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Assessing the impact of irrigation and nitrogen management on potato performance under varying climate in the state of Florida, USA

Andre Luiz Biscaia Ribeiro da Silva [a,1], Henrique Boriolo Dias [b,*], Rishabh Gupta [a], Lincoln Zotarelli [a], Senthold Asseng [b,2], Michael D. Dukes [b,c], Cheryl Porter [b], Gerrit Hoogenboom [b,d]

[a] Horticultural Sciences Department, University of Florida, Gainesville, FL 32611, United States
[b] Department of Agricultural and Biological Engineering, University of Florida, Gainesville, FL 32611, United States
[c] Center for Land Use Efficiency, University of Florida, Gainesville, FL 32611, United States
[d] Global Food Systems Institute, University of Florida, Gainesville, FL 32611, United States

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ABSTRACT

Optimizing irrigation and nitrogen (N) fertilizer management in irrigated potato crops grown on sandy soils in subtropical regions such as in northeastern Florida, USA is essential to sustain a high yield and to minimize leaching. N applications in this region typically occur at approximately 25–30 days prior to planting (N_{pre}), at emergence (N_{eme}), and at tuber initiation (N_{ti}). However, recent studies suggest that applying N near planting (N_{pl}) enhances fertilizer N use efficiency (FNUE). We combined experimentation with modeling to assess irrigation and N management options for potato in northeastern Florida. We first aimed to evaluate the DSSAT/CSM-SUBSTOR-Potato model using two-year irrigated field experiments conducted on sandy soils with variable N rates and application timings. CSM-SUBSTOR-Potato accurately simulated aboveground plus tuber dry weight [Relative root mean squared error (RRMSE) = 26.4%, Willmott's index (d) = 0.98] and N accumulation (RRMSE = 28.6%, d = 0.97). Soil moisture and mineral N were captured well overall, but they were often underestimated due to a water table influence that is currently not considered in DSSAT. Subsequently, CSM-SUBSTOR-Potato was applied to simulate tuber yield, N leaching, and FNUE under scenarios of irrigation scheduling and N-fertilizer application (rate/timing) strategies, focusing on N_{pre} versus N_{pl} aiming to improve resource use efficiency. The simulations indicated that a target of 60% and 70% of the available soil water can be safely used as an irrigation strategy to achieve a high yield, while reducing irrigation water applied and N leached to the environment. Overall N_{pl} increased crop N uptake by 10%, tuber yield by 7%, reduced N leached by 13%, and consequently increasing FNUE by 9%, compared to N_{pre} across the irrigation treatments. Thus, N_{pl} should be preferred in sandy soils and climate-risky subtropical environments, along with N_{eme} and N_{ti} as key timings to synchronize N supply with potato growth.

1. Introduction

Worldwide the inadequacies of fresh water used in irrigation practices and the excessive application of fertilizer in seeking potential crop yield have been constraining agricultural growth. In subtropical regions, frequent heavy rainfall events induce soil nutrient loss (Hendricks and Shukla, 2011), such as nitrogen (N). Thus, over-fertilization is a common practice to compensate for N losses in response to the subtropical weather variability. Due to the shallow root zone, potato (*Solanum tuberosum* L.) may have low N fertilizer use efficiency if timing and rate of application do not match the plant uptake curve, which can substantially increase the potential of N loss to the environment (Milroy et al., 2019; Rens et al., 2016; Wang et al., 2020).

The state of Florida, USA, which is located in a subtropical region,

* Corresponding author.
E-mail address: henrique.boriolo@ufl.edu (H.B. Dias).
[1] Present address: Department of Horticulture, Auburn University, Auburn, AL 36849, United States of America
[2] Present address: Technical University of Munich, School of Life Sciences, Department of Life Science Engineering, Chair of Digital Agriculture, HEF World Agricultural Systems Center, Freising 85354, Germany

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contributes to approximately 31% of national spring potato production with an average yield of 29.7 Mg ha^{-1} (USDA, 2023). Research focused on best management practices (BMP) for potato production in Florida's subtropical agricultural areas has highlighted the importance of combining N rate and application timing with irrigation management to minimize the risk of N leaching and to maintain potato yield (Alva et al., 2012; da Silva et al., 2023; Rens et al., 2018, 2015; Zotarelli et al., 2014). In general, splitting N fertilizer applications is key to mitigate soil N losses and to reduce the N rate applied in sandy soils, increasing the soil N availability for plant uptake during the potato season.

The application of N fertilizer by growers typically occurs three times during the potato growing season: prior to planting (N_{pre}), at emergence (N_{eme}) and at tuber initiation (N_{ti}) (Asci et al., 2015). Under northeast Florida conditions, the N fertilizer application at N_{pre}, around 25–40 days prior to planting, has been considered a risk because the long exposure of N fertilizer in the soil increases the potential for N leaching (Zotarelli et al., 2014). da Silva et al. (2018b, 2023) investigated yield and crop development response for varying rates of N fertilizer applied at planting (N_{pl}), N_{eme}, and N_{ti} to match the application rate with crop growth. Applying N fertilizer at planting resulted in a higher fertilizer N uptake efficiency of 18% (da Silva et al., 2018b) compared to 11% of N_{pre} reported by Rens et al. (2016) using labeled N forms. The application timings of N_{eme} and N_{ti} fertilizers, specifically during tuber initiation and mid-bulking stages, are considered optimal for tuber yield. This is attributed to the exponential N uptake by potatoes during these stages, as indicated by Alva (2004) and Zotarelli et al. (2015), (2014). These findings align with the results of Rens et al. (2018), highlighting that the highest tuber yields are attained when applying N rates of 114–138 kg ha^{-1} at crop emergence.

Although the N fertilizer application timing and rate have an important role on soil N availability during potato growth and tuber bulking, irrigation practices should be taken into account to mitigate the N losses (Alva, 2008). During the last 10 years, sprinkler irrigation has been adopted by Florida potato growers to improve agricultural water conservation replacing a commonly used sub-irrigation method, termed as seepage irrigation. Seepage irrigation uses groundwater distributed to furrows to supply water to the crop root zone through an upward soil water flux from the water table, which requires large volumes of water applied to maintain the desired levels (~35 cm below the soil surface) (Dukes et al., 2010). In contrast, sprinkler is characterized by high water application efficiency (70–90%) that can minimize excessive water requirements (Dukes and Perry, 2006). Despite requiring less water compared to other irrigation methods, sprinkler irrigation is characterized by its potential to promote soil N leaching due to the downward soil water flux created after irrigation events (da Silva et al., 2018a). Only a few studies so far have reported the effect of sprinkler irrigation on tuber yield in Florida sandy soils (da Silva et al., 2023; Liao et al., 2016). However, there is still insufficient information regarding the effect of irrigation management on tuber yield and its long-term impact on soil N leaching.

In addition to the influence of local weather conditions, particularly rainfall, soil water management has a significant impact on how N behaves and moves within the soil, therefore, it affects the tuber yield response (Alva, 2008). Consequently, it is crucial to implement optimal management practices for both water and N to enhance uptake efficiencies while reducing the loss through leaching. One way to understand all these interactions is by using dynamic cropping simulation models or simply crop models. Crop models can be used as a tool to support strategies to optimize management and minimize the impact of climate variability and change (Ahuja et al., 2022; Boote et al., 1996; Tsuji et al., 1998). The crop model should describe the specific growth and development as a function of genotype, management, weather, and soil conditions for potato (Haverkort and Top, 2011). Once a model has been calibrated and evaluated, it can be used in support of analysis and interpretation of field experiments, for extrapolation of experimental results over a wider range of management practices and weather conditions towards efficient use of water and N, for example (Ahuja et al., 2022; Boote et al., 1996; Tsuji et al., 1998).

Currently, there are around 35 potato models and their variations available for crop model users, however, less than half of those models (14) include the water and N routines in their structure (Fleisher et al., 2017; Islam and Li, 2023; Raymundo et al., 2014). The Cropping System Model (CSM)-SUBSTOR-Potato (Griffin et al., 1993; Singh et al., 1998) of the Decision Support System for Agrotechnology Transfer (DSSAT; Hoogenboom et al., 2019a; Jones et al., 2003), is one of the most widely used crop models for simulating potato production systems worldwide. The model has been successfully applied to perform yield gap analysis, to explore water and N management scenarios and to assess the impact of climate variability and change on a range of different potato cropping systems (Arora et al., 2013; Bender and Sentelhas, 2020; Fleisher et al., 2021; Grados et al., 2020; Prasad et al., 2015; Raymundo et al., 2018; Tooley et al., 2021; Wang et al., 2023; Woli et al., 2016; Woli and Hoogenboom, 2018).

Using the CSM-SUBSTOR-Potato model to simulate coarse-textured soils in a subtropical environment can provide valuable information on crop growth, tuber yield, N uptake, and N leaching under different management scenarios of water demand and N fertilizer application timing and rate. The outputs of crop models assist with the development and validation of BMP for irrigation and N fertilization strategies for the potato crop according to a historical weather dataset. In this context, the objectives of this study were: i) to evaluate the performance of the CSM-SUBSTOR-Potato model to simulate plant growth and N dynamics, soil water content and mineral N using data from field trials with varied N rate and timing treatments under sprinkler irrigation and; ii) to identify irrigation and N fertilizer strategies that reduce N leaching and optimize potato tuber yield for sandy soils in a subtropical environment using historical weather data.

2. Material and methods

2.1. Experimental trials and data collection

A detailed description of the experiments that were used for model calibration and evaluation is provided in detail by da Silva et al. (2018a, 2023) and the main features of the experiments are briefly described here. Field experiments were conducted at the Hastings Agricultural and Extension Center, Institute of Food and Agricultural Science - University of Florida, located in Hastings, FL (29.690531 N, 81.441505 W). Potato was grown during the spring of 2015 and 2016. On 29 January of both years, potato seed pieces of cultivar "Atlantic" were planted in an area 76 m long and 18 m wide, comprised of 16 potato rows spaced 1 m with in-row seed spacing of 20 cm. Planting date expresses zero days after planting (DAP) and any crop management before planting was expressed with negative DAP. Potato tubers were harvested on 8 May 2015 and 7 May 2016.

The N fertilizer treatments combined three fertilizer application timings (N_{pl}, N_{eme}, N_{ti}) and fertilizer N rates (three at N_{pl}, two at N_{eme}, and two at N_{ti}), a total of 12 treatments replicated four times. The N fertilizer used for all treatments was a granular ammonium nitrate (34% of N). N applications at N_{pl} occurred at −2 and −4 DAP for 2015 and 2016, respectively, and treatment plots received rates of 0, 56, or 112 kg ha^{-1} of N. At N_{eme}, N fertilizer was applied 23 and 21 DAP for 2015 and 2016, respectively and N rates were 56 or 112 kg ha^{-1}. At N_{ti} (last N application), 56 or 112 kg ha^{-1} of N was applied 47 and 46 DAP in 2015 and 2016, respectively. The total N rates ranged from 112 and 336 kg ha^{-1} (Table 1). In both years, all experimental plots received 112 kg ha^{-1} of P_2O_5 and 112 kg ha^{-1} of K_2O at planting and an additional 85 kg ha^{-1} of K_2O was also applied at tuber initiation. All fertilizer applications were banded using a four-row hydraulic fertilizer applicator.

