1.

RZWQM2 was used to investigate possible management practices that could lessen the impacts of climate change. Planting, harvest, and irrigation dates were adjusted to a week earlier, and changes in rotation sequences were explored. The changes in rotation sequences from Rotation 1 (present rotation) were Rotation 2 (spring wheat-sugarbeet-spring barley-potato), Rotation 3 (sugarbeet-spring wheat-spring barley-potato), Rotation 4 (spring wheat-spring

Table 1. The range of minimum and maximum temperatures and average annual precipitation for the 40 GCM's and historical climate data ± one standard deviation. RCP4.5 and RCP8.5 is projected weather data for 2071 to 2099, historical climate is measured weather data for 1991 to 2019, and the table information is calculated from daily weather data for the specified years.

	RCP4.5	RCP8.5	Historical Climate
Average Minimum Temperature °C	4.98 ± 7.71	7.12 ± 8.07	2.96 ± 7.48
Average Maximum Temperature °C	19.72 ± 11.20	22.04 ± 11.62	16.41 ± 10.88
Minimum Temperature Range °C	-33.10 to 26.44	-29.1 to 29.47	-27.09 to 22.91
Maximum Temperature Range °C	-23.72 to 45.80	-17.47 to 50.41	-13.10 to 40.87
Average Annual Precipitation (cm)	27.0 ± 2.7	29.1 ± 2.9	26.5 ± 7.4



	a	b	c
RCP2.6	-201.947	0.2019	-4.9006e-5
RCP4.5	-173.9853	0.1717	-4.0883e-5
RCP6.0	56.7571	-0.0555	1.5022e-5
RCP8.5	94.71	-0.0959	2.575e-5

Figure 1. Representative Concentration Pathways (RCP's) for future time periods. RCP trajectories are adapted from the IPCC for its fifth Assessment Report (AR5) in 2014 by Meinhausen et al. (2011). The parameters for each RCP equation are presented in the table right of the graph.

barley-spring wheat-spring barley), and Rotation 5 was the original rotation with DSSAT parameters for potato adjusted to simulate greater heat tolerance for the cultivar (table 2). The parameters P2 and TC influence tuber initiation, and G3 and G2 affect biomass accumulation and partitioning after tuber initiation. If the temperature is higher than TC, the tuber initiation and expansion will be reduced or inhibited (Wang et al., 2023). The PD parameter (index that suppresses tuber growth) was left unchanged.

STATISTICAL ANALYSIS

A nonparametric analysis using PROC NPAR1WAY and the Dwass, Steel, Critchlow-Fligner (DSCF) multiple comparison analysis, which is based on pairwise two-sample Wilcoxon comparisons (SAS Version 9.4), was used to analyze the output of the RZWQM2 scenarios. The results are presented in tables A3.1–A8.4 in the Appendix.

RESULTS AND DISCUSSION

SPRING WHEAT YIELD

Each crop responded differently to the climate change projections. The combination of high temperature, high CO_2 (RCP8.5), and manure had a significant positive effect on spring wheat yield (fig. 2 and table A3.1). Compared to the baseline scenario (FertHist, fig. 3), median wheat yield was 22% higher for the manure treatments and 16% higher for the fertilizer treatments with temperature and CO_2 increases under RCP4.5 and RCP8.5 (fig. 4). Because increases in yield were similar for RCP4.5 and RCP8.5 simulations for the fertilizer treatments and the manure treatments, it is possible that the impacts of heat stress during anthesis and other phenological periods are not adequately simulated in spring wheat (Qian et al., 2019). When increases in temperature alone were considered, median spring wheat yield was also higher than the baseline scenario, as yield increased by 18% and 12%, respectively, for the 5245AMB and 5285AMB scenarios and 14% and 8%, respectively, for the FT45AMB and FT85AMB scenarios, suggesting there is little impact of higher CO_2 concentrations (fig. 4). These results are similar to those of Broberg et al. (2019), where spring wheat yield leveled off at approximately a CO_2 concentration of 600 ppm and CO_2 concentrations above 600 ppm did not increase yields significantly. Qian et al. (2019) found that crop production of small grains reached a maximum when temperatures increased up to 2.5°C of the pre-industrial global mean temperature. Qian et al. (2016) also suggested that spring wheat would benefit from breeding to take advantage of more growing degree days and for heat tolerance. Spring wheat yield in figure 2 has greater variability than spring barley yield, especially for the fertilizer treatment, indicating there may be some years over the long term when wheat yield is potentially reduced. Carew et al. (2018) mentioned that projected climate change under different carbon scenarios would increase wheat yield variability. They stated that it would be helpful to develop strategies for expanding the diversity of wheat varieties and cropping systems to reduce yield fluctuations and stabilize wheat production levels over the long term.

Table 2. DSSAT parameters for the Russet Burbank cultivar adjusted for greater heat tolerance in Rotation 5.

DSSAT Russet Burbank Parameters	Original Parameters	Adjusted Parameters
G2, leaf expansion rate after tuber initiation	1000.00	750.0
G3, potential tuber growth rate	17.0	25.0
P2, tuber initiation sensitivity to long photoperiods	0.6	0.4
TC, critical upper temperature for tuber initiation	17.0	25.0

POTATO YIELD

Projected high temperatures had a significant negative impact on potato tuber yield (fig. 2, table A3.2), with yield reductions as high as 60% to 65% for both fertilizer treatments and manure treatments when compared to the baseline scenario (fig. 4). RCP4.5 scenarios simulate reductions of 18% to 19% for manure treatments and 25% to 26% for fertilizer treatments. Increases in CO_2 concentration had no impact on potato yield in these simulations (figs. 2 and 3, tables A3.2 and A4.2). The application of manure had a positive impact on potato yield (figs. 2 and 3, tables A3.2 and A4.2). Changing planting, harvest, and irrigation dates to a week earlier decreased yield slightly from 3403 kg ha^{-1} to 3238 kg ha^{-1} in the Fert85 scenarios and 3871 kg ha^{-1} to 3661 kg ha^{-1} in the 52TA85 scenario. A climate change study on potato yields for Prince Edward Island, Canada, used CMIP6 and SSP-4.5 and SSP5-8.5 scenarios (similar to RCP4.5 and RCP8.5 climate scenarios), and results indicated potato yields would decrease -2.2% and -18.8% for the 2050s period, -18.3% and -60.0% for the 2070s period, and -36.4% and -80.1% for the 2090s periods for SSP-4.5 and SSP5-8.5 scenarios, respectively (Adekanmbi et al., 2023). Rajagopalan et al. (2018) reported that increased CO_2 levels would have a positive effect on potato yields in the Pacific Northwest and increased temperatures would have a negative impact. However, the overall impact of increased CO_2 and temperature would have a negative impact, indicating the CO_2 effects could not offset temperature increases. However, their model parameters for CO_2 were not crop specific (one set of parameters for C3 crops and another for C4 crops; Rajagopalan et al., 2018). Hatzenbuehler et al. (2021) concluded that planting new seed varieties better suited for growth under warm temperatures should be considered. Vashisht et al. (2015) came to a similar conclusion for sustaining potato yields in Minnesota: heat and water stress tolerant varieties need to be considered. A study on the potential benefits of climate change on potatoes in the United States by Zhao et al. (2022) also reported that in Idaho and Washington, the most productive states for potato, the prolonged duration and intensity of heat spells predicted in future climate scenarios would threaten yield loss without pursuing adaptation measures.

SPRING BARLEY YIELD

Spring barley yields were higher with both increased temperatures and CO_2 in the RCP8.5 regime, as the increase in yield was 33% greater for both the manure and fertilizer treatments when compared to the baseline scenario (figs. 2 and 4). Spring barley yield for the RCP4.5 fertilizer and manure scenarios were 12% and 11% higher, respectively,

