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Sensitivity of Potato Yield and Biomass to Climate Change Effects in Gisozi, Burundi, and Washington, USA, and Assessment of LINTUL4 Model Behavior

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Abstract: Understanding climate change effects on crop production and evaluate the effectiveness of adaptation strategies in both developed and developing countries is of key importance. Crop simulation models can provide useful insight on the effects of increasing temperatures and rising CO_2 concentrations [CO_2] as well as rainfall variations. In this study, the LINTUL4 model was used to study the sensitivity effect of five temperature (T) levels (-3, 0, 3, 6, and 9^{o}C above/below minimum/maximum temperatures), three precipitation (W) changes (30% decrease, baseline and 30% increase), and CO_2 levels (baseline(360), 450, 540, 630 and 720ppm) on nutrient limited yield (Yn), water limited yield (Yw), water and nutrient limited yield (Ynw) and potential yield (Yp) of potato crop in high-input Washington, USA and low-input Gisozi, Burundi. The maximum weight of the tuber yield and aboveground biomass for Yp and Yw in Gisozi, and Yn and Yp in Washington was observed at combinations of lower temperature and elevated [CO_2]. For Gisozi, maximum tuber yield for Yn and Ynw was observed at [CO_2] of less than 720ppm. The results suggest that nutrient supply will continue to be the major limiting factor for potato production under elevated [CO_2] in Gisozi, and water availability will limit Yw and Ynw rain-fed production in Washington. Generally, the LINTUL4 model performs well with few data input, but fails to predict the differential effect of high temperature on assimilate partitioning to aboveground and belowground biomass.

Keywords: Climate Change, LINTUL4, Potato yield

Introduction

Climate change has become one of the most important concerns for humanity. Being the most important greenhouse gas, the atmospheric CO_2 concentration ([CO_2]) has reached 400 ppm in November 2015 (NOAA/ESRL, 2016) compared to 278 ppm during industrial revolution, in 1750 (Stocker *et al.*, 2013). Between 2002–2011 the concentration has increased at an average rate of 2.0 ± 0.1 ppm per year, faster than during any other decades since direct atmospheric [CO_2] measurement has begun in 1958 (Ciais *et al.*, 2014). Recent research shows that changing climate and variability will significantly affect agricultural activities in both developing and developed countries (www.agmip.org), and compromises food security for the increasing world population that is expected to reach 9 billion in 2050. The climate change impact depends on intensity and distribution of precipitation, temperature change and atmospheric CO_2 level (Howden *et al.*, 2007; Reilly *et al.*, 1996).

The major climate change repercussion on agriculture arises from changes in temperature, [CO_2] and change in rainfall distribution and intensities and combinations of variables (Amthor, 2001; Haverkort and Verhagen, 2008). Water is the major component of plant tissue, and when the availability of water is less than the amount needed for optimal plant growth, the yield will be reduced. Most of the water absorbed by plants, 99%, is transpired and the remaining is used for metabolic purposes (Van Loon, 1981). Climate change affects precipitation patterns during the crop growing season and affects plant available water in the soil. Plants in turn respond to precipitation change by altering physiological processes such as growth, transpiration, photosynthesis and enzymatic activities. The effect of precipitation on crop yield varies depending on crop sensitivity to moisture and the developmental stage of the crop. On crops such as potato (*Solanum tuberosum L.*) the effect of water shortage on the yield intensifies during tuber bulking stage (Van Loon, 1981).

The consistent temperature rise, due to climate change, also has a direct effect on plant growth and development, and has the potential to alter global agricultural systems by changing land suitability and length of growing season. Some cold parts of the world benefit from rising temperature, but other arid and semi-arid parts of the world where crops are grown close to their thermal tolerance limits will suffer most and many of these marginal agriculture areas are likely to be forced out of production (Collier *et al.*, 2008). The rising temperature affects plant phenology, photosynthesis, autotrophic respiration and evapotranspiration. Higher temperature increases respiration at the cost of photosynthesis, and increases plant growth rate and reduces length of growing season and subsequently time for light interception and photosynthesis. As a consequence yield and biomass production diminish (Asseng *et al.*, 2013; Supit *et al.*, 2010). The magnitude of temperature effects on yield also depends on crop developmental stage. A few days of high temperature during flowering stage in arid and semi-arid parts can seriously affect the yield of some crops. Seasonal temperature fluctuation during growing seasons (during anthesis/tuberization and maturity) also affect grain yield. Early warmer temperature facilitates anthesis (flowering) and later cooler temperature enhances grain yield (Asseng *et al.*, 2013). The damage from heat stress, disease, and pest infestation also increases with rising temperature (Haverkort and Verhagen, 2008).