Water application during the crop development was performed by a linear move irrigation machine (Zimmatic by Lindsay Corporation, City,

Table 1
Nitrogen fertilizer rates applied at planting (N_{pl}), at plant emergence (N_{eme}), and at tuber initiation (N_{ti}), total N applied and timing of application to the experimental fields of 2015 and 2016 in northeast Florida agricultural conditions. Note: treatments were used for the CSM-SUBSTOR-Potato model evaluation.

Treatments	N_{pl}	N_{eme}	N_{ti}	Total N applied
	N rate (kg ha^{-1})			
1	0	56	56	112
2	0	56	112	168
3	0	112	56	168
4	0	112	112	224
5	56	56	56	168
6	56	56	112	224
7	56	112	56	224
8	56	112	112	280
9	112	56	56	224
10	112	56	112	280
11	112	112	56	280
12	112	112	112	336

NE, USA). The timing and volume of the irrigation application were determined according to the soil moisture status, in which the volumetric soil water content (VWC) was maintained between 0.11 and 0.18 cm^3 cm^{-3} in the first 20 cm of soil depth. The VWC was recorded using time domain reflectometry (TDR) sensors (CS650, Soil Water Content Reflectometer, Campbell, Scientific Inc., Logan, UT, USA). The TDR sensors were installed in the center of a bed at 38 and 39 DAP for the 2015 and 2016 potato season, respectively. Soil water probes were installed horizontally in the soil profile at 15, 30 and 45 cm of depth below the soil surface. The VWC data were recorded every 15 min and data were aggregated to daily time step to be used in the modeling work. Soil samples were collected five times during each season, and soil mineral N [nitrate N (NO_3-N) and ammonium N (NH_4-N)] content at 0–15, 15–30 and 30–60 cm of soil depth layers were determined.

Crop phenological stages were monitored through bi-weekly field evaluations, and plant biomass was sampled at four stages of crop development: plant emergence (28 and 38 DAP for 2015 and 2016, respectively), tuber initiation (42 and 52 DAP for 2015 and 2016, respectively), tuber maturation (82 and 73 DAP for 2015 and 2016, respectively) and at harvest (97 and 89 DAP for 2015 and 2016, respectively). A sample consisted of two representative potato plants separated in aboveground tissue and tubers. Subsequently, samples were oven dried at 65 °C to a constant weight and submitted for total N Kjeldahl analysis.

2.2. Weather and soil data

The climate of the studied region ranges from warm to hot, with wet summers and cool and wet winters. The climate is classified as Cfa (humid subtropical climate) according to Köppen's classification system. During the experimental trials, the weather conditions of solar radiation, maximum and minimum air temperature, relative air humidity, wind speed and precipitation were measured every 15 minutes using an automated weather station (UT30, Campbell, Scientific Inc. Logan, UT, USA) from the Florida Automated Weather Network (FAWN – http://fawn.ifas.ufl.edu/). The data were summarized into daily data as input for the crop model.

A summary of the weather conditions in the experimental years compared to historical records (2000–2023) is presented in Fig. 1. The cumulative precipitation in 2016 (294 mm) was higher than 2015 (176 mm) and included a large rainfall event (60 mm d^{-1}) shortly after planting in 2016. Solar radiation during the growing season was also higher in 2016 (1767 MJ m^{-2}) compared to 2015 (1571 MJ m^{-2}), suggesting that although receiving less rainfall, 2015 was cloudier. Air temperature averaged around 18.5 °C for both seasons, while cumulative thermal time for potato growth (following Griffin et al., 1993) was also relatively similar, with roughly 90 °C d accumulated from planting

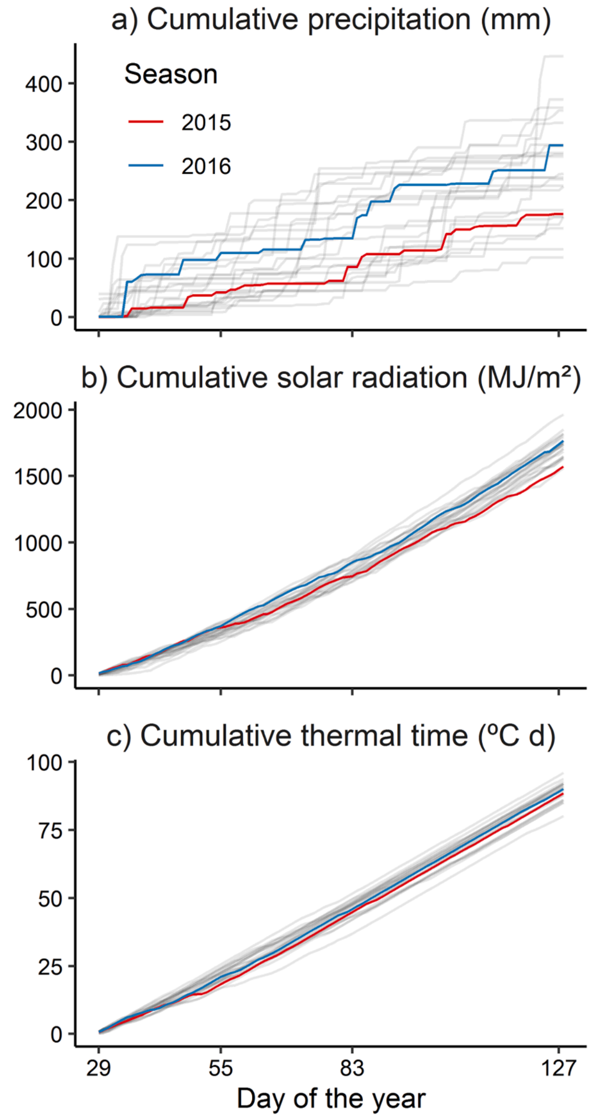

Fig. 1. Weather conditions of the 2015 and 2016 potato seasons (29 January to 8 May, expressed as day of the year), including cumulative precipitation (a, mm), cumulative solar radiation (b, MJ m^{-2}), and cumulative thermal time (c, °C d) over the season. Grey lines represent the corresponding cumulative value for each day of the year from historical records (2000–2023). The labels in x-axis correspond to planting and around emergence, tuber initiation and harvest for both experimental years. Data recorded at 15 min intervals and retrieved from the Florida Automated Weather Network (FAWN) at the University of Florida, Hastings Agricultural Extension Center (HAEC) in Hastings, FL, USA. Thermal time was based on CSM-SUBSTOR function for vine growth with cardinal temperatures of 2, 17, 24 and 35 °C.

to harvest in both years. Overall, weather in 2015 and 2016 seasons were within the historical ranges, with the only exception being cumulative radiation for 2015 which was close to the lower historical range after tuber initiation stage.

The soil of the experimental area was classified as sandy, siliceous, hyperthermic Arenic Ochraqualf belonging to the Ellzey series (Soil Survey Staff, 2017). The particle size distribution along the soil profile (0–60 cm) was 916, 26.3, and 57.7 g kg^{-1} for sand, silt, and clay, respectively. The soil has a very poorly drainage capacity due to a shallow impermeable soil horizon that ranges from a depth of 150–300 cm (Matson and Sanford, 1913). Soil properties used in the simulations were obtained and adapted from previous local measurements (Table 2).

Table 2
Soil profile properties used in the simulations.

Soil property, unit	Soil depth layer (cm)			
	0–15	15–30	30–45	45–60
Soil organic carbon, %	0.30	0.28	0.38	0.12
Bulk density, g cm^{-3}	1.36	1.49	1.53	1.53
Lower limit, cm^3 cm^{-3}	0.03	0.03	0.03	0.03
Drained upper limit, cm^3 cm^{-3}	0.15	0.20	0.25	0.30
Soil water content at saturation, cm^3 cm^{-3}	0.42	0.42	0.40	0.40
Saturated hydraulic conductivity, cm h^{-1}	8.90	14.80	33.20	33.20
Root growth factor, 0.0–1.0	1.00	0.50	0.10	0.01
Initial soil water content, cm^3 cm^{-3}	0.12	0.15	0.30	0.30
Average soil mineral nitrogen, g Mg^{-1}				
Season 2015	7.09	3.99	7.01	1.00
Season 2016	6.23	3.74	1.97	1.00

2.3. The CSM-SUBSTOR-Potato model

The Simulation of Underground Bulking Storage Organs (SUBSTOR) model was developed for aroids (taro and tanier) and potato (Griffin et al., 1993; Singh et al., 1998). Recently, the model received changes to better account for responses to elevated atmospheric CO_2 and high temperature under a changing climate (Raymundo et al., 2018). SUBSTOR-Potato is one of the crop modules in CSM framework of the DSSAT (Hoogenboom et al., 2019a; Jones et al., 2003), currently in its version 4.8.2 (Hoogenboom et al., 2023) which is the version we used in this study.

Briefly, CSM-SUBSTOR-Potato is a process-based simulation model designed for simulating potato crop development, growth, and yield on a daily time scale as affected by environment (weather and soil properties), genotype and management practices. Crop development is divided into five phenological stages: (i) pre-planting, (ii) planting to sprout germination, (iii) sprout germination to emergence, (iv) emergence to tuber initiation, and (v) tuber initiation to maturity. Development, growth, and yield rely on various cultivar-specific parameters, such as potential leaf and tuber growth rates, determinacy, factors related to photoperiod and both soil and air temperature effects on emergence and tuber initiation.

The model calculates daily potential carbon fixation using two radiation use efficiencies (before and after tuber initiation) that rely on the intercepted photosynthetically active radiation (using Monsi and Saeki's approach) and are adjusted according to the plant density and leaf area index. Soil water and N (as a function of leaf N concentration) stress factors, along with atmospheric CO_2 and temperature-specific response functions, determine the crop biomass accumulation. The model also accounts for atmospheric CO_2 effects on stomatal resistance and transpiration efficiency. Leaf area index is derived from potential leaf area, determined by leaf dry weight and specific leaf area. Leaf area is reduced by age-driven senescence and stress-driven reductions related to water availability, light competition, and temperature. Senesced leaf area is estimated based on these factors and normalized by specific leaf area index. Tuber growth is determined by sink strength, carbon demand, and various stress factors. Tuber fresh weight is converted from its dry weight assuming a fixed dry matter content of 20%.

For this study we used the default DSSAT methods with respect to soil, water, nutrients, and atmosphere representations, as follows: potential evapotranspiration was calculated with the Priestley-Taylor/Ritchie approach (Ritchie, 1972; Priestley and Taylor, 1972); soil water movement was simulated using a tipping bucket model (Ritchie, 1998); soil evaporation was estimated with the Ritchie two-stage model (Ritchie, 1972) and; the carbon and N dynamics were simulated with the soil organic matter model developed for the CERES model (Godwin and Jones, 1991).

2.4. Model evaluation

Experimental, soil and weather data were used as inputs for the evaluation of CSM-SUBSTOR-Potato. Simulations for 2015 and 2016 seasons were performed using all N fertilizer treatments from the field experiments. The model's ability to predict growth and N accumulation for the cultivar "Atlantic" required no further calibration from the pre-determined cultivar coefficients provided for the refereed potato cultivar in previous version of DSSAT (Hoogenboom et al., 2019b). The cultivar coefficients were 1000 for leaf expansion rate (G2, cm^2 m^{-2} d^{-1}), 25 for tuber growth rate (G3, g m^{-2} d^{-1}), 0.8 for cultivar determinacy (PD, relative index), 0.1 for sensitivity of tuber initiation to photoperiod (P2, relative index), and 21 for critical temperature for tuber initiation (TC, °C).