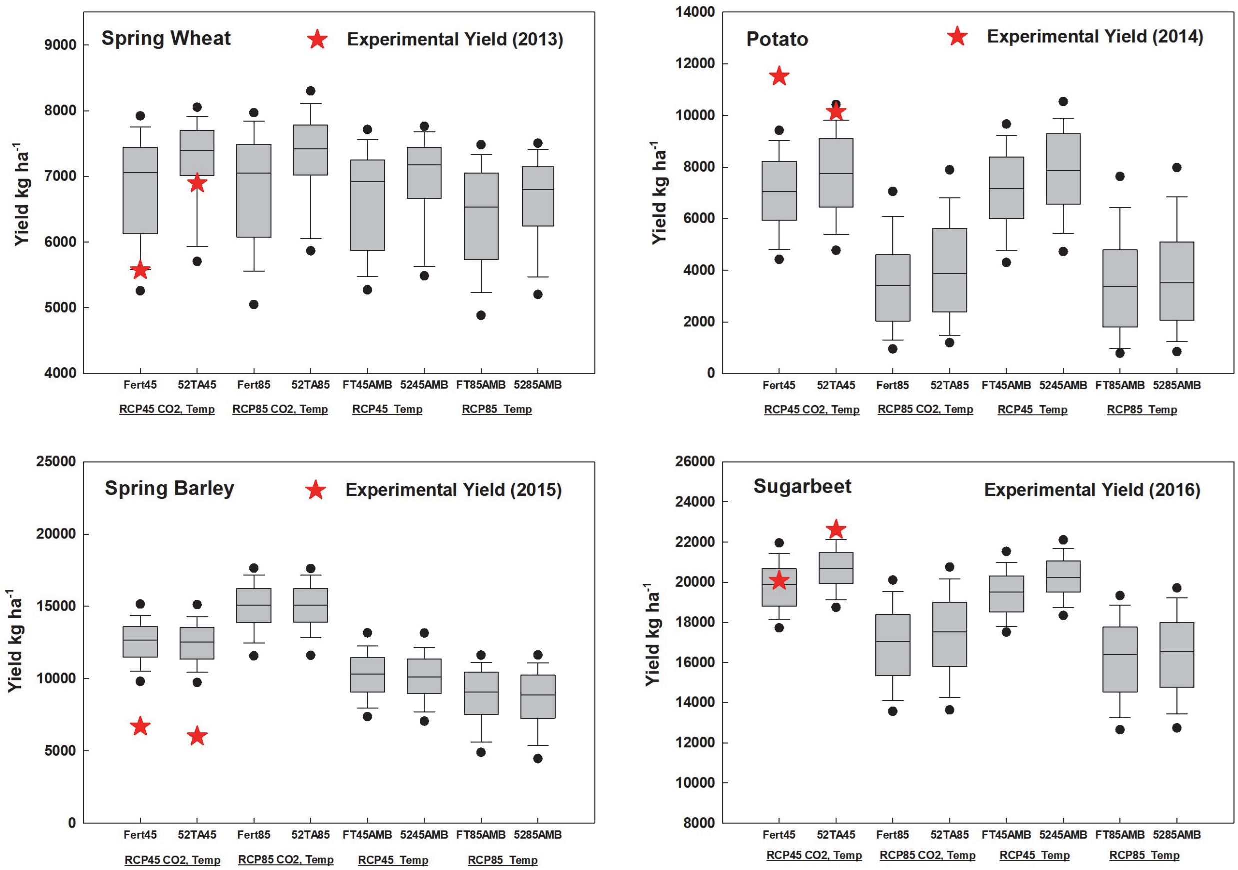


Figure 2. Crop yields for each crop, each box represents all the results from 40 climate projections and seven 4-yr crop rotations (280 observations). The 4-yr crop rotation is spring wheat, potato, spring barley, and sugarbeet. The solid line in the box plot represents the median, and black circles represent 5th and 95th percentile boundaries. Fert = chemical fertilizer treatment, 52 = 52 T Annual manure treatment, '45' = RCP4.5 temperature and CO_2 = 530 - 539 ppm, '85' = RCP8.5 temperature and CO_2 = 688 - 947 ppm, '45AMB' = RCP4.5 temperature and CO_2 = 410 ppm, '85AMB' = RCP8.5 temperature and CO_2 = 410 ppm. The experimental yield is the original yield from the field study as a reference point.

when compared to the baseline scenario. The greatest increase in yield was with the RCP8.5 CO_2 regime combined with historical weather (fig. 3, table A4.3, 50% increase for both fertilizer and manure scenarios). Increases in temperature alone with ambient CO_2 decreased yield by 20%-22% for the RCP8.5 scenarios and by 9%-11% for the RCP4.5 scenarios when compared to the baseline scenario (fig. 4). A study in Slovenia using the AGROS model reports that doubling CO_2 alone increased yield in spring barley by 94%; however, an increase of 4°C and present levels of CO_2 reduced spring barley yields by 63% because of a shortened growing season and grain filling period (Kajfež-Bogataj, 1993). Yawson et al. (2016) found in their climate change simulations that barley would remain a viable rain-fed crop with the increase in yields in their 'High Emissions Scenarios' compared to their baseline scenarios. They cautioned that stresses related to heat and soil water deficits could pose risks to stable and high yields in some years.

Sugarbeet Yields

Sugarbeet yield significantly decreased with increasing temperature (fig. 2, table A3.4). Under RCP8.5, manure and fertilizer treatments had decreased yields of 16%-18% compared to the baseline scenario. Yield for the RCP4.5 scenarios decreased by 1.0% and 5.0% for the manure and fertilizer treatments, respectively (fig. 4). Sugarbeet yields increased with increasing CO_2 and manure applications (fig. 3, table A4.4). However, the highest yield of 23799 kg ha^{-1} was with the RCP8.5 CO_2 and historical temperature (14% higher than yields in the baseline scenario), indicating sugarbeet benefits from increasing CO_2 when there is no increase in temperature. King and Tarkalson (2017) suggested that sugarbeet yield would increase with climate change when adequate nutrients and water were supplied because of a longer growing season. RZWQM2 simulations indicated that the most extreme increases in temperature (RCP8.5) would reduce yield, and higher CO_2 did not offset the consequences of higher temperatures. In addition, higher temperatures would increase irrigation water requirements when water resources were predicted to decrease because of a diminished snowpack (King and Tarkalson, 2017).

Mineralization, Nitrogen Seepage, Water Seepage from the Soil Profile, and N_2O Emissions

The median annual nitrogen mineralization was 932 kg ha^{-1} for the manure simulations compared to 148 kg ha^{-1} for the conventional fertilizer scenarios (fig. 5, tables A5.1–A5.4). According to the statistical analyses, there was little impact of increased temperature or CO_2 on nitrogen mineralization in the manure and fertilizer scenarios. Nitrogen mineralization corresponds to the average inorganic N in the soil profile at the end of the year reported in table 3, where

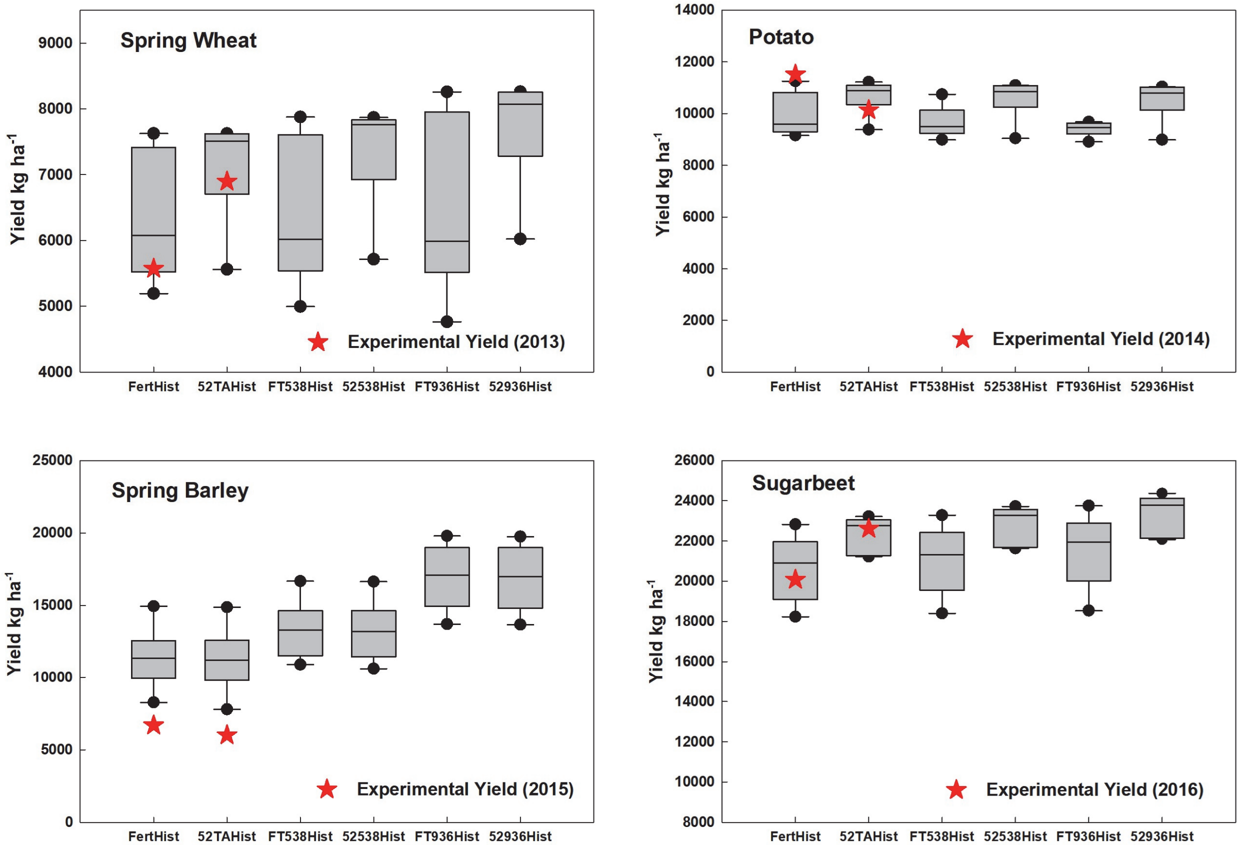


Figure 3. Crop yields for each crop from seven 4-yr crop rotations (spring wheat, potato, spring barley, and sugarbeet, 7 observations). The 28-yr scenarios used measured historical weather data from 1990 to 2018. The scenarios FertHist and 52TAHist scenarios set the CO_2 at 410 ppm. Fert = chemical fertilizer treatment, '52' = 52 T Annual manure treatment, '538' = RCP4.5 CO_2 ppm regime (530 - 539 ppm) for the scenario, '936' = RCP8.5 CO_2 ppm regime (688 - 947 ppm) for the scenario. The solid line in the box plot represents the median, and black circles represent 5th and 95th percentile boundaries. The experimental yield is the original yield from the field study as a reference point.

