Agricultural Water Management 152 (2015) 198–206

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Adaptation of water and nitrogen management to future climates for sustaining potato yield in Minnesota: Field and simulation study

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ARTICLE INFO

Article history:
Received 5 February 2014
Accepted 15 January 2015
Available online 9 February 2015

Keywords:
Climate change
Potato yield
Water use efficiency
Water and nitrogen stress
NO_3 leaching

ABSTRACT

The present study focuses on (i) evaluation of potato crop yield under present time slice (PTS) with recommended management of nitrogen (N) fertilizer and irrigation on sandy soils of Minnesota, USA (ii) simulation of potato productivity and nitrate leaching with the SUBSTOR DSSAT-potato model in a projected future climatic environment (2038–2067) and (iii) evaluation of alternative irrigation and N management strategies with the DSSAT model as adaptation measures to minimize climate change impacts. Ensemble global climate model output for each of three future mid-century (MC) 10-years time slices of crop growing season predicts increases in maximum temperature (T_{max}) of 0.7, 1.2 and 2.1 °C; and in minimum temperature (T_{min}) of 0.6, 1.3 and 2.0 °C in MC1 (2038–2047), MC2 (2048–2057) and MC3 (2058–2067), respectively, during the tuber bulking periods. Rainfall (RF) of 253.1 mm in PTS decreased by 29.7, 16.7 and 6.5 mm in MC1–MC3, respectively. Under the changed climate, simulations indicated decreases in potato yields of 19–29%, harvest index of 4–9% and water use efficiency of 22–32% compared with current irrigation and fertilizer rates (260 mm irrigation, 270 kg ha^{-1} N fertilizer). Potato yields could be sustained at present levels by increasing irrigation levels to 390 mm, with 450 kg ha^{-1} N in the years 2038–2047; and 326 and 390 mm irrigation with 450 kg N ha^{-1} in year 2048–2057. However, leaching losses in 2048–2057 would increase (relative to current losses) by 34–62%. In the years 2058–2067 yield in the region evaluated can no longer be sustained with increased N and irrigation levels and leaching losses would increase by 41–67%. Use of varieties tolerant to drought and heat or adapting alternative cultural practices will be required to maintain productivity.

1. Introduction

The increasing concentration of CO_2 and other green house gases has resulted in a 0.74 ± 0.18 °C rise in global average temperature over the past 100 years (Trenberth and Jones, 2007). Eleven of the last twelve years (1995–2006) rank among the twelve warmest years in the recorded weather records of global temperature since 1850 (IPCC, 2007). Winter temperatures have increased more rapidly than summer temperatures, and night time T_{min} have increased more than the daytime T_{max}. The Special Report on Emissions Scenarios (SRES) predicted that in an A2 emissions scenario (a future scenario in which the world remains divided into independently operating self reliant nations, population continuously increases, and economic development is regionally oriented) the atmospheric concentration of CO_2 would increase to approximately double present values (380 ppm), which would increase global average surface temperature by 2.0 °C to 5.4 °C (Nakicenovic et al., 2000). A rise in global average temperature will lead to changes in weather patterns (temperature and precipitation) that affect crop growth.

Potatoes are an important staple food worldwide and Minnesota ranks 7th in U.S. for potato (*Solanum tuberosum* L.) production. In 2010, irrigated potato production in reportedly covered an area of 18,000 ha (NASS, 2010). This region has ample supplies of surface and groundwater that are used for irrigation. The crop is mainly grown on coarse textured soils low in organic matter, cation exchange capacity and soil nutrient reserves. The inherently low soil fertility and high nutrient requirement of the crop (Dean, 1994) necessitates high inputs of fertilizer in this region. High N input, high hydraulic conductivity of the soil and the shallow rooting system of irrigated potato crop collectively make for conditions conducive to the leaching of nitrate–nitrogen (NO_3–N)

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http://dx.doi.org/10.1016/j.agwat.2015.01.011
0378-3774/

which results in low nutrient use efficiency (Lynch et al., 2012; Rosen and Bierman, 2008; Zebarth and Rosen, 2007; Zvomuya et al., 2003). It is hypothesized that with future increases in temperature, potato yield in this region may decrease without changes in irrigation and N fertilizer management (Haverkort and Verhagen, 2008). The implementation of increased irrigation and fertilizer to cope with the adverse effects of elevated temperature could however lead to greater NO_3–N leaching losses, leading to worsening ground water quality. To sustain crop yield and minimize NO_3–N leaching in the future, it is important to understand the magnitude of climate change and its impact on the productivity of potatoes and leaching of NO_3–N as adjustments in irrigation and N fertilization are made. The impact of elevated temperature and CO_2 under climate change scenarios are often studied using free air carbon dioxide enrichment experiments (FACE), open top chamber (OTC) and temperature gradient tunnel (TGT) experiments, but these are very costly. Alternately crop simulation models are used to study the integrated effect of climate parameters (T_{max}, T_{min}, RF, relative humidity, solar radiation, and CO_2 concentration) on crop growth, biomass, water balance, and N balance on a daily basis. A number of crop models in cropping systems (DSSAT, CropSyst) are available in the literature. In this study we chose to use SUBSTOR-Potato model with the decision support system of agrotechnology transfer (DSSAT) to evaluate effects of changing climate on potato production, because this model is able to accurately assess the effects of changes in CO_2 and climate parameters on potato growth, biomass, and water or nitrogen balances on a daily basis (Arora et al., 2013; Griffin et al., 1993; Jones et al., 2003). Before using any model, there is a prerequisite that model performance should be tested on the data observed under field conditions.