Crop model performance was evaluated by comparing simulated and observed data. Experimental crop measurements included tuber dry weight (kg ha^{-1}), aboveground dry weight (kg ha^{-1}), tuber N (kg ha^{-1}) and aboveground N (kg ha^{-1}). Experimental soil measurements included soil NO_3-N content (μg g^{-1}), soil NH_4-N content (μg g^{-1}), and soil water content (cm^3 cm^{-3}).

Model performance was evaluated by the mean error or bias (ME), the mean absolute error (MAE), and the root mean square error (RMSE), the relative RMSE (RRMSE) and the Willmott's agreement index (*d*) (Willmott et al., 1985) as follows:

$$\mathrm{ME} = \frac{1}{\mathrm{n}} \times \sum_{i=1}^{\mathrm{n}} (\mathrm{Sim}_i - \mathrm{Obs}_i) \tag{1}$$

$$\mathrm{MAE} = \frac{1}{\mathrm{n}} \times \sum_{i=1}^{\mathrm{n}} (|\mathrm{Sim}_i - \mathrm{Obs}_i|) \tag{2}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{n}} \times \sum_{i=1}^{\mathrm{n}} (\mathrm{Sim}_i - \mathrm{Obs}_i)^2} \tag{3}$$

$$\mathrm{RRMSE} = \left(\frac{\mathrm{RMSE}}{\mathrm{Obs_m}}\right) \times 100 \tag{4}$$

$$d = 1 - \frac{\sum_{i=1}^{\mathrm{n}} (\mathrm{Sim}_i - \mathrm{Obs}_i)^2}{\sum_{i=1}^{\mathrm{n}} (|\mathrm{Sim}_i - \mathrm{Obs_m}| + |\mathrm{Obs}_i - \mathrm{Obs_m}|)^2} \tag{5}$$

Where: Sim_i and Obs_i are the simulated and observed values, respectively; Obs_m is the average of observed values.

Values close to 1 for *d* (ranges from 0 to 1) and lower values of error metrics imply better model performance. Data processing and visualizations were built using the support of the *DSSAT* package (Alderman, 2020) and the *tidyverse* collection packages (Wickham et al., 2019) in the *R* environment version 3.5.2 (R CORE TEAM, 2023).

2.5. Seasonal analysis

The analysis of different environmental scenarios (Thornton and Hoogenboom, 1994), or seasonal analysis, was performed after the CSM-SUBSTOR-Potato model evaluation using a historical weather data set from 2000 to 2023. This analysis simulates a fixed set of scenarios or treatments for a number of weather years, providing an evaluation of the variability of outputs due solely to weather variability. Maximum and minimum air temperature, solar radiation, wind speed, relative air humidity and precipitation data from "Hastings" weather station were collected from FAWN (http://fawn.ifas.ufl.edu/). Quality control and gap-filling process followed the Global Yield Gap Atlas protocol (GYGA; https://www.yieldgap.org/web/guest/methods-weather-data). Daily solar radiation was limited to maximum clear-sky solar radiation as in Food and Agriculture Organization of the United Nations (FAO), Irrigation and Drainage Paper No. 56 (Allen et al., 1998). The Prediction of

Worldwide Energy Resources (POWER; https://power.larc.nasa.gov/) provided data when gap filling was needed. The weather variability for key agrometeorological variables for a usual potato growing season can be visualized from the historical records (grey lines) presented in Fig. 1.

The seasonal analysis was conducted using 640 hypothetical treatments combining five irrigation scheduling treatments, two N fertilizer application timing strategies, and four N rates applied at three application timing. The irrigation scheduling treatments consisted of triggering irrigation at 50, 60, 70, 80 and 90% of available soil water in the top 30 cm of the soil profile. The two N fertilizer application timing strategies were applying N at N_{pre} (-25 DAP), N_{eme} (25 DAP), and N_{ti} (50 DAP), and applying N at N_{pl} (0 DAP), N_{eme} (25 DAP), and N_{ti} (50 DAP). There were four N applied rates of 0, 50, 100 or 150 kg ha^{-1} in each of three N fertilizer application timings previously described. The source of N fertilizer was granular ammonium nitrate (34% N), applied as banded on soil surface and incorporated in the soil 10 cm deep, identical to the field trials.

In summary, the hypothetical "treatments" for the seasonal analysis were five irrigation scheduling, two N fertilizer application timing strategies and four N fertilizer rates applied in each application timing, simulated for the 24 harvested years. Simulated tuber dry yield (kg ha^{-1}), crop N (kg ha^{-1}) and N leached (kg ha^{-1}) and fertilizer N use efficiency (FNUE, kg tuber kg N^{-1}) were analyzed. N leaching was considered after the nutrient moved below 45 cm where most of the potato roots have been previously reported (Munoz-Arboleda et al., 2006; Reyes-Cabrera et al., 2016). Data processing and visualizations also relied on the tool and packages mentioned previously.

3. Results

3.1. Model evaluation

The CSM-SUBSTOR-Potato model was evaluated for simulation of tuber dry weight, aboveground dry weight, tuber N accumulation, aboveground N accumulation, total soil mineral N content, and VWC according to soil parameters, weather conditions, and N fertilizer regimes from the field experiments (Table 1). There was a satisfactory match between simulated and observed aboveground and tuber dry weight, and N accumulation in tubers and aboveground biomass (Table 3).

The RMSE for tuber and aboveground dry weight was 1331 and 1116 kg ha^{-1}, respectively. Willmott's agreement *d* index was 0.84 for tuber dry weight, whereas for aboveground dry weight *d* was slightly lower, yielding 0.60. Tuber dry weight had a ME of 878 kg ha^{-1}, while for aboveground dry weight ME was – 591 kg ha^{-1}. Nevertheless, tuber plus aboveground dry weights had a slight negative bias of – 131 kg ha^{-1}, RMSE of 1149 kg ha^{-1}, and an index *d* of 0.98. There was an increase in aboveground dry weight after planting, which reached a plateau at tuber initiation and after tuber initiation, tuber dry weight increased exponentially until the harvest, which CSM-SUBSTOR-Potato was able to capture (Fig. 2). The model tended to overestimate tuber dry weight close to harvest, particularly for high N amounts, compared to observed records (Fig. 2).

The N accumulation in aboveground components plus tubers over time was well represented by CSM-SUBSTOR-Potato for contrasting N rates and timings of application (Fig. 3), yielding an overall *d* of 0.97 and RMSE of 22 kg ha^{-1} (RRMSE of 29%) (Table 3). The timing of plant N

Table 3
Performance of CSM-SUBSTOR-Potato to simulate crop over seasons 2015 and 2016 for nitrogen all treatments under irrigated conditions in Hastings, Florida, USA. *n* is the number of observations, ME is the mean error (variable unit), MAE is the mean absolute error (variable unit), RMSE is the root mean square error (variable unit), RRMSE is the relative root mean square error (%), and *d* is the Willmott's agreement index (unitless).

Variable	*n*	ME	MAE	RMSE	RRMSE	*d*
Aboveground + Tuber dry weight (kg ha^{-1})	96	-131	692	1149	26.4	0.98
Aboveground + Tuber N (kg ha^{-1})	96	-0.1	16.6	22.3	28.6	0.97
Tuber dry weight (kg ha^{-1})	48	878	1146	1331	21.7	0.84
Tuber N (kg ha^{-1})	48	22.6	24.1	27.7	36.4	0.74
Aboveground dry weight (kg ha^{-1})	96	-591	644	1116	86.1	0.60
Aboveground N (kg ha^{-1})	96	-11.7	18.7	23.0	57.4	0.75
Total soil mineral N (μg g^{-1}) at 0–15 cm	120	2.1	12.3	20.7	154.3	0.50
Total soil mineral N (μg g^{-1}) at 15–30 cm	120	0.4	4.6	7.0	64.3	0.87
Total soil mineral N (μg g^{-1}) at 30–45 cm	120	4.6	4.9	6.9	110.3	0.61
Soil water content (cm^3 cm^{-3}) at 15 cm	172	-0.01	0.02	0.03	20.6	0.81
Soil water content (cm^3 cm^{-3}) at 30 cm	172	-0.01	0.04	0.04	19.5	0.53
Soil water content (cm^3 cm^{-3}) at 45 cm	172	0	0.03	0.03	11.6	0.34
Soil water content (cm^3 cm^{-3}) at 60 cm	172	0	0.01	0.01	3.1	0.59

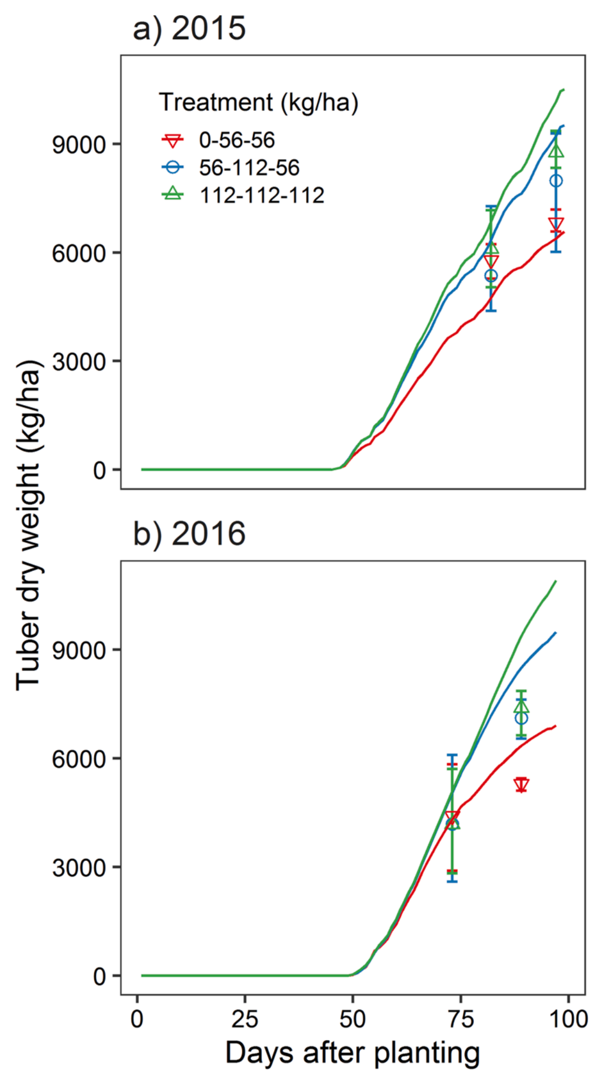

Fig. 2. Simulated (lines) and observed (symbols) tuber dry weight (kg ha^{-1}) over time for nitrogen fertilizer rates (kg ha^{-1}) applied at planting, emergence and tuber initiation (0–56–56, 56–112–56 and 112–112–112; distinguished by colors) under northeast Florida weather conditions of 2015 (a) and 2016 (b). Error bars indicate the bootstrap confidence limits of observed replications obtained from *mean_cl_boot* in *ggplot2*.