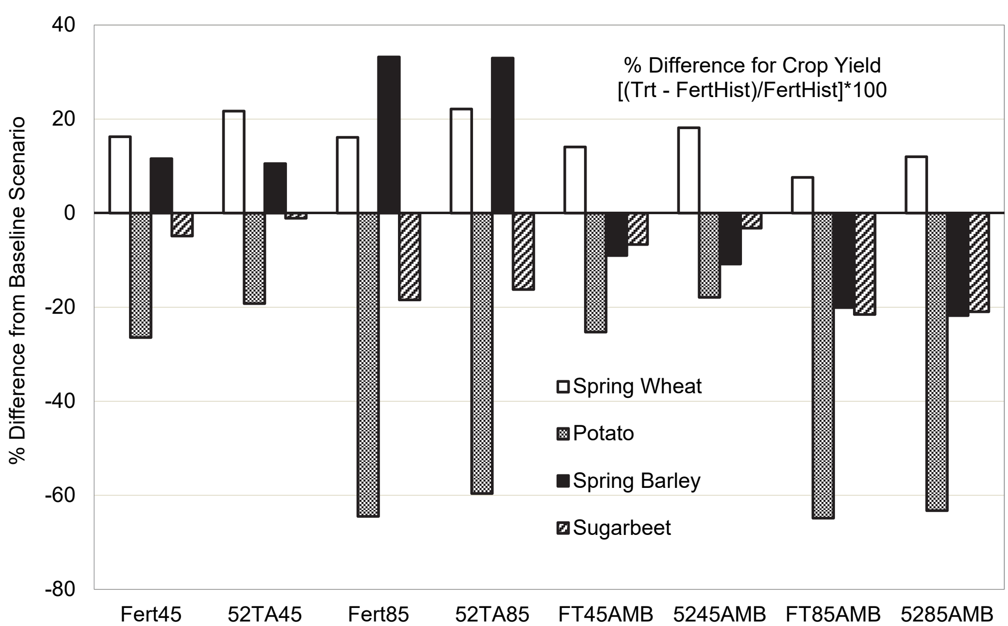


Figure 4. Percent difference in median crop yields from the FertHist baseline scenario. Fert = chemical fertilizer treatment, 52 = 52 T Annual manure treatment, '45' = RCP4.5 temperature and CO_2 = 520 - 539 ppm, '85' = RCP8.5 temperature and CO_2 = 688 - 947 ppm, '45AMB' = RCP4.5 temperature and CO_2 = 410 ppm, '85AMB' = RCP8.5 temperature and CO_2 = 410 ppm.

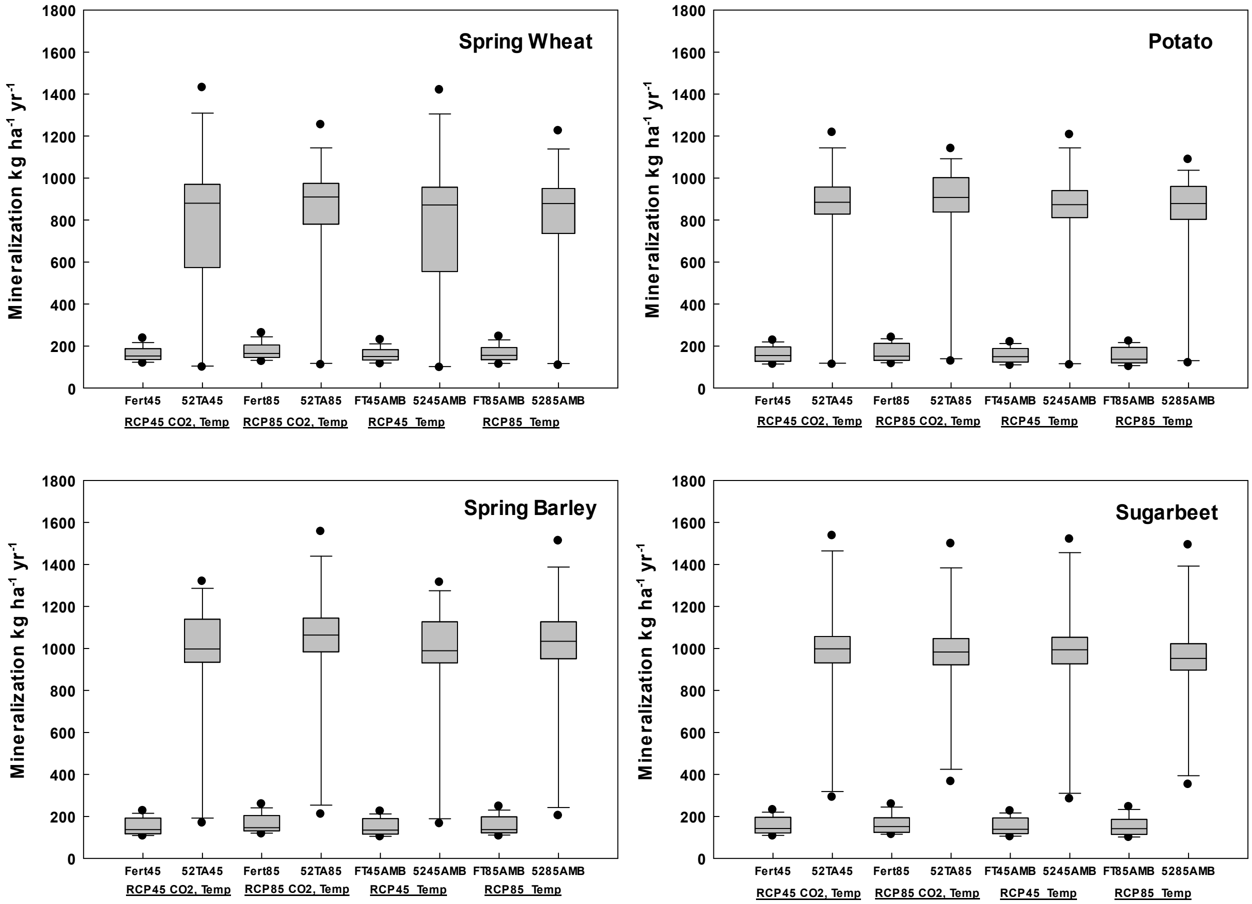


Figure 5. Soil nitrogen mineralization where each box represents all the results from 40 climate projections and seven 4-yr crop rotations (280 observations). The 4-yr crop rotation is spring wheat, potato, spring barley, and sugarbeet. The solid line in the box plot represents the median and black circles represent 5th and 95th percentile boundaries. Fert = chemical fertilizer treatment, 52 = 52 T Annual manure treatment, '45' = RCP4.5 temperature and CO_2 = 530 - 539 ppm, '85' = RCP8.5 temperature and CO_2 = 688 - 947 ppm, '45AMB' = RCP4.5 temperature and CO_2 = 410 ppm, '85AMB' = RCP8.5 temperature and CO_2 = 410 ppm.

the range was 1472 to 2410 kg ha^{-1} for the manure scenarios and 80 to 258 kg ha^{-1} for the fertilizer scenarios, indicating a significant effect of manure on soil nitrogen. The median N mineralization from 16-year scenarios published from the long-term study (Koehn et al., 2021) was 1014.9 kg ha^{-1} for the 52TA manure treatment with historical weather data and 181.9 kg ha^{-1} for the fertilizer treatment. The median range for N mineralization for all crops in the 28-yr climate scenarios was 872 to 1065 kg ha^{-1} for manure treatment and 135 to 165 kg ha^{-1} for fertilizer treatments, which are comparable to previously published results. Schlingmann et al. (2020) did not find significant changes in gross mineralization in grasslands treated with cattle slurry in their climate change treatments. In a study that assessed the interactive effects of elevated CO_2, warming climate, increased precipitation, and enhanced nitrogen supply in a grassland in California, increased CO_2 had no effect on gross N mineralization under ambient precipitation; however, with elevated CO_2, elevated precipitation, and increased nitrogen supply, gross N mineralization increased (Niboyet et al., 2011). In this study, all scenarios received the same amount of irrigation water, and the average annual precipitation for the 40 GCM's was within the standard deviation range of historical weather, resulting in significant differences between the fertilizer and manure treatments but few differences within these treatments (tables A5.1–A5.4).

Table 3. The average annual inorganic nitrogen in the soil profile at the end of the year for the 8 climate change scenarios for each crop in the 28-yr rotation (n=280).