The adverse effects of climate change on potential yield needs to be combined with the potential benefit from 'carbon fertilization effect' caused by elevated CO_2. The results from greenhouse, field chamber, laboratory chamber and Free-Air CO_2 Enrichment (FACE) experiments suggest that elevated CO_2 has a potential to moderate yield increase (Amthor, 2001; Collier *et al.*, 2008). An increased [CO_2] stimulates plant growth and increases crop yield and biomass (Hijmans, 2003; Idso *et al.*, 1987). However, plants differ in their response to elevated CO_2 (Cure and Acock, 1986). Under elevated [CO_2], C3-plants (e.g. potato and wheat) reduce stomatal opening and transpiration, improve water use efficiency, increase net CO_2 fixation, which increases plant dry matter weight, even at low water availability (Amthor, 2001). Whereas, C4-plants (e.g. maize and sorghum) do not directly respond to elevated [CO_2]. Yet there is evidence that shows drought tolerance of both C3- and C4- plants increases under elevated CO_2 (Bishop *et al.*, 2014; Morison and Gifford, 1984).

Potato grows in a wide range of agro-ecological zones and is well adapted to various environments (http://www.fao.org/docrep/010/i0200e/I0200E10.htm). Temperature and photoperiod are considered to be the two most important determining factors for potato growth and development. The crop is best adapted to cooler frost free temperate and tropical highland climates. Being the most important tuber crop and the third most important food crop in the world, following wheat and rice (Haverkort and Struik, 2015 ; http://cipotato.org/potato/facts/), the predicted change in potato yield can be one of the indicators for how climate change affects global food production.

Potato is very sensitive to water stress (van Loon, 1981), higher temperature (Allen *et al.*, 1996; Haverkort and Verhagen, 2008; Kooman and Haverkort, 1995; Kooman and Rabbinge, 1996; Pulatov *et al.*, 2015) and rising CO_2 (Lee *et al.*, 2020). Potato dry matter concentration reduces with increasing temperature, and low dry matter concentration affects storability and processing quality (Haverkort and Verhagen, 2008). In addition, low dry matter concentration hampers potato growth in warm places. The lower temperature threshold varies between 0-5^{o}C, with optimum being 13-24^{o}C, and temperatures above 25-30^{o}C increase leaf senescence and reduce crop yield (Kooman and Rabbinge, 1996; Pulatov *et al.*, 2015). At higher temperature assimilates are allocated to leaf and consequently tuber formation is reduced. In warm areas, higher temperature enhances phenological development and reduces the time required for light interception; whereas cold regions benefit from an increased length of growing season. Temperature below 0^{o}C severely affects potato growth and yield. The rising CO_2 increases the tuber yield (mainly by increasing tuber size) but the tuber quality is reduced (Craigon *et al.*, 2002; Fangmeier *et al.*, 2002; Lee *et al.*, 2020).

Crop models are widely used to simulate the effect of global change and crop management. Models integrate several climatic, edaphic, biological factors, and crop management aspects to answer how the variables interact and influence yield formation, and aid decisions to maximize yield or minimize yield loss. Models are broadly categorized into statistical (empirical) models and process based models. Statistical (empirical) models are descriptive and use empirical functions derived from observations. Hence, they are limited to a spatial and temporal condition where they are developed. Whereas mechanistic or physiological crop models are mathematical representations of our understanding of biophysical processes such as photosynthesis, respiration, allocation and evapotranspiration, and crop responses to environmental factors. Crop growth is therefore explained based on the underlying physiological processes and environmental conditions. Unlike empirical models, process based models can be used to predict yields beyond temporal and spatial scope as long as the underlying processes are captured.

Application of dynamic and process-based crop simulation models is important to enhance our understanding of the impacts of climate change and variability on crop production systems. Process-based crop models differ in the way they simulate dynamic processes and simulate results due to their difference in approaches, complexity, ability to capture reality and sensitivity to input parameters (Asseng *et al.*, 2013). Testing and comparing models performance under changing environmental and management conditions, and using efficient and suitable models for the desired objective is crucial to plan appropriate climate mitigation and adaptation responses in agricultural and food security sector (Martre *et al.*, 2015); www.agmip.org).

LINTUL model (LIght INTerception and UtiLization) is a mechanistic crop model developed by the Wageningen University (Shibu *et al.*, 2010). It simulates dry matter production based on intercepted light and light use efficiency in the absence of yield reducing factors such as pests, disease and weeds. The model is helpful to simulate yield gap between benchmark yield (which could be potential, water or nutrient limited yield) and actual yield. It is generic and can be applied to annual crops. It predicts crop yield and biomass with low data input. LINTUL reacts to temperature and day-length and it helps to select appropriate crop cultivar for selected environmental condition (Kooman and Haverkort, 1995). It was originally applied to simulate growth and yield of potato

(Spitters, 1990) and later extended to other crops. It was extensively used for yield estimation and growth analysis of crops such as maize, rapeseed, crambe, grain amaranth and grasses (Gimplinger and Kaul, 2012), wheat production under elevated C and temperature change (Wolf *et al.*, 2002). Gimplinger and Kaul (2012) used LINTUL for the characterization of potato agro-ecology and to simulate biotic and abiotic stresses. The model accurately predicted the effect of various irrigation regimes on yield and soil moisture in Northern Spain (Farré *et al.*, 2000). The detailed information of the model on crop phenology, radiation use efficiency, biomass partitioning and soil and nitrogen balance can be found on Shibu *et al.* (2010).