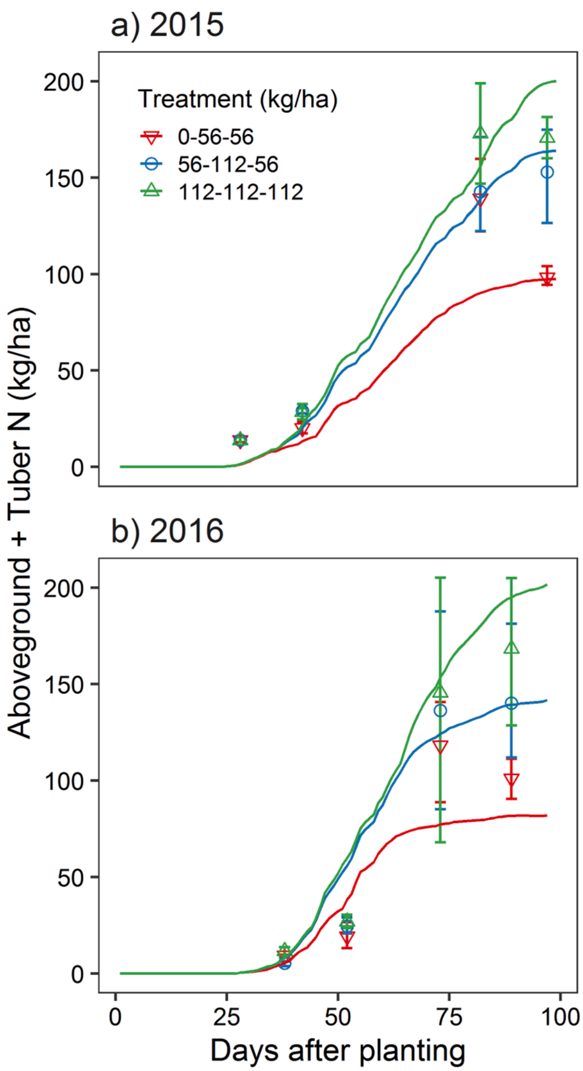

Fig. 3. Simulated (lines) and observed (symbols) aboveground plus tuber nitrogen weights (kg ha^{-1}) over time for nitrogen fertilizer rates (kg ha^{-1}) applied at planting, emergence and tuber initiation (0–56–56, 56–112–56 and 112–112–112; distinguished by colors) under northeast Florida weather conditions of 2015 (a) and 2016 (b). Error bars indicate the bootstrap confidence limits of observed replications obtained from *mean_cl_boot* in *ggplot2*.

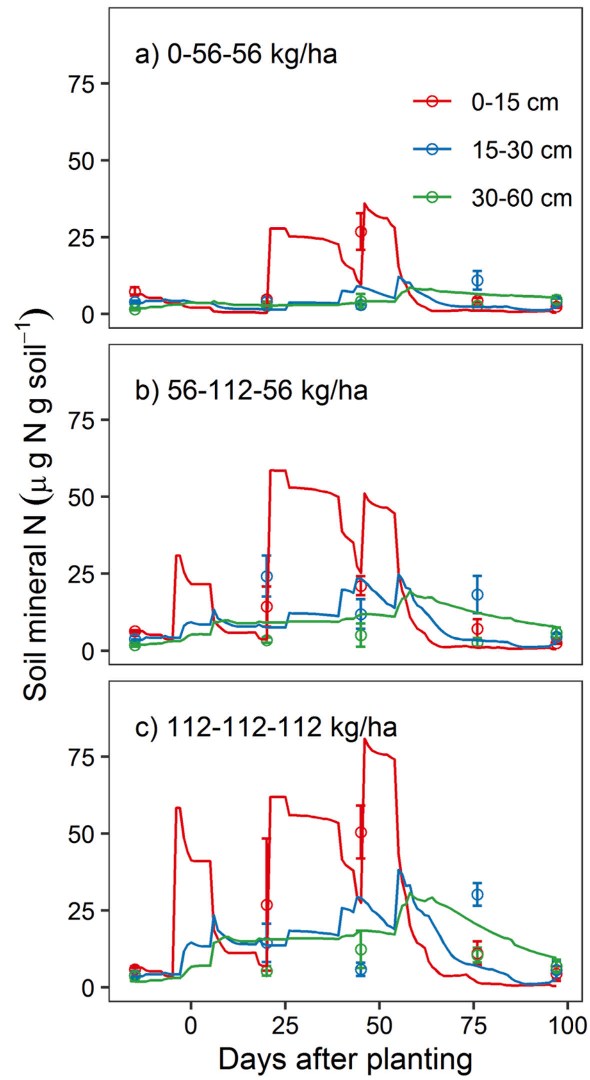

Fig. 4. Simulated (lines) and observed (symbols) data of soil mineral N (µg N g soil^{-1}) at 0–15, 15–30 and 30–45 cm of soil depth layers over time for the applications 0-56-56 (a), 56-112-56 (b) and 112-112-112 kg ha^{-1} of N at planting, emergence and tuber initiation, respectively, under northeast Florida weather conditions of 2016. Error bars indicate the bootstrap confidence limits of observed replications obtained from *mean_cl_boot* in *ggplot2*. Note: in-season measurements of mineral soil N were taken shortly before fertilizer N applications.

accumulation differed between the model simulations and observations, however, there were a few instances when the model under and overestimated the biomass weight and N accumulation, particularly before the beginning of tuber bulking (first two samplings). Nevertheless, most model simulation curves intersect with the bootstrapping error ranges of observed data, particularly for tuber bulking stage (Fig. 3). The N accumulation in the tuber tissue exponentially increased during tuber bulking. In contrast, the aboveground N accumulation had a peak of N at tuber maturation and a decrease from tuber maturation to harvest. The RMSE for N accumulation in aboveground tissues and tubers were 23 and 28 kg ha^{-1}, respectively (Table 3). Simulated data of N accumulation yielded d of 0.74 and 0.75 for tuber and aboveground tissues, respectively (Table 3).

Model simulation of total soil mineral N content was reasonable (Table 3). The RMSE for the soil mineral N content ranged from 6.9 to 20.7 µg g^{-1}, while d ranged from 0.50 to 0.87 across soil depths. Soil mineral N content was higher in the upper soil depth layer (0–15 cm) compared to deeper soil depth layers (15–30 and 30–60 cm). A representation of soil N dynamics for three treatments in 2016 is presented in Fig. 4. After each N fertilizer application (N_{pl}, N_{eme} and N_{ti}), there was a peak of simulated soil mineral N content, which reduced over time. Simulated soil mineral N content closely matches measured data for all soil depths; however, soil samples were collected shortly before N fertilizer applications, therefore field sampling did not necessarily capture the complete variation of soil mineral N content in the days after N fertilization.

The model was able to capture the magnitude and seasonal patterns for soil VWC over time for different soil layers (Fig. 5). There was a reasonable range of RMSE (0.01–0.04 cm^3 cm^{-3}) and d (0.34–0.81) between simulated and observed data. However, VWC was usually underestimated by the model (Fig. 5). Overall, soil VWC had a peak after each rainfall and irrigation event and the water drainage after those events was faster simulated than that measured (Fig. 5). The simulated soil VWC for the 2016 potato season in the 0–15, 15–30 and 30–60 cm soil depth layers had an average of 0.11, 0.19, 0.25, and 0.30 cm^3 cm^{-3}, respectively, while the observed records averaged 0.16, 0.23, 0.27, and 0.30 cm^3 cm^{-3} in the same order. Situations of underestimation of soil VWC by the model was primarily due to the presence of a shallow water

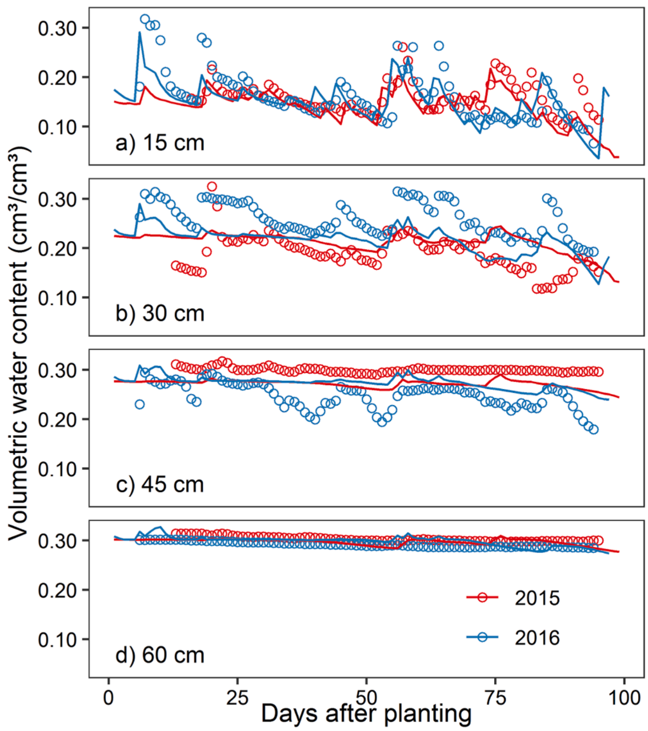

Fig. 5. Simulated (lines) and observed (symbols) data of soil moisture content (cm^3 cm^{-3}) at 15 (a), 30 (b), 45 (c) and 60 (d) cm of soil depth over time under northeast Florida weather conditions of 2015 and 2016 (distinguished by colors). Note: measured soil water data were influenced by a shallow water table.

table, which created an upward soil water flux that supply the crop root zone in periods after rainfall or irrigation events (da Silva et al., 2018a).

3.2. Seasonal analysis

Following the model evaluation, CSM-SUBSTOR-Potato was employed to assess crop response and soil N leaching to the interactive effects of irrigation application rates based on variable target of VWC and N fertilizer application timing and rate strategies. We considered all the combinations for this analysis but excluded the treatment without N (0–0–0 kg ha^{-1} at N_{pre} or N_{pl}, N_{eme}, and N_{ti}, respectively) when FNUE results were presented. The effect of irrigation treatments on total irrigation water applied, tuber yield, plant N uptake, N leached, and FNUE is shown in Table 4. The average volume of irrigation water applied for the 24 years simulated was 208, 228, 259, 303 and 383 mm for soil VWC triggering levels of 50, 60, 70, 80 and 90%, respectively. Total water used had a relatively low impact on crop N uptake and tuber yield.

Triggering irrigation at 50% slightly increased N uptake (4%) and maintained tuber yield compared to triggering at 90% of the available soil water in the first 30 cm regardless of the first N application being at pre-planting or at planting (Table 4). However, soil N leached was 19–22% higher under the 90% compared to 50% available soil water strategy. The irrigation water applications at 60% or 70% compared favorably in terms of tuber yield and FNUE while reduced the volume of water applied by ~32% and ~40%, respectively, compared to the 90%. Furthermore, those treatments minimized the N leached in up to 23% compared to the triggering irrigation at 90% available soil water.

Overall, applying the first N fertilization at N_{pl} resulted in more positive outcomes, regardless of the soil water level that triggered the irrigation, when contrasted with the application at N_{pre} (Table 4). Although requiring slightly but not substantially more irrigation water (up to 10 mm in the irrigation 50%), N_{pl} increased plant N uptake by 10% (155–170 kg ha^{-1}) and tuber yield by 7% (8361 to 8971 kg ha^{-1}),

Table 4
Total irrigation water used, tuber dry yield, plant N uptake, N leached from the start of the simulation to harvest, and N fertilizer use efficiency (FNUE) for each irrigation treatment pooling all the N fertilizer treatments in a 24-years simulation. Irrigation treatments include water application via sprinkler when soil volumetric water content (VWC) in the 0–30 cm soil depth layer reaches 50%, 60%, 70%, 80%, and 90% of the available soil VWC. The simulated data from the treatment without N fertilization was excluded for this table.