The present study was undertaken with the objectives to (i) evaluate yield of potato crop under present time slice with recommended management of N fertilizer and irrigation and calibration of the model, (ii) simulate potato productivity in a projected future climatic environment and (iii) evaluate alternative irrigation and N management strategies as adaptation measures to minimize climate change impacts.

2. Materials and methods

The approach used in this study involved calibration and validation of the SUBSTOR-potato crop model of DSSAT using field measurements, and acquisition of the future climate data from five climate models generated by the North America Regional Climate Change Assessment Program (NARCCAP). The projected climate data on T_{max}, T_{min} and RF from the selected climate models and CO_2 from the Bern model were employed in the calibrated and validated crop model. Simulations were run yearly. Tuber yield, water and N stress, and N leaching were simulated for three future time slices viz. 2038–2047, 2048–2057 and 2058–2067.

2.1. Field study site, climate, and design

Accurate modeling of potato productivity depends on proper model calibration and validation of the using field measurements. A field study involving irrigated potato production was carried out over two years (2010 and 2011) at the University of Minnesota Sand Plain Research Farm (45°23′N, 95°53′W) near Becker, MN. The soil at this site is classified as excessively drained Hubbard loamy sand (sandy, mixed, frigid Typic Hapludoll) comprised of 85% sand, 9% silt, and 6% clay. The available water holding capacity in the top 1.2 m of soil is 100 mm. Soil physical and chemical properties were determined up to a 120 cm depth (Table 1) following standard procedures. The sand, silt and clay contents were determined with pipette method (Gee and Bauder, 1986), bulk density with core method (Blake and Hartage, 1986) and hydraulic conductivity with constant head method (Jalota et al., 1998). pH with potentiometric method (Jackson, 1973) and OC by wet digestion method (Walkley and Black, 1934). Nitrate–N was determined by Kjeldahal method (Keeney, 1982).

Table 1
Soil profile characteristics of the experimental site.

Depth	Sand (%)	Clay (%)	FC	PWP	BD	OC (%)	pH
15	85	6	0.13	0.04	1.54	1.45	6.8
30	85	6	0.12	0.04	1.59	1.16	6.4
45	86	6	0.08	0.03	1.62	1.16	6.4
60	92	4	0.08	0.03	1.63	0.87	6.2
90	98	0	0.05	0.01	1.65	0.29	6.2
120	99	0	0.05	0.01	1.66	0.29	6.2

FC—field capacity ($m^3 m^{-3}$); PWP—permanent wilting point ($m^3 m^{-3}$); BD—bulk density (mg m^{-3}); OC—organic carbon (%).

The experiment was conducted in quadruplicate using plot sizes of 13.7 m × 6.3 m with randomized complete block design having split plot restrictions on randomization. The potato variety Russet Burbank, which has a 111–120 days duration (Whitworth et al., 2011), was planted on April 16 in 2010 and April 29 in 2011. This is the most commonly planted potato variety for processing in Minnesota. Irrigation water was applied with an overhead sprinkler at 320 mm in 2010 and 260 mm in 2011 and scheduled based on the check book water balance method (Nigon, 2012). The planting times and irrigation levels were different in both years due to variation in weather conditions. A total of 270 kg ha^{-1} N fertilizer was applied; 158 kg ha^{-1} was applied as pre-emergence (34 kg ha^{-1} at planting through mono-ammonium phosphate +124 kg ha^{-1} at two day after emergence through urea) and 112 kg ha^{-1} as post-emergence (applied four times as mixture of urea and ammonium nitrate in 2010 and five times as a mixture of urea and ammonium nitrate by spray boom and tractor in 2011). Chemicals were applied during the season for control of pests, diseases and weeds as per recommended practice in the region (Engel et al., 2012). In both the 2010 and 2011 studies the previous crop was non-irrigated cereal rye (*Secale cereal* L.). Over the 30 years period from 1971 to 2000, temperature and rainfall during the growing season (April–September) averaged 16.5 °C and 550 mm, respectively. Vines were mechanically killed and tubers were mechanically harvested from the third and fourth rows from the alley in each treatment plot approximately 1–2 weeks after the vines were killed. Tubers were sorted into weight classes for total and graded yield. Grade 'A' yield was determined by subtracting undersized tuber yields (85 g) from the total yield. To determine N lost due to leaching, water samples from below the rooting zone were collected at a depth of 1.2 m using suction cup lysimeters according to the methods of Venterea et al. (2011). Water samples were collected on 22 dates in 2010 and 28 dates in 2011. Daily rates of nitrate leaching were calculated according to the methods of Errebhi et al. (1998).

2.2. Climate change scenario data

Weather data were observed daily from 1980 to 2010 for RF, T_{max} and T_{min} at the meteorological observatory on the Sand Plain Research Farm, near Becker, MN compiled and used as a baseline for the present time slice (PTS) in this study. Climate data modeled at daily intervals from 1980 to 1998 and mid-century (MC) data for T_{max}, T_{min} and RF for 2038–2067 under an A2 emission scenario were taken from the North America Regional Climate Change Assessment Program (NARCCAP) for five climate models viz. Canadian Regional Climate Model–Community Climate System Model (CRCM–CCSM), Canadian Regional Climate Model–Coupled General Circulation Model version 3 (CRCM–CGCM3), Regional