	Average Inorganic N (kg ha^{-1})			
Scenario	Spring Wheat	Potato	Spring Barley	Sugarbeet
Fert45	148	80	223	109
52TA45	1660	1559	2275	1978
Fert85	169	91	234	127
52TA85	1551	1472	2091	2060
FT45AMB	154	83	226	107
5245AMB	1832	1722	2338	2103
FT85AMB	196	122	258	133
5285AMB	2089	1830	2410	2396

Because of the high N applied in the manure applications, the N seepage of 451.9 kg ha^{-1} for the manure scenarios was much higher than 20.5 kg ha^{-1} for the fertilizer scenarios (fig. 6, tables A6.1–A6.4). N seepage in spring wheat manure scenario 52TA85 was significantly higher compared to the other manure scenarios (table A6.1). Spring barley followed low yields of potato and did take advantage of more nitrogen that might be available with increased yields in the higher CO_2 and temperature climate change projections, and as a result, the N seepage during spring barley crop years was among the lowest of the projections (table A6.3). The range of the N seepage projections from the 28-yr climate

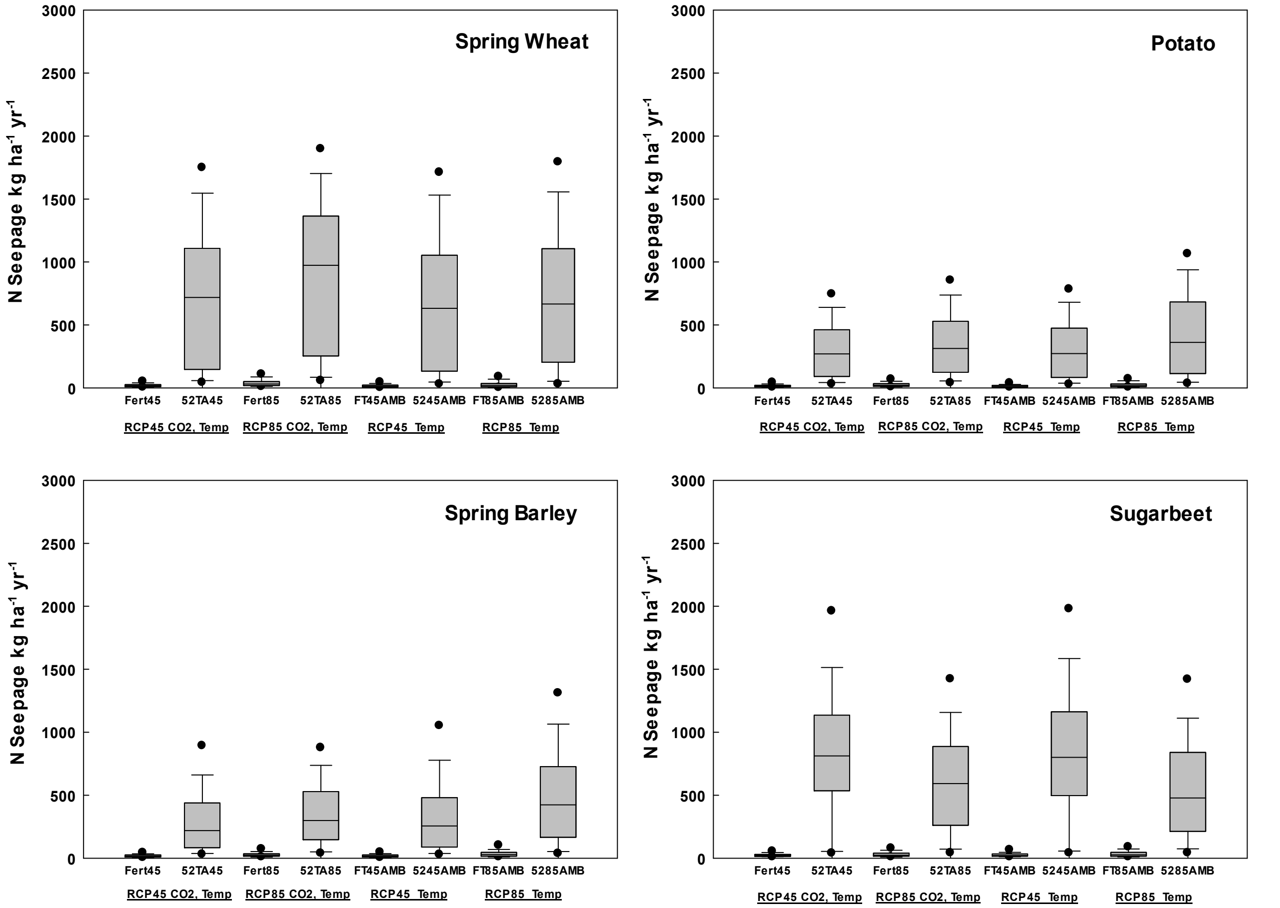


Figure 6. Nitrogen seepage through the soil profile where each box represents all the results from 40 climate projections and seven 4-yr crop rotations (280 observations). The 4-yr crop rotation is spring wheat, potato, spring barley, and sugarbeet. The solid line in the box plot represents the median, and black circles represent 5th and 95th percentile boundaries. Fert = chemical fertilizer treatment, 52 = 52 T Annual manure treatment, '45' = RCP4.5 temperature and CO_2 = 530 - 539 ppm, '85' = RCP8.5 temperature and CO_2 = 688 - 947 ppm, '45AMB' = RCP4.5 temperature and CO_2 = 410 ppm, '85AMB' = RCP8.5 temperature and CO_2 = 410 ppm.

change scenarios is like previously published 16-yr scenarios, where the median N in the seepage was 515.8 kg ha^{-1} for the 52TA manure treatment and 22.4 kg ha^{-1} for the fertilizer treatment (Koehn et al., 2021).

The amount of water seepage from the soil profile appears to depend more on the small precipitation increase in the RCP8.5 scenarios (fig. 7, tables A7.1–A7.4), as the RCP8.5 scenarios usually have the highest water seepage, whereas ambient scenarios often have reduced seepage. Keep in mind that all scenarios received the same irrigation regime, and most precipitation occurs during the non-growing season. One note, simulated median transpiration was often slightly higher in ambient scenarios (except spring barley which had simulated high yields); spring wheat range = 30.9 to 31.9 cm (ambient scenarios) vs. 25.6 to 29.7 cm (increased CO_2 scenarios), potato range = 63.9 to 66.7 cm (ambient scenarios) vs. 62.0 to 62.4 cm (increased CO_2 scenarios), spring barley = 25.9 to 29.3 cm (ambient scenarios) vs 27.0 to 30.1 cm (CO_2 scenarios), and sugarbeet range = 61.4 to 69.7 cm (ambient scenarios) vs. 59.5 to 63.3 cm (CO_2 scenarios). There is some information in the literature that indicates that increased CO_2 concentration will cause stomata to close to some extent, causing reduced transpiration (Kirschbaum, 2004). In C_3 and C_4 species, it is reported that stomatal conductance could be reduced by 40% with a doubling of the CO_2 concentration (Kirschbaum, 2004). Spring barley apparently has high genetic variability, is well-adapted to different environmental conditions, and uses water more efficiently than other cereals, which could explain the different response in transpiration rates (Moualeu-Ngangué et al., 2020; Clark, 2007).

Simulated N_2O-N emissions have similar trends to N mineralization and seepage, where the manure scenarios have much higher emissions than fertilizer scenarios (fig. 8, tables A8.1.–A8.4). The range of median values for the 28-yr climate change scenarios for N_2O-N emissions from the manure treatments was 21.58 to 31.21 kg ha^{-1} yr^{-1} and 0.69 to 1.43 kg ha^{-1} yr^{-1} for the fertilizer scenarios. Statistical analyses indicate that higher temperatures increased N_2O-N emissions (tables A8.1–A8.4) when comparing Fert45 to Fert85 scenarios, whereas in the manure treatments, there was no significant difference between the scenarios. The median N_2O-N emissions for fertilizer treatments were higher for potato than the other crops, as potato received more chemical fertilizer (263.2 kg ha^{-1} yr^{-1} vs. 43.46, 53.76, and 123.2 kg ha^{-1} yr^{-1} for spring wheat, spring barley, and sugarbeet, respectively). Hunt et al. (2019) measured N_2O-N emissions from a perennial forage grass applied with a slurry