LINTUL4 is one of the models that are included in Agriculture Model Intercomparison and Improvement Project (AgMIP) to assess climate impact on potato in agro-ecologically diverse regions of the world including Bolivia, Peru, USA, Burundi and Denmark. The objective of the AgMIP project is to improve crop-climate interactions and promote the application of best performing models or model-ensembles in climate impact assessments (Asseng *et al.*, 2013; Rosenzweig *et al.*, 2013). Previous study in AgMIP wheat plot by Asseng *et al.* (2013) showed that partially calibrated and fully calibrated models were able to reproduce observed experimental data, but uncertainty was reduced after full calibration. Fleisher *et al.* (2017) also used nine partially calibrated and fully calibrated potato models to inter-compare the performance of the models across varying climates. In this study fully calibrated LINTUL4 model was used with the objective of assessing the effect of precipitation, temperature and CO_2 on potato production in Washington, USA, and Gisozi, Burundi, and how the model responds to climate change and suggest ways through which the model can be improved. The specific objective of the present study is: i) to understand how climate change affects potato yield in Washington site, USA (representative of a high input system in a developed country) and Gisozi site, Burundi (representative of a low input, rain-fed system in sub-Saharan Africa) ii) to understand the major limiting factors for potato production under changing climate, and (iii) to assess how the LINTUL4 model behaves under nutrient limited yield (Yn), water limited yield (Yw), water and nutrient limited yield (Ynw) and potential yield (Yp).

Methodology

Definition of concepts

- Yield potential or potential yield (Yp) is a yield of a crop cultivar obtained when a crop is grown with optimum water and nutrient supply and completely protected against growth-reducing factors (Van Ittersum and Rabbinge, 1997; van Ittersum *et al.*, 2003). The yield is limited by growth defining factors (radiation intensity, carbon dioxide concentration, temperature and crop characteristics) and optimized by improving crop management aspects such as sowing date, sowing density and breeding.
- Water limited yield (Yw) is the production ceiling for rainfed (water-limited) condition with optimum nutrient supply and optimal crop management. The growth-limiting factor, in this case, soil moisture level, is influenced by soil type, topography and management (Wolf *et al.*, 2015).
- Nutrient limited yield (Yn) is the maximum yield that can be obtained under nutrient limited condition (Diepen *et al.*, 1989), but the crop is provided with optimum water supply and crop management.
- Nutrient and water limited yield (Ynw) is yield that can be obtained under both nutrient and water limited conditions.

Study location

This simulation was conducted in two AgMIP potato study sites: namely Gisozi, Burundi, and Washington, USA (Rosenzweig *et al.*, 2013). The study sites were purposefully selected to understand the climate change impact on potato production in high input system in developed countries such as USA and a low input, rain-fed system in sub-Saharan Africa. The two sites differ in their agro-ecology and agricultural input. The Gisozi site is located in the tropical highland at an elevation of 2091masl with 29.68E longitudes and 3.57S latitude. The Washington site is situated at low altitude temperate region (an elevation of 520masl) and 45.9N latitude and 119.5W longitude. The soil type in Gisozi is loamy with medium and fine sized alluvial deposits whereas that of Washington is sandy.

The potato varieties and the management used in the two sites also differ. Both potato varieties are moderately photoperiod sensitive, but the Gisozi potato variety, victoria cultivar (yellow fleshed Dutch potato), is early maturing, and the one tested in Washington, Ranger Russet cultivar, is late maturing. The Washington site is high input (supplied with automated irrigation system, and 572.6kg ha^{-1} of nitrogen fertilizer was broadcasted at different times during the growing season). Gisozi site is low input (rainfed production with organic fertilizer amendments), and a total of 100 kg/ha of nitrogen fertilizer, 20 tons of manure/ha, 150kg ha^{-1} of phosphate and 100 kg/ha of K fertilizer was applied at planting. In both sites tubers were pre-sprouted at planting. The planting density was 50700 plants/ha in Washington and 41,667plants/ha in Gisozi. The planting density is high in Washington because the Ranger Russet potato cultivar sets few large tubers that benefit from closer seed-drop spacing. The detailed information about the management in the study sites is presented in Table 1.

Table 1 - Experimental conditions of the study sites (Washington in 2004, and Gisozi in 2007).