First N application	Variable	Irrigation treatments				
		50%	60%	70%	80%	90%
Pre-Planting	Total irrigation water applied (mm)	203	224	255	301	382
	Tuber dry yield (kg ha^{-1})	8100	8393	8586	8594	8133
	Total plant N uptake (kg ha^{-1})	151	158	161	160	146
	N leached (kg ha^{-1})	95	94	96	100	117
	FNUE (kg tuber kg N^{-1})	36	38	39	39	37
Planting	Total irrigation water applied (mm)	213	232	262	306	384
	Tuber dry yield (kg ha^{-1})	8750	9004	9182	9185	8733
	Total plant N uptake (kg ha^{-1})	167	173	175	175	160
	N leached (kg ha^{-1})	82	81	84	88	105
	FNUE (kg tuber kg N^{-1})	40	41	42	43	40

reduced N leached by 13% (100–88 kg ha^{-1}), consequently increasing FNUE by 9% (increment of 3 kg of tuber dry weight per kg of N applied), compared to N_{pre} across the irrigation treatments.

The average rainfall accumulation during the potato season (January 1 to May 8) for the 24 years studied was 302 mm. The year with the highest volume of rainfall was 2013 with 448 mm, while the lowest volume of rainfall was measured for 2020 (107 mm) (Fig. 6). Simulated tuber dry weight was impacted by the crop N uptake, which varied according to the soil N leached. An increase in rainfall accumulation increased the soil N leached, hence there was a low crop N uptake that resulted in a low tuber dry weight.

Simulated N fertilizer strategies were applied to the scenario analysis in seeking to identify the best N fertilizer application timing and rates that along the 24 years could minimize the N leached but maintained tuber yield. Overall, N fertilizer strategies only differ on the timing of the first N fertilizer application, at N_{pre} versus N_{pl}, since the other two applications (N_{eme} and N_{ti}) were simulated for the same date for both treatments. The difference in tuber dry weight, crop N uptake, soil N leached and FNUE for the 24 years simulated is shown in Fig. 6, considering the irrigation treatment 60% of available soil water. A N fertilizer rate of 50 kg ha^{-1} was applied at N_{pre} or N_{pl}, followed by similar applications of 100 and 50 kg ha^{-1} at N_{eme} and N_{ti}, respectively. Tuber yield, in general, was higher under the strategy of applied N at N_{pl} than at N_{pre}. Simulated tuber yield weight averaged 9368 and 9673 kg ha^{-1} for N_{pre} and N_{pl}, respectively. Overall, tuber yield was responsive to soil N availability, and the N fertilizer at N_{pl} had lower soil N leached than N_{pre} in most of the simulated years. Simulated soil N leached averaged 88 and 77 kg ha^{-1} for N_{pre} and N_{pl}, respectively. On the other hand, FNUE was slightly improved by 3% for this scenario.

Cumulative probability function plots, where the distribution is ordered from the smallest to the largest value and plotted against equal increments of cumulative probability, are presented in Fig. 7 for the same data underlying Fig. 6 (irrigation treatment 60% and N rates 50–100–50 kg ha^{-1} applied at N_{pre} or N_{pl}, N_{eme} and N_{ti}), but excluding precipitation and including FNUE. Under low- or high-yielding years, tuber dry weight at harvest, N uptake, N leaching, and FNUE were similar regardless of the time of the first N application being at N_{pre} or N_{pl}. On the other hand, ~ 30–75% of the simulated outcomes with N_{pl}

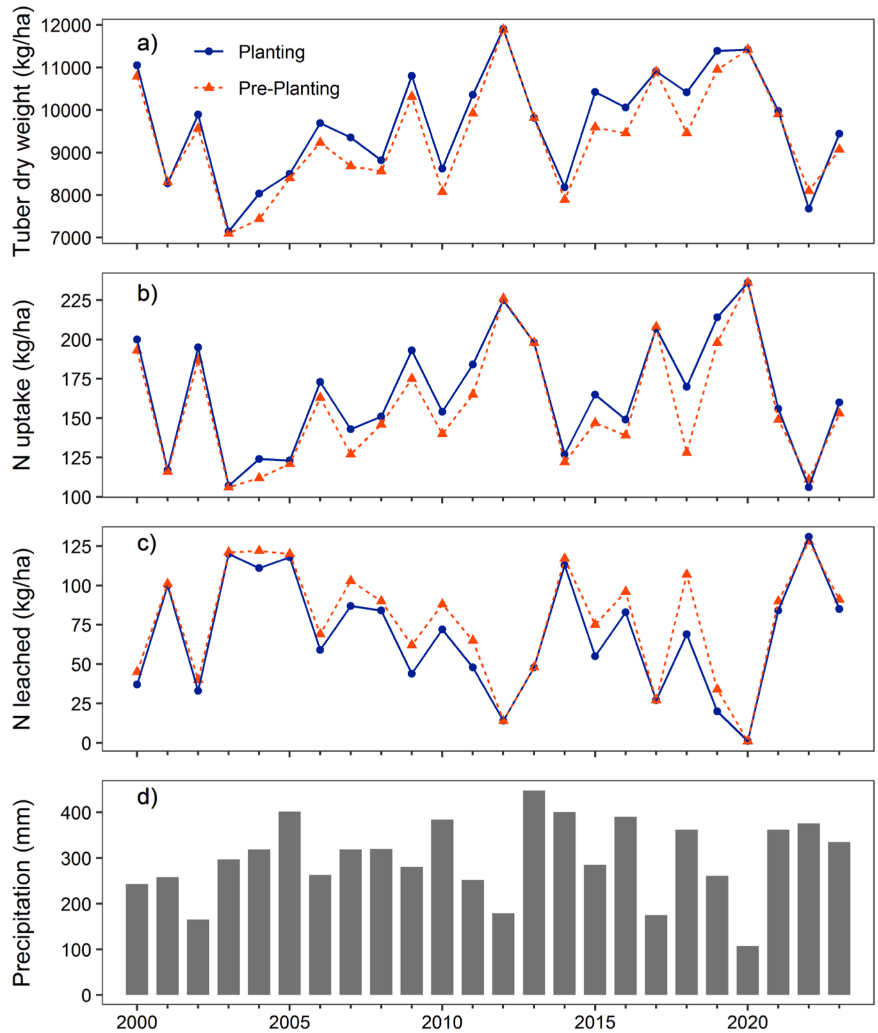

Fig. 6. Simulated tuber dry weight (a, kg ha^{-1}), N uptake (b, kg ha^{-1}), N leached from the start of the simulation to harvest (c, kg ha^{-1}) and observed precipitation accumulated from the start of the simulation to harvest (d, mm) from 2000 to 2023. N fertilizer corresponds to the application of 50, 100 and 50 kg ha^{-1} at pre-planting or planting (results distinguished by colors), emergence and tuber initiation, respectively. The simulation results with irrigation triggered at 60% of available water content in the first 30 cm of soil. Note: the y-axis differs between different panels.

implied higher yield, N uptake and FNUE, and decreased leaching over the season compared to N_{pre}.

The comparison of tuber yield and soil N leached between N rates applied at N_{pre} and N_{pl} is shown in Fig. 8, as well as the influence of the first application on the other application timing and rates. Soil N leached from the N_{pre} application was higher than the N_{pl} with same N rates (Fig. 8a). Lowering the soil N leaching increased the soil N availability when N was supplied at N_{pl}, resulting in a higher tuber yield weight than the N_{pre} for all N fertilizer rates simulated. Regardless of whether the first N fertilizer application was N_{pre} or N_{pl}, increasing N rate increased tuber yield and soil N leached as well. The N leached was 10%, 16%, and 18% higher for the N_{pre} compared to N_{pl}, while tuber yield was 7%, 10% and 10% lower for the N_{pre} compared to N_{pl} for the applications of 50, 100 and 150 kg ha^{-1}, respectively. Further, the N rate applied at N_{pre} had similar tuber yield weight than the previous lower N rate applied at N_{pl}. For example, the application of 150 kg ha^{-1} at N_{pre} had an average of 9720 kg ha^{-1} of tuber yield, while the application of 100 kg ha^{-1} at N_{pl} even slightly increased average tuber yield weight to 9844 kg ha^{-1}.

The impacts of N_{pre} and N_{pl} on the following N fertilizer application timings and rates, namely at N_{eme} and at N_{ti} are presented in Fig. 8b and Fig. 8c, respectively. N_{pl} application reduced the N rates required at N_{eme} (Fig. 8b) and at N_{ti} (Fig. 8c) compared to N_{pre} application. Applying either 100 kg ha^{-1} N_{eme} with a N_{pl} or 150 kg ha^{-1} N_{eme} with a N_{pre}, resulted in a difference in tuber yield of only 1000 kg ha^{-1}, on average, while there was a reduction in N leaching of approximately 23% (~25 kg ha^{-1}) between these two combinations (Fig. 8b). The highest FNUEs were simulated in no N fertilization treatments (values above the upper quartile 75th), regardless of the timing (Fig. 8). However, median FNUE was similar among N_{eme} rates except no N fertilization that efficiency was decreased. This tendency was also observed for the N_{ti} rates, but median FNUE decreased as N rates increased (Fig. 8c).

Overall, some N was required in the first N fertilizer application to increase tuber yield (Fig. 8). If this N fertilizer application occurred at N_{pre}, there was an increase on tuber yield and N leached with the increasing N rates. However, if the first N fertilizer application was supplied at N_{pl}, tuber yield tended to plateau with the application of 100 kg ha^{-1} of N, while the application of 50 kg ha^{-1} of N had similar N leached as the 0 kg ha^{-1}. Along the 24 years simulated, the N fertilizer rates required at N_{eme} and N_{ti} were 100 and 50 kg ha^{-1} of N, respectively, regardless of the timing of the first N application. These N rates had a similar yield as 150 kg ha^{-1} but resulted in lower N leaching.