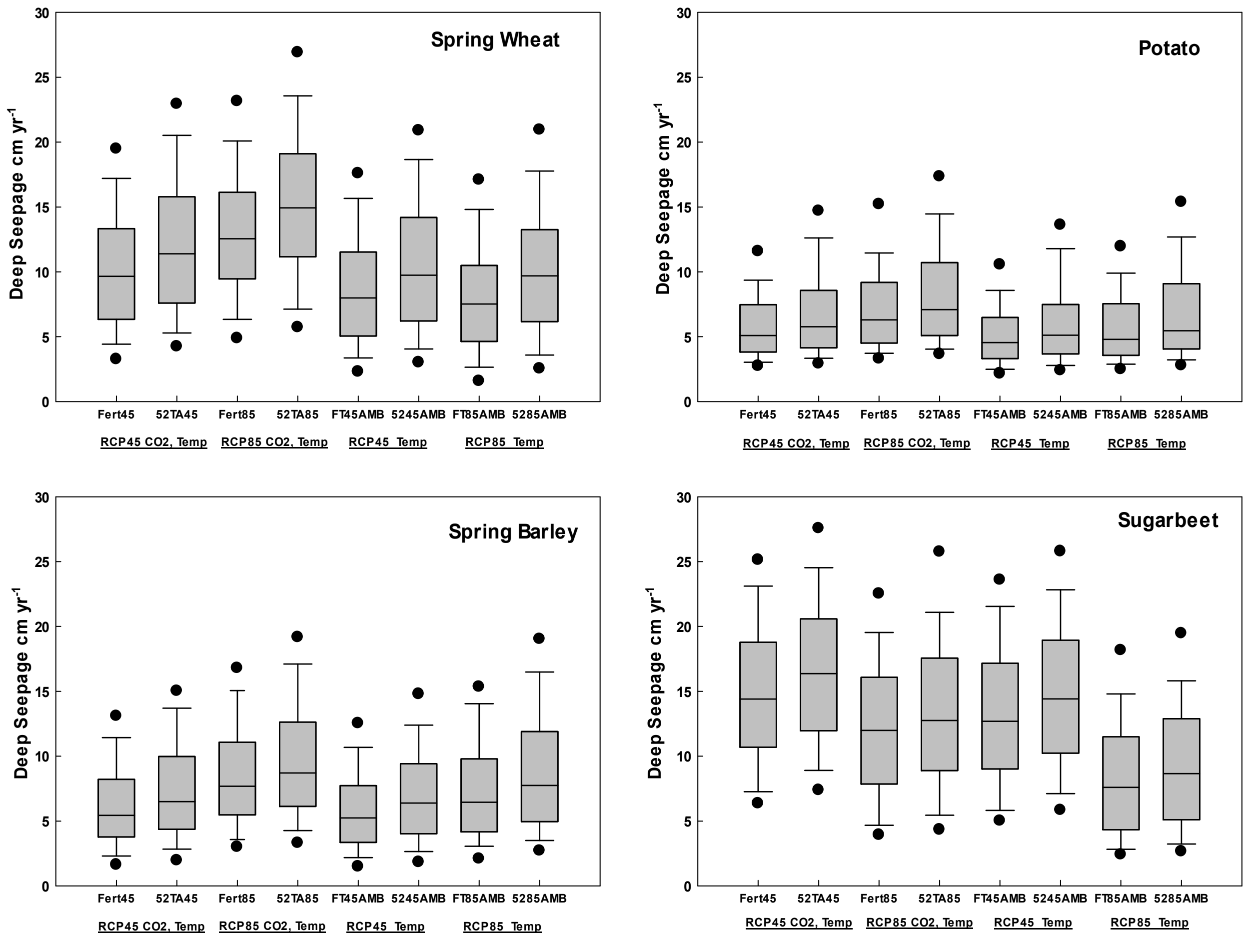


Figure 7. Deep seepage represents the water leaving the soil profile, where each box represents all the results from 40 climate projections, seven 4-yr crop rotations (280 observations). The 4-yr crop rotation is spring wheat, potato, spring barley, and sugarbeet. The solid line in the box plot represents the median, and black circles represent 5th and 95th percentile boundaries. Fert = chemical fertilizer treatment, 52 = 52 T Annual manure treatment, '45' = RCP4.5 temperature and CO_2 = 530 - 539 ppm, '85' = RCP8.5 temperature and CO_2 = 688 - 947 ppm, '45AMB' = RCP4.5 temperature and CO_2 = 410 ppm, '85AMB' = RCP8.5 temperature and CO_2 = 410 ppm.

containing 584 kg ha^{-1} yr^{-1} of Total N and the average emissions over 5 years were 4.0 kg N_2O-N ha^{-1} yr^{-1} with a range of 2.12 to 6.68 kg ha^{-1} yr^{-1}. In this study, the average total N applied per year for the 52TA manure treatment was 922.9 kg ha^{-1} yr^{-1}. In the previously published 24-yr 52TA scenario where manure applications ended after 2008, N_2O-N emissions declined from 32.5 kg ha^{-1} yr^{-1} in 2008 to 1.9 kg ha^{-1} yr^{-1} in 2013 (Koehn et al., 2021). N_2O-N emissions were measured again in 2020 in the fertilizer and 52TA (after 8 consecutive years of manure applications) treatments using an automated measuring system (Dungan et al., 2023). Annual N_2O-N emissions from the fertilizer treatment for 2020 were 0.995 kg N_2O-N ha^{-1}, in the range of the simulated N_2O-N emissions in the fertilizer climate change scenarios. Dungan's N_2O-N emissions measurements for the 52TA manure treatment were 3.609 kg N_2O-N ha^{-1}, so the median range of simulated N_2O-N emissions from the 28-yr 52TA scenario was much higher. Understanding N_2O-N emissions is a challenge because of the complexity of soil microbial processes (Jansson and Hofmockel, 2020). Warming has been shown to increase microbial activity, thus increasing nutrient availability; however, plant growth may then shift to other limiting factors such as light or temperature (Schlingmann et al., 2020). Niboyet et al. (2011) report in their interactive study that elevated CO_2 and higher temperatures had no significant impact on denitrification and a weak response of nitrification to higher CO_2, the processes by which N_2O is released. The greatest impact on denitrification was the long-term addition of nitrogen (Niboyet et al., 2011), which would be the case with the high manure treatments in this study.

Crop Yields under Alternate Rotations

Alternate rotations were designed to investigate if climate change impacts can be reduced using different crop rotations. Comparisons of the alternate 28-yr rotations were made to the original 28-yr rotation. Rotation 2, where spring wheat followed potato, crop yields were reduced by 16% and 11% for the RCP4.5 and RCP8.5 fertilizer treatments, respectively, whereas the manure-treated scenarios experienced no decline in spring wheat yield, indicating the added nitrogen from the manure applications was beneficial in this rotation for maintaining yield (table 4). Sugarbeet yields also decreased in the RCP4.5 and RCP8.5 fertilizer treatments by 18% and 9%, respectively. Spring barley, on the other hand, did not benefit from the added nitrogen in manure treatments, as there was a decrease in yield of 9% and 4% in RCP4.5 and RCP8.5 manure treatments, respectively

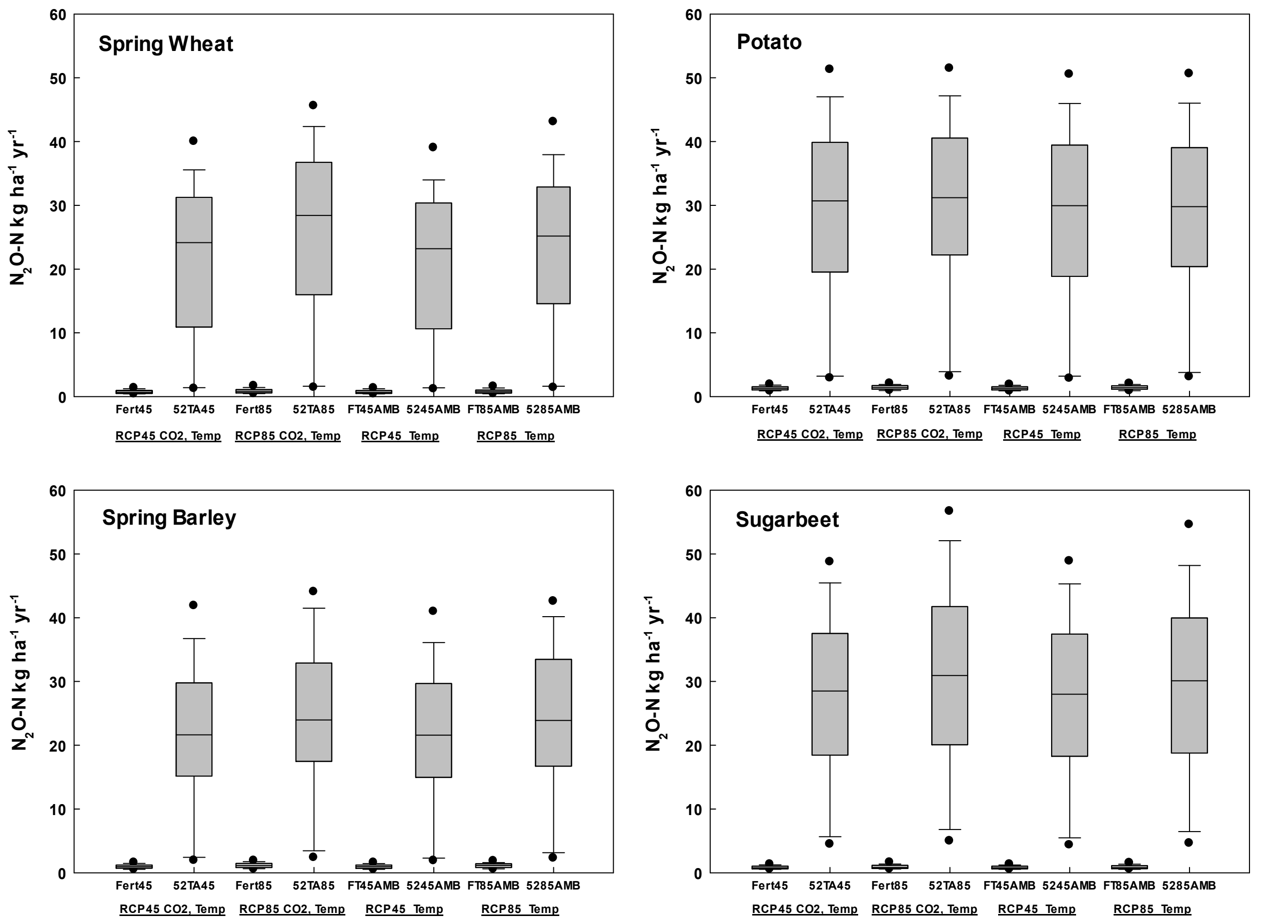


Figure 8. N_2O-N emissions from the soil surface. Each box represents all the results from 40 climate simulations for seven 4-yr crop rotations (280 observations). The 4-yr crop rotation is spring wheat, potato, spring barley, and sugarbeet. The solid line in the box plot represents the median, and black circles represent the 5th and 95th percentile boundaries. Fert = chemical fertilizer treatment, 52 = 52 T Annual manure treatment, '45' = RCP4.5 temperature and CO_2 = 530 - 539 ppm, '85' = RCP8.5 temperature and CO_2 = 688 - 947 ppm, '45AMB' = RCP4.5 temperature and CO_2 = 410 ppm, '85AMB' = RCP8.5 temperature and CO_2 = 410 ppm.