MANAGEMENT AND SOIL PARAMETERS	STUDY SITE	
Management type	Washington	Gisozi
Cultivar	Ranger Russet	Victoria
Seed size (g of DM)	10	10
Planting depth (cm)	18	10
Row-Spacing (m)	0.23	0.3
Distance between rows (m)	0.86	0.8
Density (pl ha^{-1})	50700	41667
Initial mineral nitrogen (kg ha^{-1})	120	60
Nitrogen fertilizer applied (kg ha) Manure applied (t ha^{-1})	572.6 0	100 20
Emergence date (Julian day number)	110 (April 20)	223 (August 11)
Maturity date	235	345
Irrigation treatment	Yes	No (rainfed)
SOIL PARAMETERS		
Maximum rootable depth (depth of water uptake in cm)	120	100
Saturation (cm^3cm^{-3})	0.388	0. 5855
Field Capacity (cm^3cm^{-3})	0.1722	0.34
Wilting Point (cm^3cm^{-3})	0.0812	0.1915

Model calibration

Before starting the calibration process, daily weather data (maximum and minimum temperatures, radiation, vapour pressure, precipitation and average wind), soil data (maximally rootable soil depth, water holding capacity at field capacity and wilting point), crop data and management information (planting/emergence date, physiological maturity) of the sites were collected. Then to obtain a match between simulated and observed values, LINTUL4 was calibrated with local soil, weather and management parameters (Table 1). The standard crop data file was used and subsequently adapted for temperature sums (TSUMs), nitrogen uptake and radiation use efficiency (RUE). The crop CO_2 effects was reported by ALLEN *et al.* (1990) , Goudriaan *et al.* (1984), Goudriaan *et al.* (1985), Goudriaan (1990), Goudriaan and De Ruiter (1983), Goudriaan and Unsworth (1990), and Idso (1990), and on literature surveys on crop responses to C doubling by Cure (1985), Cure and Acock (1986), and Kimball (1983). Field experiments under doubled C done more recently, appeared to give lower CO_2 responses due to more plant interaction (e.g. shadowing in canopy), being about 25 to 40% yield increase for doubled CO_2 (De Temmerman *et al.*, 2002; Wolf and Van Oijen, 2002; Wolf and Van Oijen, 2003; Wolf *et al.*, 2002). The fertilization effect of elevated atmospheric [CO_2] curve indicated in Figure 1 is based on the above papers.

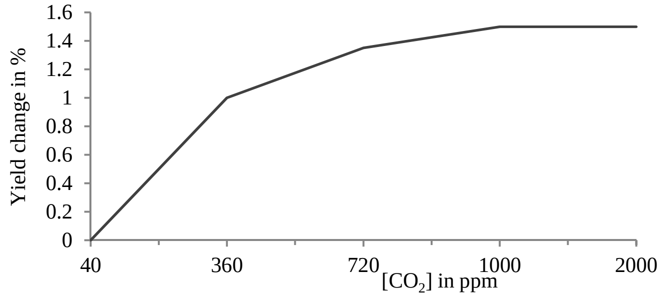

Figure 1-Yield change response for potato plant at different concentration of CO_2. The model considers yield change at 40ppm C =0; at 360ppm (baseline) = 1, the effect continues to increase to a maximum of 1.5 at 1000ppm and then stagnates.

The procedure was started by setting actual emergence date and appropriate TSUM that fit to the observed growth duration. TSUM1 (thermal time from emergence to tuber initiation) was calibrated first, and then TSUM2 (tuber initiation to maturity) was followed. The actual emergence date and appropriate TSUMs that fit to the observed growth duration was set. The Gisozi potato emerged on Julian day 223, and reached physiological maturity on DOY 345. The TSUM1 for Gisozi was set at 120°C d (9 days after emergence) and TSUM2 was set at 1700°C d (122 days after emergence). The Washington potato emerged on Julian day 118, and reached physiological maturity on DOY 209. TSUM1 value for Washington was set to 200°C d and 1610°C d for TSUM2. The role and effect of nutrients other than nitrogen was not included in the model and therefore their effect was not considered. The surface N residue at Gisozi site was estimated to 60kg ha^{-1}, and this amount was considered as pre-planting fertilizer input. The nitrogen content of 20 tons/ha manure applied at Gisozi site was corrected and added to the 100kg ha^{-1} of mineral fertilizer (urea) at planting. At Washington a total of 572.6 kg ha^{-1} nitrogen fertilizer was applied on different days of the growing season (206 kg ha^{-1} was applied on DOY 72, initial application day), and 56 kg ha^{-1} surface N residue on top 30 cm soil depth was considered as an additional pre-planting fertilizer. The root mean square error (RMSE) and mean bias error (MBE), the regularly employed statistical indictors in meteorology, air quality and climate research studies (Chai and Draxler, 2014), Willmott (1981) coefficient of agreement (*d*-index) and graphical comparisons between observed and simulated values were used to select the best RUE for tuber yield, and aboveground biomass. MAE and RMSE are calculated as:

$$\text{MBE} = \left(\frac{1}{n}\right) \sum_{\mathrm{i}=1}^{\mathrm{n}} |\mathrm{ei}|$$

$$\text{RMSE} = \sqrt{\left(\frac{1}{n}\right) \sum_{i=1}^{n} ei^2}$$

where n is number of comparisons and e_i is model error for sample i.