4. Discussion

The response of the potato crop to N fertilizer treatments was satisfactorily simulated by the CSM-SUBSTOR-Potato model with no further

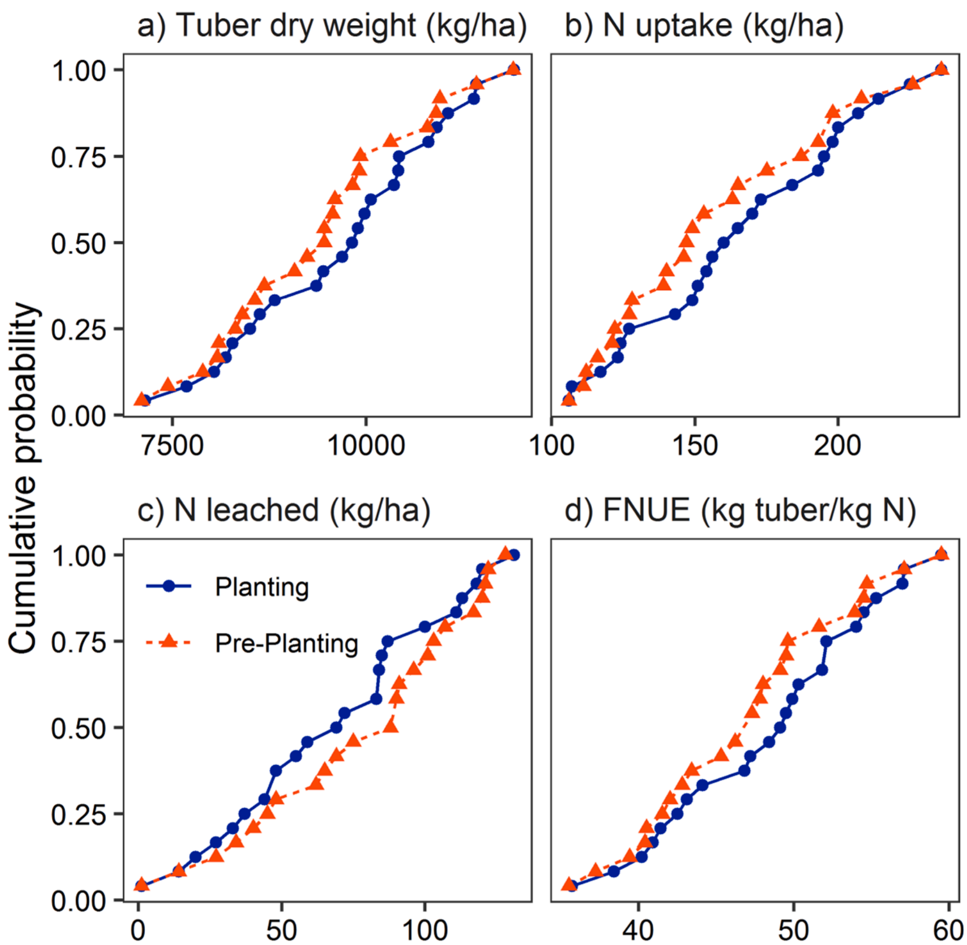

Fig. 7. Cumulative probability distribution of simulated tuber dry weight (a, kg ha^{-1}), N uptake (b, kg ha^{-1}), N leached from the start of the simulation to harvest (c, kg ha^{-1}) and N fertilizer use efficiency (c, FNUE, as kg tuber produced per kg of N applied over the season) from 2000 to 2023. N fertilizer corresponds to the application of 50, 100 and 50 kg ha^{-1} at pre-planting or planting (results distinguished by colors), emergence and tuber initiation, respectively. The simulation results with irrigation triggered at 60% of available soil water content in the first 30 cm of soil. Note: the x-axis differs between different panels.

change in the genotype coefficients. Tuber yield and other crop variables varied with the timing of application and N rates applied. Similar results were previously reported in the literature. Raymundo et al. (2017) reported a RRMSE of 37%, 85%, 40%, and 86% for tuber dry weight, aboveground dry weight, tuber N, and aboveground N, respectively, when the CSM-SUBSTOR-Potato model was used to simulate potato performance in several locations across the globe. However, the CSM-SUBSTOR-Potato model results were more accurate for lower N fertilizer treatments. There was an overestimation of aboveground and tuber dry biomass, and N accumulation when soil N supplied increased, and the model constantly simulated crop growth until soil water and N limited tuber yield.

The overestimation could be attributed to the lack of maturation prediction by the model and to the high tuber sink assumption in the model under aboveground growth stimulus caused by high N fertilization. Further, other crop yield-limiting factors, such as insufficiency of other nutrient(s) beyond N could also be the reason for the overestimation that the current version of the model did not take into account. According to Khan et al. (2013), the maturity type of cultivars and the impact of soil water and N on crop senescence is still unclear, and subtropical regions, like in Florida, should consider air temperature as a factor that accelerates the crop senescence (Rahman et al., 2014; Worthington and Hutchinson, 2006).

Soil VWC and soil mineral N contents were reasonably simulated by the CSM-SUBSTOR-Potato model. There were discrepancies between observed and simulated data, which was also previously reported by Raymundo et al. (2017). The limitations for the simulation of soil VWC and soil mineral N content by the CSM-SUBSTOR-Potato should be attributed to the one-dimensional, tipping-bucket water movement model in DSSAT (Ritchie, 1998). In addition, the shallow water table in the of northeastern Florida agricultural areas affects the soil moisture in the potato root zone (Reyes-Cabrera et al., 2016). The upward soil water flux from the water table contributes to the irrigation management, but the downward soil water flux created after rainfall or sprinkler water application can lead to increasing soil N leaching (da Silva et al., 2018a). Additionally, the reduced number of soil samples to account for N variability within the plots and changes over time also may have led to differences between model and observations to some extent.

Overall, the model evaluation indicated that the CSM-SUBSTOR-Potato model was able to mimic the potato crop development cultivated under subtropical environmental conditions. Subsequently, the model was imposed to 24 years of weather data and used to explore irrigation and N fertilizer application timing and rate strategies for potato production. Regarding sprinkler irrigation for potato in Florida, irrigation scheduling should consider the evapotranspiration demand and crop stage to minimize nutrient leaching. Likewise, the N fertilizer application rates and timings should be in synchronous with plant N demand. Ideally, optimizing the irrigation strategy in conjunction with N fertilizer application timing and rate was key to reduce nutrient leaching without any impact on tuber yield.

In the present study, triggering irrigation at 60% or 70% of the available soil water slightly increased tuber yield compared to the 90%

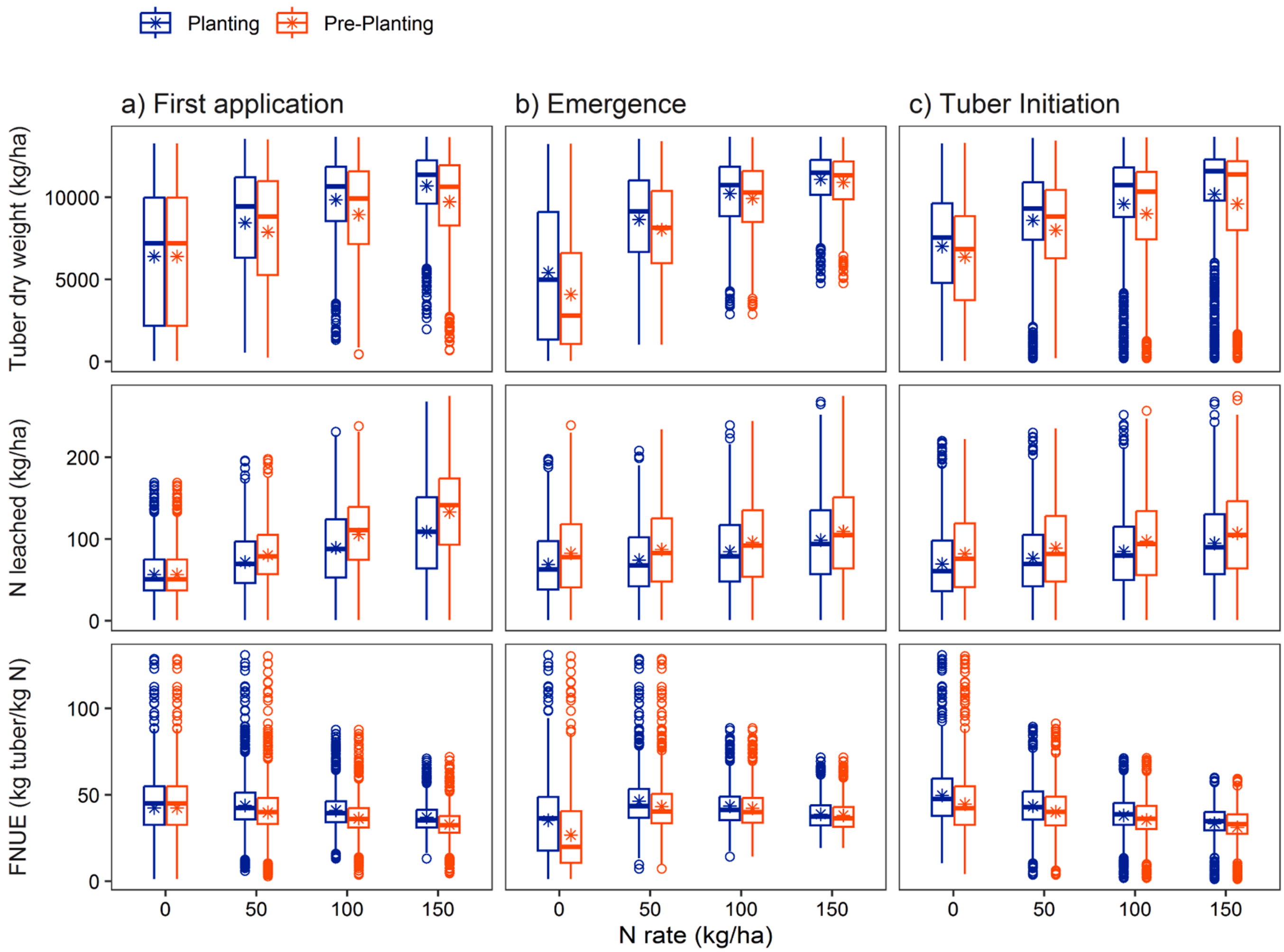

Fig. 8. Simulated tuber dry weight at harvest, N leached and N fertilizer use efficiency (FNUE, as kg tuber produced per kg of N applied over the season) in the northeast Florida conditions weather (2000–2023) for N fertilizer rates of 0, 50, 100 and 150 kg ha^{-1} applied at each application timing, categorized by the thee key timings (first application, a; emergence, b; and tuber initiation, c) as influenced by the first application timing (Pre-planting *versus* Planting, distinguished by colors). The simulation results with irrigation triggered at 50, 60 and 70% of available water content in the first 30 cm of soil were pooled and used. Boxplots were set at 90th (upper whisker), 75th (upper quartile), 50th (median), 25th (lower quartile), and 10th (lower whisker) percentiles. The means are presented as asterisks while outliers are shown as open circles. Note: the y-axis differs between different panels.

threshold, while it reduced the amount of water applied by 40% (60% vs 90%) and 32% (70% vs 90%), and N leaching by 23% (60% vs 90%) and 20% (70% vs 90%). Curwen (1993) also emphasized that the irrigation criteria of maintaining the water application at 70% of available soil water could avoid tuber yield reductions ensuring no water stress in the plant. Nevertheless, the irrigation scheduling for the potato season should periodically be adjusted according to the rainfall patterns and crop demand. Rainfall events during a potato season increased the N leached, which had a negative impact on N uptake and tuber yield due to the downward soil water flux, especially in sandy soils, that moves the N to deeper soil layers, increasing the potential of soil N leaching (Gehl et al., 2005). Therefore, high precipitation rates or irrigation volumes above the crop evapotranspiration rate might lead to excessive soil N leaching.

Regarding the N fertilizer applied rates and timings optimizations, our findings suggest that the first N fertilizer application is necessary to sustain the tuber yield regardless of application timing, N_{pre} or N_{pl} (Fig. 8) (Rens et al., 2018). Roberts et al. (1991) also suggested that N rates applied early season are required to stimulate tuber initiation. However, refining the timing of the first N fertilizer application for minimizing N leaching favored the selection of N_{pl} over N_{pre}, since simulated N fertilizer applied at N_{pre} had higher N leached compared to N_{pl} in most of the years (Figs. 6 and 7). The practice of applying N at N_{pre} could be risky because of the long period between N application and the high N demand by potato plants (Rens et al., 2018; Zotarelli et al., 2014). Conversely, N_{pl} shortens the period between the fertilizer application and high N demand by potato, and could improve a fertilizer N uptake efficiency to 18% (da Silva et al., 2018b) against 11% with N_{pre} as reported by Rens et al. (2016), which can be attributed to less N leaching as predicted by model simulations (Figs. 6 to 8).