Table 4. Comparisons of alternate rotations. Each crop rotation was repeated seven times for a 28-yr scenario except for Rotation 4 where the spring wheat-spring barley rotation was repeated 14 times. The results are from 40 climate change projections.

	Median Yield (kg ha^{-1})			
	Fertilizer		52TA Manure	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Rotation 1 (Original)				
Spring Wheat	7062	7054	7392	7420
Potato	7049	3403	7742	3871
Spring Barley	12658	15111	12538	15083
Sugarbeet	19897	17059	20687	17521
Rotation 2				
Spring Wheat	5925	6308	7385	7456
Sugarbeet	16354	15498	20470	17772
Spring Barley	12590	15147	11405	14429
Potato	7185	3144	8013	3535
Rotation 3				
Sugarbeet	14499	13921	20806	16821
Spring Wheat	5005	5851	6110	6406
Spring Barley	12796	15284	12775	15276
Potato	7140	3148	8011	3597
Rotation 4				
Spring Wheat	7245	7228	7410	7413
Spring Barley	12514	15092	12480	15058
Rotation 5 (Original, DSSAT Potato)				
Spring Wheat	6529	6867	7392	7413
Potato	13629	9551	14530	10246
Spring Barley	12678	15095	12526	15017
Sugarbeet	19508	16896	20651	17305

(table 4). Potato yields were reduced in the most extreme RCP8.5 fertilizer and manure treatments by about 8% and 9%, respectively, whereas in the RCP4.5 fertilizer treatments there was no decline in yield.

Rotation 3, where sugarbeet was planted following potato, resulted in decreased yields for sugarbeet by 27% and 18% for the RCP4.5 and RCP8.5 fertilizer treatments, respectively. The RCP8.5 manure treatment had decreased yields of only 4%, indicating less yield impacts compared to fertilizer treatment. Sugarbeet following potato would be able to maintain yields with the increased nitrogen provided by the high manure treatment (table 4). Rotation 3 reduced spring wheat yields, which followed sugarbeet, by 29%, 17%, 17%, and 14% for the RCP4.5 and RCP8.5 fertilizer treatments, RCP4.5 and RCP8.5 manure treatments, respectively. Sugarbeet yields were decreased by 27% and 18% for the RCP4.5 and RCP8.5 fertilizer treatments, respectively, and by 4% for the RCP8.5 manure treatments. Spring barley, which followed spring wheat in the rotation, had no decreases in yield compared to the original rotation. Potato had reduced yields in the RCP8.5 fertilizer and RCP8.5 manure treatments of 7%, following the same trend of reduced yields in extreme climate conditions as the original rotation.

Rotation 4 alternated spring wheat and spring barley for the 28-yr simulations without potato or sugarbeet. The reason for including this rotation is because grain crops require a shorter growing season and require less irrigation water (41.06 cm and 46.14 cm for spring wheat and spring barley, respectively vs. 59.3 m and 72.64 cm for potato and sugarbeet, respectively). In periods of extreme weather conditions Rotation 4 would be the recommended rotation as there are no reductions in spring wheat or spring barley yields compared to the original rotation (table 4). Rotation 4 would conserve about 45 cm of water every 4 years compared to the other rotations. Changing DSSAT potato parameters to represent a cultivar that would grow faster (G3=25.0 vs G3=17.0) and be more heat tolerant (TC=25.0 vs TC=17.0), the yield was doubled in the RCP4.5 climate change simulations compared to the original rotation and increased by 180% and 165% for the fertilizer and 52TA RCP8.5 treatments (table 4). Potato yields for the most extreme climate change conditions with the new cultivar settings (9551 kg ha^{-1} and 10246 kg ha^{-1} for the fertilizer and manure treatments, respectively) were similar to the experimental yields of 11514 kg ha^{-1} and 10137 kg ha^{-1} for the fertilizer and manure treatments, respectively. Potato yields for the less extreme RCP4.5 scenarios were higher than the experimental yield (13629 kg ha^{-1} and 14530 kg ha^{-1} for the fertilizer and manure treatments, respectively) indicating that a breeding program focused on faster growth and greater heat tolerance would not sacrifice yield if conditions were less extreme.

Conclusions

As populations grow and climate changes, shifting to a more sustainable future in agriculture is important. In this study, the simulated responses to climate change indicate spring wheat would best be able to cope with increases in temperature and/or CO_2 associated with climate change projections, even in the most extreme cases associated with RCP8.5. However, spring wheat exhibits the most variation in yield, indicating there could be good and bad years, suggesting breeding programs should focus on cultivars that provide predictable yields with high temperatures and CO_2. Potatoes would be the most detrimentally affected by climate change, according to the simulations, with decreases in yield even in the RCP4.5 regimes. Breeding for cultivars with faster growth and the ability to tolerate growing at higher temperatures will be necessary to continue to grow potatoes in the semi-arid irrigated environment, as changing management practices may not mitigate the impact of climate change. Spring barley has more mixed results, with yield increasing with a combination of higher temperatures and CO_2. However, when CO_2 remains at ambient concentrations of 410 ppm, there is a decrease in yield with increasing temperature. These results for spring barley indicate it would benefit in a similar fashion to spring wheat to breeding programs, however, the climate change simulations indicate there is less variation in crop yield. Sugarbeet yields also decreased in the extreme RCP8.5 scenario but were able to tolerate the RCP4.5 scenario with minimal decreases in yield. If climate change is allowed to progress to extreme conditions, breeding programs for heat-tolerant sugarbeet will become more important. Manure applications had a positive impact on yield for all crops except for spring barley, where the simulation results indicated little impact of manure on yield. Soil nitrogen mineralization was high in the manure simulations, resulting in high nitrogen seepage from the profile, but mineralization and seepage were not impacted by climate change scenarios. The results from the RZWQM2 simulations indicate that all the crops in the rotation would benefit from more research on breeding cultivars for characteristics that would increase resilience and adaptability in response to climate change. Spring wheat and spring barley could be planted and would conserve water while maintaining a reasonable yield if high temperatures and CO_2 associated with the RCP8.5 scenarios occurred.

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APPENDIX

Table A1. The RZWQ2 performance rating measures for each treatment scenario using the 4-year data and the present ambient CO_2 concentration of 410 ppm. Calibration treatments are the Control, Fertilizer, and 52 T Annual. Validation treatments are the 18 T Annual, 18 T Biennial, 36 T Annual, 36 T Biennial, and 52 T Biennial. Default denitrification parameters were used in RZWQM2, so there was no calibration for N_2O-N emissions.

	Treatment	Yield	Soil NO_3-N	Mineralization	Total N	Plant Uptake	N_2O Emissions	Soil H2O
PBIAS (%)	Control	-1.39	-44.13	10.88	3.67	-57.80	35.37	-8.26
	Fertilizer	1.10	--22.20	-4.77	6.39	-13.56	32.53	-8.66
	18 T Annual	0.23	-30.54	16.34	12.57	-13.77	-3.78	-5.86
	18 T Biennial	-0.62	-13.32	-21.10	16.20	-17.41	-	-7.21
	36 T Annual	0.80	-10.78	13.52	9.41	-0.46	-	-6.35
	36 T Biennial	-1.51	-27.83	21.25	9.29	-12.38	-1.43	-7.51
	52 T Annual	-1.76	-24.50	14.17	13.38	8.92	15.89	-3.73
	52 T Biennial	-4.49	-19.37	10.28	9.15	4.90	-	-5.45
	Calibration Treatments	-0.64	-27.83	9.74	8.60	-10.46	N/A	-6.83
	Validation Treatments	-1.08	-19.70	8.31	11.22	-6.91	-12.95	-6.47
RRMSE	Control	0.14	0.62	0.32	0.15	0.98	0.52	0.10
	Fertilizer	0.04	0.83	0.36	0.10	0.44	0.48	0.10
	18 T Annual	0.06	0.63	0.32	0.16	0.22	0.31	0.08
	18 T Biennial	0.03	0.42	0.61	0.17	0.33	-	0.08
	36 T Annual	0.06	0.55	0.45	0.12	0.14	-	0.08
	36 T Biennial	0.03	0.84	0.48	0.10	0.19	0.32	0.09
	52 T Annual	0.08	0.69	0.56	0.14	0.22	0.44	0.07
	52 T Biennial	0.08	0.62	0.51	0.13	0.07	-	0.07
	Calibration Treatments	0.09	0.78	0.59	0.14	0.44	N/A	0.09
	Validation Treatments	0.05	0.63	0.45	0.14	0.19	0.49	0.08
	Overall R^2	0.99	0.42	0.29	0.65	0.40	0.62	0.70

Table A2. Average minimum temperature, average maximum temperature, and average annual precipitation and the standard deviation for each GCM projections used in the RZWQM2 simulations.