To complement the MBE, RMSE and graphical comparisons, Willmott (1981) coefficient of agreement (*d*-index) was used. The d-index measures the degree to which a model’s predictions are error free or the degree to which observed deviations about observed means (O bar) correspond, both in size and sign, to predicted deviations about O. The d-index varies between 0.0 and 1.0. The d-value equal to 1 indicates a complete agreement between observed and predicted values and 0 indicates no agreement at all.

$$d = \frac{\sum_{i=1}^{n}(Oi - Pi)^2}{\sum_{i=1}^{n}(|\mathrm{Pi} - \mathrm{Obar}| + |\mathrm{Oi} - \mathrm{Obar}|)(Oi - Pi)^2}$$

where O_i is the observation value and Pi is the forecast value and Obar is the average observation values and Pbar is the average forecast values.

Table 2 -Observed experimental results of tuber yield and Aboveground Biomass (AGB) and calculated Harvest Index (HI) for Victoria variety at Gisozi site (2007) and Ranger Russet variety at Washington site (2004).

VICTORIA VARIETY AT GISOZI SITE				RANGER RUSSET VARIETY IN WASHINGTON			
DOY	Dry matter biomass		HI (fraction)	DOY	Dry matter biomass		HI (fraction)
	tuber yield (t ha^{-1})	AGB (t ha^{-1})			tuber yield (t ha^{-1})	AGB (t ha^{-1})	
223	Emergence date	-	-				
232	0 (tuber initiation)	na*	na*	118	0	0	0
284	4.5	6.3	0.71	134	0	0.98	0.00
297	6.9	8.3	0.83	150	0.97	3.64	0.27
298	(50% tuberization)	na*	na*	158	4.55	10.93	0.42
311	7.7	9.0	0.85	175	9.75	15.48	0.63
325	6.8	7.5	0.92	194	12.97	16.72	0.78
345	na* (Maturity)	na*	na*	**209	12.34	17.70	0.70
347	Harvest	na*	na*	237	22.08	28.40	0.78

na - data not available*
*** - not considered in error calculation during calibration*

Scenario analysis

Thirty year historic daily weather data (1980-2009) of precipitation (mm/d), maximum and minimum temperatures (^{o}C), solar radiation (kJ $m^{-2}d^{-1}$), vapour pressure (kPa) and wind (ms^{-1}) was used for simulations. Quality control of baseline weather data and bias correction for outliers and anomalous values were carried out by Agricultural modelling version of the Modern Era Retrospective-Analysis for Research and Applications (AgMERRA)[1]. The historical weather data were modified on a daily basis to include variations in C, T, and/or W.

The simulations were conducted for five CO_2 levels (360, 450, 540, 630, 720 ppm), five minimum and maximum temperature changes (-3, 0, +3, +6, +9^{o}C) and three rainfall changes (-30, 0, +30%). The extreme values of temperature was included in the scenario analysis mainly to assess how the model behaves under behaves under such conditions. The simulation was done for four production systems: Yw, Yn, Ynw and Yp. Since the automated irrigation removes yield and biomass loss from water deficiency, the effect of precipitation was investigated by switching the model to water limited yield. Nutrient

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[1] *AgMERRA provides historical climate datasets for daily outputs from retrospective analyses, gridded temperature and precipitation stations, and satellite information for solar radiation and rainfall (http://data.giss.nasa.gov/impacts/agmipcf/agmerra/ Retrieved January 2, 2018).*

limited and potential yield were simulated by setting the model on automated irrigation, and automated irrigation plus unlimited nutrient supply respectively. In general for both sites a total of 12000 simulation were conducted; 9000 simulation runs for Yw and Ynw (2 production systems*3W*5T*5C*30 ‘weather years’*2sites), and 3000 simulation runs for Yn and Yp in both sites (2 production systems*5T*5C*30 ‘weather years’*2sites). Finally the tuber yield and aboveground biomass simulation results for each production system and combination of climate variables were analysed with respect to a baseline scenario of 360 ppm C and 1980-2009 temperature and precipitation levels (i.e. with respect to C1T2W2). Model behaviour and average yield and biomass response to changes in individual and multiple climate variables were analysed.