Since moving N application timing from N_{pre} to N_{pl} prevented a part of N applied fertilizer from leaching, N_{pl} over N_{pre} could reduce the total N rates while maintaining the tuber yield. The application timing strategy of N_{pre} or N_{pl} had a direct impact on the N applied at N_{eme} and N_{ti} (Fig. 8), which match the high crop N uptake demand. The potato N uptake was low during the sprout development, but there was an exponential N uptake by potato plants after emergence, which decreased after tuber bulking until harvest (Alva, 2004; Webb et al., 1978; Zotarelli et al., 2014). Tuber yield was higher when N_{eme} or N_{ti} were combined to N_{pl} instead of N_{pre}. Further, the N rate required at N_{eme} and N_{ti} was lower with the N_{pl} than with the N_{pre} application. In general, the results of this simulation study corroborated with the field literature for potato grown in subtropical regions, in which N rates at N_{eme} may range between 112 and 168 kg ha^{-1} of N, while 56 kg ha^{-1} of N was sufficient at N_{ti} to sustain tuber yields (da Silva et al., 2023; Rens et al., 2018) with the least amount of N leached.

In summary, triggering irrigation at 60–70% of the available soil water is recommended to simultaneously reduce leaching and sustain tuber yields. Further, the analysis presented in this study supported the first N fertilizer application at planting rather than weeks before planting, capping at around 50 kg ha^{-1} of applied N rates for maximizing tuber yield while minimizing environmental impacts, since the excess of N fertilizer before planting might cause delayed the tuber initiation and increase N leaching (Errebhi et al., 1998; Roberts et al., 1991). Therefore, the irrigation scheduling recommendation when combined with N_{pl} over N_{pre} rate of not more than 50 kg ha^{-1}, 100–150 kg ha^{-1} applied N rates at emergence, and 0–50 kg ha^{-1} applied N rates at tuber initiation, could be a promising approach to minimize leaching and improve FNUE to maximize the tuber yield. These N rates ranges provided at different application timings account for different weather conditions to optimize tuber yield and N leaching. These general recommendations demonstrate efficacy in most years in our simulations, excluding seasons characterized by frequent and intense rainfall events. In extreme weather conditions, the suggested approach may not be effective. For such scenarios, further investigation is warranted, focusing on a comprehensive analysis taking into account the accumulated rainfall, risk of leaching, and stage of the crop during the periods of fertilization events to further optimize the N fertilizer application rates and timings.

5. Conclusions

The CSM-SUBSTOR-Potato model was able to simulate an irrigated potato cropping system in northeast Florida subtropical environmental conditions for different N fertilizer regimes across two years with different weather patterns. Based on long-term model simulations, a target of 60% or 70% of the available soil water can be safely used as an irrigation strategy to achieve high tuber yields, while irrigation used and N leached were reduced. Applying N_{pl} over N_{pre}, can minimize leaching and could potentially reduce the total N rates in the following application timings (N_{eme} and N_{ti}) without substantial yield loss while improving FNUE. These strategies align with Florida BMP guidelines for potato production and aim to concurrently optimize yield, enhance fertilizer use efficiency, conserve agricultural water, and minimize N losses to the environment. Future studies should consider the contribution of the water table to the soil moisture and soil N movement in the potato root zone and develop BMP to keep nutrients in the root zone throughout the cropping season.

CRediT authorship contribution statement

Andre Luiz Biscaia Ribeiro da Silva: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Henrique Boriolo Dias:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rishabh Gupta:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Lincoln Zotarelli:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Senthold Asseng:** Writing – review & editing, Supervision, Software, Methodology, Formal analysis. **Michael D. Dukes:** Writing – review & editing, Supervision. **Cheryl Porter:** Writing – review & editing, Supervision, Software, Formal analysis. **Gerrit Hoogenboom:** Writing – review & editing, Supervision, Software, Methodology, Formal analysis.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

Acknowledgments

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References

Ahuja, L.R., Kersebaum, K.C., Wendroth, O., 2022. Modeling processes and their interactions in cropping systems: Challenges for the 21st Century, Advances in Agricultural Systems Modeling. American Society of Agronomy, Inc. / Crop Science Society of America, Inc. / Soil Science Society of America, Inc. https://doi.org/10.1002/9780891183860.

Alderman, P.D., 2020. A comprehensive R interface for the DSSAT Cropping Systems Model. Comput. Electron. Agric. 172, 105325 https://doi.org/10.1016/j.compag.2020.105325.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements. Paper No. 56 Irrigation and Drainage. FAO, Rome, Italy.

Alva, A.K., 2008. Water management and water uptake efficiency by potatoes: a review. Arch. Agron. Soil Sci. 54, 53–68. https://doi.org/10.1080/03650340701615822.

Alva, A.K., Ren, H., Moore, A.D., 2012. Water and nitrogen management effects on biomass accumulation and partitioning in two potato cultivars. Am. J. Plant Sci. 3, 164–170. https://doi.org/10.4236/ajps.2012.31019.

Alva, L., 2004. Potato nitrogen management. J. Veg. Crop Prod. 10, 97–132. https://doi.org/10.1300/J068v10n01_10.

Arora, V.K., Nath, J.C., Singh, C.B., 2013. Analyzing potato response to irrigation and nitrogen regimes in a sub-tropical environment using SUBSTOR-Potato model. Agric. Water Manag. 124, 69–76. https://doi.org/10.1016/j.agwat.2013.03.021.

Asci, S., Borisova, T., VanSickle, J.J., 2015. Role of economics in developing fertilizer best management practices. Agric. Water Manag. 152, 251–261. https://doi.org/10.1016/j.agwat.2015.01.021.

Bender, F.D., Sentelhas, P.C., 2020. Assessment of regional climate change impacts on Brazilian potato tuber yield. Int. J. Plant Prod. 1–15. https://doi.org/10.1007/s42106-020-00111-7.

Boote, K.J., Jones, J.W., Pickering, N.B., 1996. Potential uses and limitations of crop models. Agron. J. 88, 704–716. https://doi.org/10.2134/agronj1996.00021962008800050005x.

Curwen, D., 1993. Water management, in: Rowe, R.C. (Ed.), Potato Health Management, Plant Health Management Series. The American Phytopathological Society, ASP Press, Wooster, Ohio, St Paul, Minnesota, USA, pp. 67–75.

Dukes, M.D., Perry, C., 2006. Uniformity testing of variable-rate center pivot irrigation control systems. Precis. Agric. 7, 205–218. https://doi.org/10.1007/s11119-006-9020-y.

Dukes, M.D., Zotarelli, L., Morgan, K.T., 2010. Use of irrigation technologies for vegetable crops in Florida. HortTechnology 20, 133–142. https://doi.org/10.21273/HORTTECH.20.1.133.

Errebhi, M., Rosen, C.J., Gupta, S.C., Birong, D.E., 1998. Potato yield response and nitrate leaching as influenced by nitrogen management. Agron. J. 90, 10–15. https://doi.org/10.2134/agronj1998.00021962009000010003x.

Fleisher, D.H., Condori, B., Quiroz, R., Alva, A., Asseng, S., Barreda, C., Bindi, M., Boote, K.J., Ferrise, R., Franke, A.C., Govindakrishnan, P.M., Harahagazwe, D., Hoogenboom, G., Naresh Kumar, S., Merante, P., Nendel, C., Olesen, J.E., Parker, P. S., Raes, D., Raymundo, R., Ruane, A.C., Stockle, C., Supit, I., Vanuytrecht, E., Wolf, J., Woli, P., 2017. A potato model intercomparison across varying climates and productivity levels. Glob. Change Biol. 23, 1258–1281. https://doi.org/10.1111/gcb.13411.

Fleisher, D.H., Condori, B., Barreda, C., Berguijs, H., Bindi, M., Boote, K., Craigon, J., Evert, F., van, Fangmeier, A., Ferrise, R., Gayler, S., Hoogenboom, G., Merante, P., Nendel, C., Ninanya, J., Pleijel, H., Raes, D., Ramírez, D.A., Raymundo, R., Reidsma, P., Silva, J.V., Stöckle, C.O., Supit, I., Stella, T., Vandermeiren, K., van Oort, P., Vanuytrecht, E., Vorne, V., Wolf, J., 2021. Yield response of an ensemble of potato crop models to elevated CO_2 in continental Europe. Eur. J. Agron. 126, 126265 https://doi.org/10.1016/j.eja.2021.126265.

Gehl, R.J., Schmidt, J.P., Stone, L.R., Schlegel, A.J., Clark, G.A., 2005. In situ measurements of nitrate leaching implicate poor nitrogen and irrigation management on sandy soils. J. Environ. Qual. 34, 2243–2254. https://doi.org/10.2134/jeq2005.0047.

Godwin, D.C., Jones, C.A., 1991. Nitrogen dynamics in soi-plant systems, in: Modeling Plant and Soil Systems. John Wiley & Sons, Ltd, pp. 287–321. https://doi.org/10.2134/agronmonogr31.c13.

Grados, D., García, S., Schrevens, E., 2020. Assessing the potato yield gap in the Peruvian Central Andes. Agric. Syst. 181, 102817 https://doi.org/10.1016/j.agsy.2020.102817.

Griffin, T.S., Johnson, B.S., Ritchie, J.T., 1993. A simulation model for potato growth and development: SUBSTOR-Potato Version 2.0, Research Report Series 02. IBSNET, Department of Agronomy and Soil Science, College of Tropical Agriculture and Human Resources, University of Hawaii, Honalulu, HI.

Haverkort, A.J., Top, J.L., 2011. The potato ontology: delimitation of the domain, modelling concepts, and prospects of performance. Potato Res. 54, 119–136. https://doi.org/10.1007/s11540-010-9184-8.

Hendricks, G.S., Shukla, S., 2011. Water and nitrogen management effects on water and nitrogen fluxes in Florida Flatwoods. J. Environ. Qual. 40, 1844–1856. https://doi.org/10.2134/jeq2011.0001.

Hoogenboom, G. , Porter, C.H. , Boote, K.J. , Shelia, V. , Wilkens, P.W. , Singh, U. , White, J.W. , Asseng, S. , Lizaso, J.I. , Moreno, P.L. , Pavan, W. , Ogoshi, R. , Hunt, L.A. , Tsuji, G.Y. , Jones, J.W. , 2019a. The DSSAT crop modeling ecosystem, in: Boote, K.J. (Ed.), Advances in Crop Modelling for a Sustainable Agriculture. Burleigh Dodds Science Publishing, Cambridge, UK, pp. 173–216. https://doi.org/10.19103/AS.2019.0061.10.

Hoogenboom, G. , Porter, C.H. , Shelia, V. , Boote, K.J. , Singh, U. , White, J.W. , Hunt, L. A. , Ogoshi, R.M. , Lizaso, J.I , Koo, J. , Asseng, S. , Singels, A. , Moreno-Cadena, L.P. , Jones, J.W. , 2019b. Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.7.5 (www.dssat.net).

Hoogenboom, G. , Porter, C.H. , Shelia, V. , Boote, K.J. , Singh, U. , Pavan, W. , Oliveira, F.A.A. , Moreno-Cadena, L.P. , Ferreira, T.B. , White, J.W. , Lizaso, J.I , Pequeno, D.N. L. , Kimball, B.A. , Alderman, P.D. , Thorp, K.R. , Cuadra, S.V , Vianna, M. dos S. , Villalobos, F.J. , Batchelor, W.D. , Asseng, S. , Jones, M.R. , Hopf, A. , Dias, H.B. , Hunt, L.A. , Jones, J.W. , 2023. Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.8.2 (www.dssat.net).