	RCP4.5			RCP8.5		
GCM	Avg Min T°C	Avg Max T°C	Avg Precip (cm)	Avg Min T°C	Avg Max T°C	Avg Precip (cm)
access1-0.1	5.7 ± 7.6	20.8 ± 11.4	24.0 ± 4.8	7.8 ± 7.9	23.0 ± 11.8	24.2 ± 4.8
bcc-csm1-1.1	4.3 ± 7.7	18.9 ± 11.4	22.2 ± 4.8	6.7 ± 7.7	21.6 ± 11.8	23.2 ± 6.7
canesm2.1	5.7 ± 7.5	20.5 ± 11.1	29.4 ± 8.1	8.0 ± 7.8	22.9 ± 11.4	36.5 ± 9.6
canesm2.2	5.5 ± 7.6	20.2 ± 11.2	27.7 ± 5.4	8.0 ± 7.9	23.0 ± 11.4	33.7 ± 8.5
canesm2.3	5.8 ± 7.6	20.6 ± 11.2	29.2 ± 7.5	7.8 ± 8.1	22.7 ± 11.8	33.0 ± 7.1
canesm2.4	5.7 ± 7.6	20.4 ± 11.2	30.6 ± 8.0	7.8 ± 7.9	22.6 ± 11.5	37.0 ± 11.1
canesm2.5	5.7 ± 7.6	20.4 ± 11.2	28.7 ± 6.2	8.0 ± 7.7	22.9 ± 11.3	35.6 ± 8.4
ccsm4.1	4.7 ± 7.5	19.6 ± 11.1	24.9 ± 6.3	6.5 ± 7.9	21.6 ± 11.5	25.7 ± 7.1
ccsm4.2	4.4 ± 7.5	19.1 ± 11.0	27.0 ± 5.9	6.4 ± 7.9	21.5 ± 11.6	26.6 ± 5.9
cesm1-bgc.1	4.2 ± 7.5	19.1 ± 11.0	27.4 ± 5.8	6.5 ± 7.5	21.5 ± 11.2	31.0 ± 7.2
cnrm-cm5.1	5.1 ± 7.4	19.6 ± 11.0	28.3 ± 5.8	7.2 ± 7.5	21.8 ± 11.1	29.9 ± 5.4
csiro-mk3-6-0.1	5.3 ± 8.0	20.0 ± 11.4	25.9 ± 5.1	7.4 ± 8.7	22.4 ± 12.0	28.4 ± 8.8
csiro-mk3-6-0.2	5.2 ± 7.9	19.9 ± 11.3	28.2 ± 6.5	7.1 ± 8.6	22.0 ± 11.9	26.0 ± 6.4
csiro-mk3-6-0.3	5.3 ± 7.9	20.1 ± 11.2	24.4 ± 5.8	7.4 ± 8.6	22.3 ± 11.9	25.2 ± 6.0
csiro-mk3-6-0.4	5.3 ± 8.1	20.0 ± 11.5	25.7 ± 6.3	7.3 ± 8.8	22.2 ± 12.1	26.5 ± 6.0
csiro-mk3-6-0.5	5.2 ± 8.1	19.9 ± 11.5	24.9 ± 5.7	7.1 ± 8.7	22.0 ± 12.2	29.3 ± 6.5
csiro-mk3-6-0.6	5.1 ± 8.2	19.8 ± 11.5	25.5 ± 6.7	7.4 ± 8.8	22.3 ± 12.1	27.9 ± 7.0
csiro-mk3-6-0.7	5.2 ± 8.2	19.9 ± 11.6	23.6 ± 6.2	7.1 ± 8.7	22.2 ± 12.1	27.7 ± 7.4
csiro-mk3-6-0.8	5.1 ± 7.9	19.8 ± 11.3	27.0 ± 5.1	7.3 ± 8.6	22.2 ± 11.9	27.7 ± 4.6
csiro-mk3-6-0.9	4.8 ± 8.1	19.4 ± 11.5	26.7 ± 4.6	7.0 ± 8.8	21.9 ± 12.2	26.0 ± 6.4
csiro-mk3-6-0.10	5.3 ± 8.1	20.2 ± 11.6	26.3 ± 5.7	7.3 ± 8.9	22.3 ± 12.2	26.2 ± 5.8
gfdl-esm2g.1	4.0 ± 7.4	18.8 ± 11.2	28.1 ± 5.6	5.8 ± 7.5	21.0 ± 11.4	29.6 ± 9.3
gfdl-esm2m.1	3.4 ± 7.6	18.2 ± 11.3	26.1 ± 6.9	5.2 ± 7.6	20.3 ± 11.5	27.6 ± 5.9
inmcm4.1	3.8 ± 7.7	18.3 ± 11.6	24.2 ± 5.0	5.6 ± 8.1	20.1 ± 11.9	27.5 ± 6.2
ipsl-cm5a-lr.1	5.2 ± 7.9	20.0 ± 11.2	25.1 ± 7.2	8.0 ± 7.8	23.1 ± 11.1	30.5 ± 7.9
ipsl-cm5a-lr.2	5.2 ± 7.7	19.9 ± 11.0	27.2 ± 6.5	7.8 ± 7.9	22.7 ± 11.3	33.6 ± 7.9
ipsl-cm5a-lr.3	5.4 ± 7.5	19.9 ± 10.8	30.2 ± 6.7	7.9 ± 7.8	22.8 ± 11.2	32.4 ± 5.9
ipsl-cm5a-lr.4	5.4 ± 7.7	20.1 ± 11.0	29.8 ± 9.5	7.9 ± 7.8	22.8 ± 11.2	30.9 ± 6.8
ipsl-cm5a-mr.1	5.2 ± 7.9	20.0 ± 11.1	26.5 ± 6.4	7.9 ± 8.1	22.9 ± 11.4	27.2 ± 8.2
miroc-esm.1	6.1 ± 7.1	21.1 ± 10.6	27.5 ± 5.9	8.3 ± 7.5	23.5 ± 11.3	29.0 ± 5.9
miroc-esm-chem.1	6.0 ± 7.2	21.0 ± 10.7	29.2 ± 5.6	8.5 ± 7.4	23.9 ± 11.2	29.2 ± 5.3
miroc5.1	4.8 ± 7.5	20.1 ± 11.1	23.1 ± 4.7	6.7 ± 7.5	21.8 ± 10.9	25.2 ± 4.9
miroc5.2	4.6 ± 7.3	19.7 ± 10.7	25.8 ± 4.7	6.4 ± 7.4	21.7 ± 10.9	26.3 ± 5.4
miroc5.3	4.7 ± 7.3	19.7 ± 10.7	26.7 ± 5.8	6.6 ± 7.5	21.9 ± 10.9	26.6 ± 7.2
mpi-esm-lr.1	4.4 ± 7.7	18.8 ± 11.3	24.8 ± 6.1	6.7 ± 8.1	21.1 ± 11.7	28.7 ± 6.2
mpi-esm-lr.2	4.7 ± 7.6	19.1 ± 11.1	24.9 ± 6.4	7.0 ± 7.8	21.5 ± 11.6	26.7 ± 5.5
mpi-esm-lr.3	4.6 ± 7.7	19.1 ± 11.3	22.7 ± 6.8	6.9 ± 8.0	21.4 ± 11.8	24.5 ± 6.0
mpi-esm-mr.1	4.4 ± 7.6	18.7 ± 11.1	29.6 ± 6.3	6.5 ± 8.2	20.8 ± 12.0	27.7 ± 7.8
mri-cgcm3.1	4.0 ± 7.4	18.3 ± 10.9	26.0 ± 5.3	5.3 ± 7.8	19.6 ± 11.4	26.6 ± 3.8
noresm1-m.1	4.9 ± 7.6	19.9 ± 11.1	28.6 ± 8.5	6.7 ± 8.0	21.7 ± 11.7	31.0 ± 8.0

Table A3. Spring wheat yield results from multiple comparisons analysis where Pr > DSCF = 0.01 is represented by **, Pr > DSCF = 0.05 is represented by *, and '-' indicates no significant difference.

	Fert45	52TA45	Fert85	52TA85	FT45AMB	5245AMB	FT85AMB	5285AMB
	Median Yield (kg ha^{-1})							
A3.1. Spring Wheat	7062	7392	7054	7419	6928	7177	6536	6802
Fert45		**	-	**	-	-	**	**
52TA45			**	-	**	**	**	**
Fert85				**	*	-	**	**
52TA85					**	**	**	**
FT45AMB						**	**	-
5245AMB							**	**
FT85AMB								*
5285AMB								
A3.2. Potato	7049	7742	3403	3871	7160	7867	3367	3521
Fert45		**	**	**	-	**	**	**
52TA45			**	**	**	-	**	**
Fert85				-	**	**	-	-
52TA85					**	**	-	-
FT45AMB						**	**	**
5245AMB							**	**
FT85AMB								-
5285AMB								
A3.3. Spring Barley	12658	12538	15111	15083	10320	10115	9066	8873
Fert45		-	**	**	**	**	**	**
52TA45			**	**	**	**	**	**
Fert85				-	**	**	**	**
52TA85					**	**	**	**
FT45AMB						-	**	**
5245AMB							**	**
FT85AMB								-
5285AMB								
A3.4. Sugarbeet	19897	20687	17059	17521	19524	20249	16406	16530
Fert45		**	**	**	-	**	**	**
52TA45			**	**	**	**	**	**
Fert85				-	**	**	**	-
52TA85					**	**	**	**
FT45AMB						**	**	**
5245AMB							**	**
FT85AMB								-
5285AMB								

Table A4. Spring wheat yield results from multiple comparisons analysis where Pr > DSCF = 0.05 is represented by **, Pr > DSCF = 0.10 is represented by *, and '-' indicates no significant difference, n=7.