Table 3 - C, temperature change and precipitation changes used for scenario analysis

C		TEMPERATURE (T)		RAINFALL (W)	
Code	Value (ppm)	Code	Value (^{o}C)*	Code	Value (%) **
C1	360	T1	-3	W1	-30%
C2	450	T2	0	W2	0
C3	540	T3	3	W3	+30%
C4	630	T4	6		
C5	720	T5	9		

** Increased/decreased values from baseline daily minimum and maximum temperatures*
*** Increase/decrease from baseline daily rainfall amount*

Results

Model calibration

Based on the calibrated values, RUE of 2.2 gram dry mass per mega joule of photosynthetically active radiation (g DM/MJ PAR) was considered to be best-fit to simulate potato yield at Gisozi site (with MBE of 8% and 10%, and RMSE of 33% and 33% for tuber yield and aboveground biomass respectively) and RUE of 2.8 g DM/MJ PAR was selected to simulate yield at Washington (with MBE of 13% and 18%, and RMSE of 17% and 20% for tuber yield and aboveground biomass respectively). The graphical comparison of observed and simulated tuber yield and aboveground biomass for both sites is shown in Figure 2. The observed tuber yield and aboveground biomass shows a much different trajectory of decline due to delayed harvest time (maturity was exceeded and harvest was delayed). There are very few sampling points in Gisozi site because the data collection was started late due to logistics issues. The LINTUL4 model generally overestimates the tuber yield and aboveground biomass at Gisozi site, but reasonably mimics the observed values at Washington (see Figure 2c&d). The parameters used for calibration and the simulated and observed tuber yield and aboveground biomass values at selected RUE is indicated on Table 4.

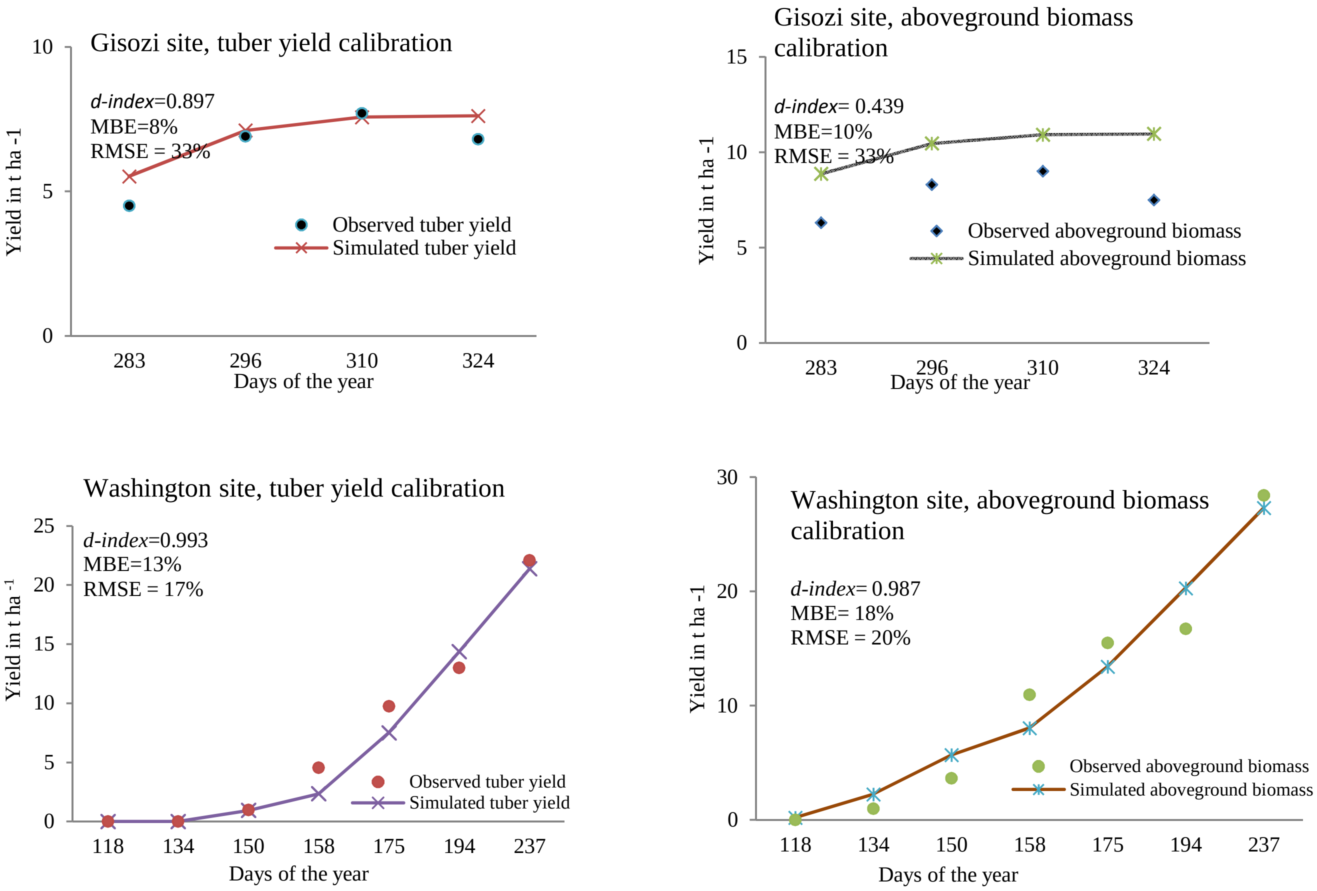

Figure 2 - Comparison of simulated and observed values of tuber yield and aboveground biomass in t ha^{-1} using LINTUL4.