Islam, M., Li, S., 2023. Identifying key crop growth models for rain-fed potato (*Solanum tuberosum* L.) production systems in Atlantic Canada: a review with a working example. Am. J. Potato Res. 100, 341–361. https://doi.org/10.1007/s12230-023-09915-5.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. Eur. J. Agron., Modelling Cropping Systems: Science, Software and Applications 18, 235–265. https://doi.org/10.1016/S1161-0301(02)00107-7.

Khan, M.S., van Eck, H.J., Struik, P.C., 2013. Model-based evaluation of maturity type of potato using a diverse set of standard cultivars and a segregating diploid population. Potato Res. 56, 127–146. https://doi.org/10.1007/s11540-013-9235-z.

Liao, X., Su, Z., Liu, G., Zotarelli, L., Cui, Y., Snodgrass, C., 2016. Impact of soil moisture and temperature on potato production using seepage and center pivot irrigation. Agric. Water Manag. 165, 230–236. https://doi.org/10.1016/j.agwat.2015.10.023.

Matson, G.C., Sanford, S., 1913. Geology and ground waters of Florida (Water Supply Paper No. 319). Department of the Interior, United States Geological Survey, Washington, DC.

Milroy, S.P., Wang, P., Sadras, V.O., 2019. Defining upper limits of nitrogen uptake and nitrogen use efficiency of potato in response to crop N supply. Field Crops Res. 239, 38–46. https://doi.org/10.1016/j.fcr.2019.05.011.

Munoz-Arboleda, F., Mylavarapu, R.S., Hutchinson, C.M., Portier, K.M., 2006. Root distribution under seepage-irrigated potatoes in Northeast Florida. Am. J. Potato Res. 83, 463–472. https://doi.org/10.1007/BF02883507.

Prasad, R., Hochmuth, G.J., Boote, K.J., 2015. Estimation of nitrogen pools in irrigated potato production on sandy soil using the model SUBSTOR. PLoS One 10, e0117891. https://doi.org/10.1371/journal.pone.0117891.

Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation, using large scale parameters. Mon. Weather Rev. 100, 81–92. https://doi.org/10.1175/1520-0493(1972)1002.3.CO;2.

R CORE TEAM, 2023. R: A language and environment for statistical computing. R Foundation for Statistical Computing [WWW Document]. URL http://www.r-project.org/.

Rahman, M.H., Patwary, M.A., Barua, H., Hossain, M., Nahar, S., 2014. Evaluation of yield and yield contributing characters of heat tolerant potato (*Solanum tuberosum* L.) genotypes in Bangladesh. Agriculturists 12, 50–55. https://doi.org/10.3329/agric.v12i1.19580.

Raymundo, R., Asseng, S., Cammarano, D., Quiroz, R., 2014. Potato, sweet potato, and yam models for climate change: a review. Field Crops Res. 166, 173–185. https://doi.org/10.1016/j.fcr.2014.06.017.

Raymundo, R., Asseng, S., Prassad, R., Kleinwechter, U., Concha, J., Condori, B., Bowen, W., Wolf, J., Olesen, J.E., Dong, Q., Zotarelli, L., Gastelo, M., Alva, A., Travasso, M., Quiroz, R., Arora, V., Graham, W., Porter, C., 2017. Performance of the SUBSTOR-potato model across contrasting growing conditions. Field Crops Res. Model. Crops genotype phenotype Chang. Clim. 202, 57–76. https://doi.org/10.1016/j.fcr.2016.04.012.

Raymundo, R., Asseng, S., Robertson, R., Petsakos, A., Hoogenboom, G., Quiroz, R., Hareau, G., Wolf, J., 2018. Climate change impact on global potato production. Eur. J. Agron. Recent Adv. Crop Model. Support Sustain. Agric. Prod. Food Secur. Glob. Change 100, 87–98. https://doi.org/10.1016/j.eja.2017.11.008.

Rens, L., Zotarelli, L., Alva, A., Rowland, D., Liu, G., Morgan, K., 2016. Fertilizer nitrogen uptake efficiencies for potato as influenced by application timing. Nutr. Cycl. Agroecosystems 104, 175–185. https://doi.org/10.1007/s10705-016-9765-2.

Rens, L.R., Zotarelli, L., Cantliffe, D.J., Stoffella, P.J., Gergela, D., Fourman, D., 2015. Biomass accumulation, marketable yield, and quality of Atlantic potato in response to nitrogen. Agron. J. 107, 931–942. https://doi.org/10.2134/agronj14.0408.

Rens, L.R., Zotarelli, L., Rowland, D.L., Morgan, K.T., 2018. Optimizing nitrogen fertilizer rates and time of application for potatoes under seepage irrigation. Field Crops Res. 215, 49–58. https://doi.org/10.1016/j.fcr.2017.10.004.

Reyes-Cabrera, J., Zotarelli, L., Dukes, M.D., Rowland, D.L., Sargent, S.A., 2016. Soil moisture distribution under drip irrigation and seepage for potato production. Agric. Water Manag. 169, 183–192. https://doi.org/10.1016/j.agwat.2016.03.001.

Ritchie, J.T., 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res. 8, 1204–1213. https://doi.org/10.1029/WR008i005p01204.

Ritchie, J.T., 1998. Soil water balance and plant water stress. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, pp. 41–54.

Roberts, S., Cheng, H.H., Farrow, F.O., 1991. Potato uptake and recovery of nitrogen-15-enriched ammonium nitrate from periodic applications. Agron. J. 83, 378–381. https://doi.org/10.2134/agronj1991.00021962008300020023x.

da Silva, A.L.B.R., Hashiguti, H.T., Zotarelli, L., Migliaccio, K.W., Dukes, M.D., 2018a. Soil water dynamics of shallow water table soils cultivated with potato crop. Vadose Zone J. 17, 180077 https://doi.org/10.2136/vzj2018.04.0077.

da Silva, A.L.B.R., Zotarelli, L., Dukes, M.D., Agehara, S., Asseng, S., van Santen, E., 2018b. Irrigation method and application timing effect on potato nitrogen fertilizer uptake efficiency. Nutr. Cycl. Agroecosyst. 112, 253–264. https://doi.org/10.1007/s10705-018-9942-6.

da Silva, A.L.B.R., Zotarelli, L., Dukes, M.D., van Santen, E., Asseng, S., 2023. Nitrogen fertilizer rate and timing of application for potato under different irrigation methods. Agric. Water Manag. 283, 108312 https://doi.org/10.1016/j.agwat.2023.108312.

Singh, U., Matthews, R.B., Griffin, T.S., Ritchie, J.T., Hunt, L.A., Goenaga, R., 1998. Modeling growth and development of root and tuber crops, in: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production, Systems Approaches for Sustainable Agricultural Development. Springer Netherlands, Dordrecht, pp. 129–156. https://doi.org/10.1007/978-94-017-3624-4_7.

Soil Survey Staff, 2017. Web soil survey. Natl. Soil Surv. Ctr., Lincoln, NE. [WWW Document]. URL http://websoilsurvey.nrcs.usda.gov/ (accessed 1.31.17).

Thornton, P.K., Hoogenboom, G., 1994. A computer program to analyze single-season crop model outputs. Agron. J. 86, 860–868. https://doi.org/10.2134/agronj1994.00021962008600050020x.

Tooley, B.E., Mallory, E.B., Porter, G.A., Hoogenboom, G., 2021. Predicting the response of a potato-grain production system to climate change for a humid continental climate using DSSAT. Agric. Meteorol. 307, 108452 https://doi.org/10.1016/j.agrformet.2021.108452.

Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), 1998. Understanding Options for Agricultural Production, Systems Approaches for Sustainable Agricultural Development. Springer Netherlands, Dordrecht. https://doi.org/10.1007/978-94-017-3624-4.

USDA, 2023. National Agricultural Statistics Services [WWW Document]. URL https://quickstats.nass.usda.gov/ (accessed 6.9.23).

Wang, C., Zang, H., Liu, J., Shi, X., Li, S., Chen, F., Chu, Q., 2020. Optimum nitrogen rate to maintain sustainable potato production and improve nitrogen use efficiency at a regional scale in China. A meta-analysis. Agron. Sustain. Dev. 40, 37. https://doi.org/10.1007/s13593-020-00640-5.

Wang, H., Cheng, M., Liao, Z., Guo, J., Zhang, F., Fan, J., Feng, H., Yang, Q., Wu, L., Wang, X., 2023. Performance evaluation of AquaCrop and DSSAT-SUBSTOR-Potato models in simulating potato growth, yield and water productivity under various drip fertigation regimes. Agric. Water Manag. 276, 108076 https://doi.org/10.1016/j.agwat.2022.108076.

Webb, R.E., Wilson, D.R., Shumaker, J.R., Graves, B., Henninger, M.R., Watts, J., Frank, J.A., Murphy, H.J., 1978. Atlantic: a new potato variety with high solids, good processing quality, and resistance to pests. Am. Potato J. 55, 141–145. https://doi.org/10.1007/BF02852087.

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L.D., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T.L., Miller, E., Bache, S.M., Müller, K., Ooms, J., Robinson, D., Seidel, D.P., Spinu, V., Takahashi, K., Vaughan, D., Wilke, C., Woo, K., Yutani, H., 2019. Welcome to the tidyverse. J. Open Source Softw. 4, 1686. https://doi.org/10.21105/JOSS.01686.

Willmott, C.J., Ackleson, S.G., Davis, R.E., Feddema, J.J., Klink, K.M., Legates, D.R., O'Donnell, J., Rowe, C.M., 1985. Statistics for the evaluation and comparison of models. J. Geophys. Res. Oceans 90, 8995–9005. https://doi.org/10.1029/JC090iC05p08995.

Woli, P., Hoogenboom, G., 2018. Simulating weather effects on potato yield, nitrate leaching, and profit margin in the US Pacific Northwest. Agric. Water Manag. 201, 177–187. https://doi.org/10.1016/j.agwat.2018.01.023.

Woli, P., Hoogenboom, G., Alva, A., 2016. Simulation of potato yield, nitrate leaching, and profit margins as influenced by irrigation and nitrogen management in different soils and production regions. Agric. Water Manag. 171, 120–130. https://doi.org/10.1016/j.agwat.2016.04.003.

Worthington, C.M., Hutchinson, C.M., 2006. Yield and quality of 'Atlantic' and 'Harley Blackwell' potatoes as affected by multiple planting dates, nitrogen rates and growing degree days. Proc. Fla State Hort. Soc. 119, 275–278.

Zotarelli, L., Rens, L.R., Cantliffe, D.J., Stoffella, P.J., Gergela, D., Fourman, D., 2014. Nitrogen fertilizer rate and application timing for chipping potato cultivar Atlantic. Agron. J. 106, 2215–2226. https://doi.org/10.2134/agronj14.0193.

Zotarelli, L., Rens, L.R., Cantliffe, D.J., Stoffella, P.J., Gergela, D., Burhans, D., 2015. Rate and timing of nitrogen fertilizer application on potato 'FL1867'. Part I: plant nitrogen uptake and soil nitrogen availability. Field Crops Res. 183, 246–256. https://doi.org/10.1016/j.fcr.2015.08.007.