	FertHist	52TAHist	Fert538Hist	52TA538Hist	Fert936Hist	52TA936Hist
	Median Yield (kg ha^{-1})					
A4.1. Spring Wheat	6074	7508	6021	7761	5988	8075
FertHist		-	-	-	-	-
52TAHist			-	-	-	-
Fert538Hist				-	-	-
52TA538Hist					-	-
Fert936Hist						-
52TA936Hist						
A4.2. Potato	9584	10887	9489	10861	9465	10790
FertHist		-	-	-	-	-
52TAHist			-	-	-	-
Fert538Hist				-	-	-
52TA538Hist					-	-
Fert936Hist						-
52TA936Hist						
A4.3. Spring Barley	11344	11215	13293	13205	17091	17010
FertHist		-	-	-	**	**
52TAHist			-	-	**	**
Fert538Hist				-	*	*
52TA538Hist					*	*
Fert936Hist						-
52TA936Hist						
A4.4. Sugarbeet	20916	22777	21316	23274	21941	23799
FertHist		-	-	-	-	**
52TAHist			-	-	-	-
Fert538Hist				-	-	*
52TA538Hist					-	-
Fert936Hist						-
52TA936Hist						

Table A5. Median nitrogen mineralization in the soil profile for the 28-yr scenarios for spring wheat. Results are from multiple comparisons analysis where Pr > DSCF = 0.01 is represented by **, Pr > DSCF = 0.05 is represented by *, and '-' indicates no significant difference.

	Fert45	52TA45	Fert85	52TA85	FT45AMB	5245AMB	FT85AMB	5285AMB
	Median N Mineralization (kg ha^{-1})							
A5.1. Spring Wheat	165	881	153	911	151	872	156	879
Fert45		**	**	**	-	**	-	**
52TA45			**	-	**	-	**	-
Fert85				**	**	**	**	**
52TA85					**	-	**	-
FT45AMB						**	-	**
5245AMB							**	-
FT85AMB								**
5285AMB								
A5.2. Potato	156	885	152	909	150	874	138	880
Fert45		**	-	**	-	**	-	**
52TA45			**	-	**	-	**	-
Fert85				**	**	**	**	**
52TA85					**	**	**	*
FT45AMB						**	-	**
5245AMB							**	-
FT85AMB								**
5285AMB								
A5.3. Spring Barley	137	998	146	1065	135	989	137	1035
Fert45		**	**	**	-	**	-	**
52TA45			**	**	**	-	**	-
Fert85				**	**	**	*	**
52TA85					**	**	**	-
FT45AMB						**	-	**
5245AMB							**	-
FT85AMB								**
5285AMB								
A5.4. Sugarbeet	142	998	152	984	139	994	141	953
Fert45		**	-	**	-	**	-	**
52TA45			**	-	**	-	**	*
Fert85				**	*	**	**	**
52TA85					**	-	**	-
FT45AMB						**	-	**
5245AMB							**	-
FT85AMB								**
5285AMB								

Table A6. Median nitrogen seepage from the soil profile for the 28-yr scenarios for spring wheat. Results are from multiple comparisons analysis where Pr > DSCF = 0.01 is represented by **, Pr > DSCF = 0.05 is represented by *, and '-' indicates no significant difference.

	Fert45	52TA45	Fert85	52TA85	FT45AMB	5245AMB	FT85AMB	5285AMB
	Median N Seepage (kg ha^{-1})							
A6.1. Spring Wheat	18	719	32	975	14	633	20	668
Fert45		**	**	**	**	**	-	**
52TA45			**	*	**	-	**	-
Fert85				**	**	**	**	**
52TA85					**	**	**	*
FT45AMB						**	**	**
5245AMB							**	-
FT85AMB								**
5285AMB								
A6.2. Potato	15	271	22	314	13	274	20	362
Fert45		**	**	**	-	**	**	**
52TA45			**	-	**	-	**	**
Fert85				**	**	**	-	**
52TA85					**	-	**	-
FT45AMB						**	**	**
5245AMB							**	**
FT85AMB								**
5285AMB								
A6.3. Spring Barley	15	218	23	298	15	255	29	424
Fert45		**	**	**	-	**	**	**
52TA45			**	-	**	-	**	**
Fert85				**	**	**	*	**
52TA85					**	-	**	**
FT45AMB						**	**	**
5245AMB							**	**
FT85AMB								**
5285AMB								
A6.4. Sugarbeet	21	813	23	593	21	802	28	480
Fert45		**	-	**	-	**	**	**
52TA45			**	**	**	-	**	**
Fert85				**	-	**	-	**
52TA85					**	**	**	-
FT45AMB						**	**	**
5245AMB							**	**
FT85AMB								**
5285AMB								

Table A7. Median water seepage from the soil profile for the 28-yr scenarios for spring wheat. Results are from multiple comparisons analysis where Pr > DSCF = 0.01 is represented by **, Pr > DSCF = 0.05 is represented by *, and '-' indicates no significant difference.

	Fert45	52TA45	Fert85	52TA85	FT45AMB	5245AMB	FT85AMB	5285AMB
	Median Deep Seepage (cm)							
A7.1. Spring Wheat	9.7	11.4	12.6	14.9	8.0	9.8	7.5	9.7
Fert45		**	**	**	**	-	**	-
52TA45			-	**	**	*	**	**
Fert85				**	**	**	**	**
52TA85					**	**	**	**
FT45AMB						**	-	*
5245AMB							**	-
FT85AMB								**
5285AMB								
A7.2. Potato	5.1	5.8	6.3	7.1	4.6	5.1	4.8	5.5
Fert45		*	*	**	*	-	-	-
52TA45			-	**	**	-	**	-
Fert85				*	**	**	**	**
52TA85					**	**	**	**
FT45AMB						*	-	**
5245AMB							-	-
FT85AMB								*
5285AMB								
A7.3. Spring Barley	5.5	6.5	7.7	8.7	5.3	6.4	6.5	7.8
Fert45		*	**	**	-	-	*	**
52TA45			**	**	**	-	-	*
Fert85				-	**	**	*	-
52TA85					**	**	**	-
FT45AMB						**	**	**
5245AMB							-	**
FT85AMB								*
5285AMB								
A7.4. Sugarbeet	14.4	16.4	12.0	12.8	12.7	14.4	7.6	8.7
Fert45		-	**	-	*	-	**	**
52TA45			**	**	**	*	**	**
Fert85				-	-	**	**	**
52TA85					-	-	**	**
FT45AMB						-	**	**
5245AMB							**	**
FT85AMB								-
5285AMB								

Table A8. Median N_2O-N emissions from the soil surface for the 28-yr scenarios for spring wheat. Results are from multiple comparisons analysis where Pr > DSCF = 0.01 is represented by **, Pr > DSCF = 0.05 is represented by *, and '-' indicates no significant difference.

	Fert45	52TA45	Fert85	52TA85	FT45AMB	5245AMB	FT85AMB	5285AMB
	Median N_2O Emission (kg ha^{-1})							
A8.1. Spring Wheat	0.69	24.18	0.81	28.44	0.69	23.22	0.79	25.18
Fert45		**	**	**	-	**	-	**
52TA45			**	**	**	-	**	-
Fert85				**	**	**	-	**
52TA85					**	**	**	-
FT45AMB						**	-	**
5245AMB							**	-
FT85AMB								**
5285AMB								
A8.2. Potato	1.31	30.71	1.43	31.21	1.31	29.97	1.42	29.79
Fert45		**	**	**	-	**	**	**
52TA45			**	-	**	-	**	-
Fert85				**	**	**	-	**
52TA85					**	-	**	-
FT45AMB						**	**	**
5245AMB							**	-
FT85AMB								**
5285AMB								
A8.3. Spring Barley	0.94	21.65	1.10	24.00	0.94	21.58	1.13	23.91
Fert45		**	**	**	-	**	**	**
52TA45			**	-	**	-	**	-
Fert85				**	**	**	-	**
52TA85					**	-	**	-
FT45AMB						**	**	**
5245AMB							**	-
FT85AMB								**
5285AMB								
A8.4. Sugarbeet	0.77	28.51	0.82	30.95	0.77	28.01	0.80	30.12
Fert45		**	*	**	-	**	-	**
52TA45			**	-	**	-	**	-
Fert85				**	*	**	-	**
52TA85					**	-	**	-
FT45AMB						**	**	**
5245AMB							**	-
FT85AMB								**
5285AMB								