Table 4 - Parameters calibrated in LINTUL4 model and the observed and simulated yields for low input Gisozi at RUE (2.2 g DM/MJ PAR) and high input Washington site at RUE (2.8 g DM/MJ PAR).

FACTORS		GISOZI SITE	WASHINGTON SITE
Parameters	TSUM1	120°C d	200°C d
	TSUM2	1700°C d	1610°C d
	Observed tuber yield (t ha^{-1})	6.8	22.1
Variables	Simulated tuber yield (t ha^{-1})	8.3	20.8
	Observed aboveground biomass (t ha^{-1})	7.5	28.4
	Simulated aboveground biomass (t ha^{-1})	10.5	25.7

TSUM1 - Temperature sums from emergence to tuber initiation (^oC d)
TSUM2 - Temperature sums from tuber initiation to maturity (^oC d)

Nutrient Limited yield (Yn) and nutrient and water limited yield (Ynw)) in Gisozi

The simulated Ynw result for Gisozi is summarized in Table 5. At baseline precipitation and temperature (T2W2) the highest tuber yield for Ynw was observed at 540ppm. Further CO_2 increase to 630 and 720 ppm reduces tuber yield, but the aboveground biomass continues to increase till 720 ppm and consequently the HI is reduced. Temperature fall to T1 (-3^{o}C from baseline) or rise beyond baseline temperature affects tuber yield negatively. At lower temperatures (T1) aboveground biomass is highest at 360ppm and 430ppm, and further CO_2 increase from 450 to 750ppm affects Ynw negatively (Table 5 and Figure 3a & 4a). At temperatures above baseline both tuber yield and aboveground biomass increase with increasing CO_2. Concerning the effect of precipitation a 30% precipitation reduction from baseline (T2C1W2) decreases the tuber yield and aboveground biomass by 10.7% and 8.4% respectively; whereas 30% precipitation addition increased the tuber yield and aboveground biomass by 5.8% and 4.6% respectively (Table 5). The effect of CO_2 on Y_n was almost similar to that of Ynw (Figure 3b for tuber yield and in Figure 4c for aboveground biomass). Similar to Ynw the yield loss for Yn intensifies at low temperature and higher CO_2, and the highest Yn tuber yield and aboveground biomass was observed at T3C5. The Yn tuber yield was reduces by 22% at T1C1 and by 15.5% at T3C1 (Table 8).

Water limited (Yw) and potential yield (Yp) in Gisozi

The maximum simulated Yw and Yp was observed at T1W3C5 (a combination of lowest temperature, highest precipitation and highest [CO_2]) (Figure 3c & d). At T2C5 the tuber yield and aboveground biomass each increased by about 50% for Yw and by above 50% for Yp from baseline scenario of T2C1. Whereas increasing temperature affects Yw and Yp negatively. Temperature rise by 3^{o}C and beyond causes significant yield loss to Yw and Yn (Figure 3d and Table 10). The potential yield (Yp) increases by 70% for tuber yield and 75% for aboveground biomass as compared to baseline Ynw. However, the effect of CO_2 on Yp was rapid initially but continues to slow with progressive increase in CO_2 (Figure 3d).

Table 5 - Dry weight of Water and nutrient limited (Ynw) tuber yield and aboveground biomass (AGB) (t ha^{-1}) at different CO$_2$, temperature and precipitation levels in Gisozi, Burundi

	C1 (360 ppm)		C2 (450 ppm)		C3 (540 ppm)		C4(630 ppm)		C5 (720 ppm)	
	Tuber	AGB	Tuber	AGB	Tuber	AGB	Tuber	AGB	Tuber	AGB
T1W1	6.3	10.0	6.0	10.0	5.7	9.9	5.3	9.8	5.0	9.7
T1W2	6.4	10.1	6.1	10.1	5.7	10.0	5.4	9.9	5.1	9.9
T1W3	6.5	10.2	6.1	10.1	5.7	10.0	5.4	10.0	5.1	9.9
T2W1	6.1	8.6	6.4	9.2	6.7	9.7	6.7	10.0	6.7	10.2
T2W2	6.8	9.4	7.1	9.9	7.2	10.3	7.1	10.5	7.0	10.6
T2W3	7.2	9.8	7.4	10.3	7.4	10.5	7.3	10.7	7.2	10.8
T3W1	3.8	5.3	4.3	6.0	4.9	6.7	5.4	7.4	5.9	8.1
T3W2	4.5	6.0	5.1	6.8	5.7	7.6	6.3	8.3	6.7	9.0
T3W3	4.9	6.5	5.6	7.3	6.2	8.1	6.8	8.9	7.3	9.5
T4W1	1.9	2.7	2.2	3.1	2.4	3.4	2.7	3.9	3.1	4.3
T4W2	2.2	3.0	2.5	3.4	2.8	3.9	3.2	4.3	3.6	4.8
T4W3	2.4	3.3	2.7	3.7	3.1	4.1	3.5	4.6	3.9	5.1
T5W1	0.7	1.1	0.8	1.2	0.9	1.3	1.0	1.5	1.1	1.6
T5W2	0.8	1.2	0.9	1.3	1.0	1.5	1.1	1.6	1.2	1.8
T5W3	0.8	1.2	1.0	1.4	1.1	1.6	1.2	1.7	1.3	1.9

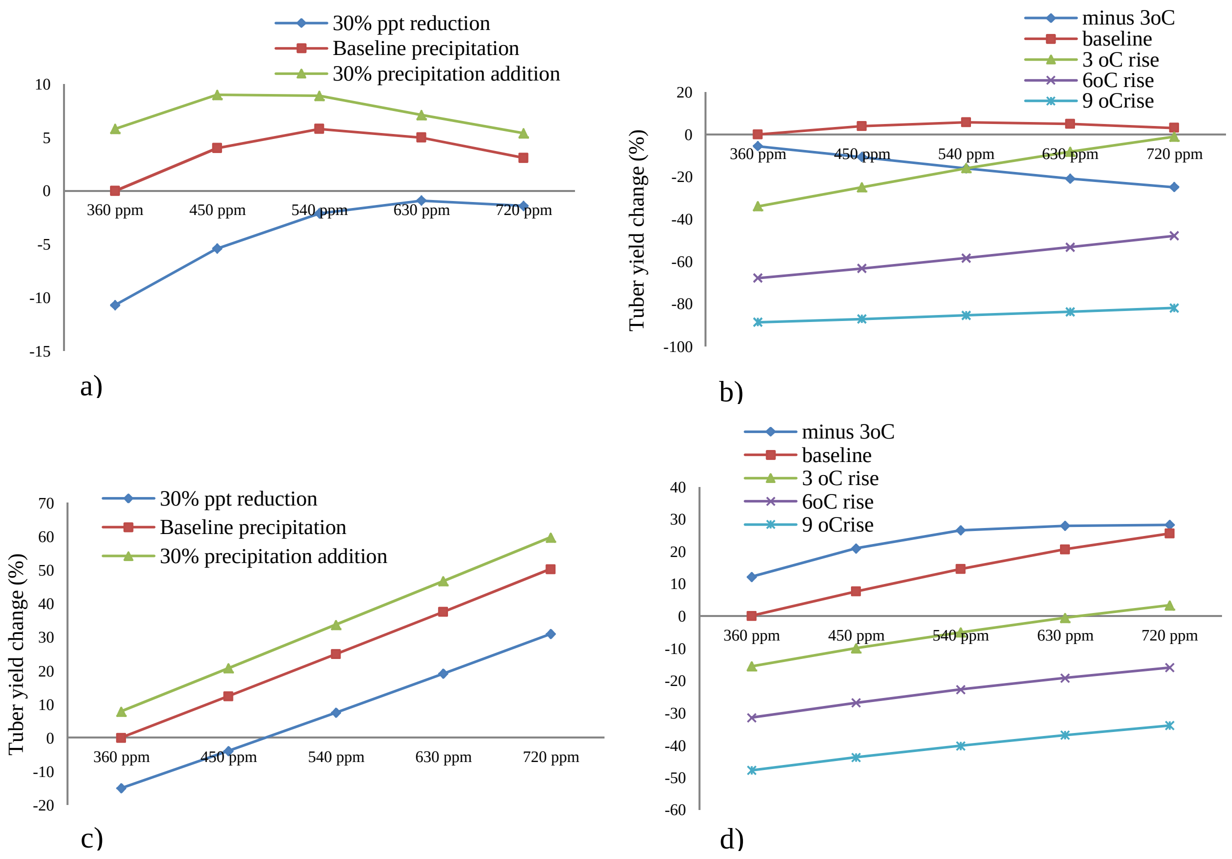

Figure 3 - effect of temperature, CO$_2$ and precipitation on tuber yield in Gisozi as simulated by LINTUL4 (a) Ynw, (b) Yn (c) Yw and (d) Yp

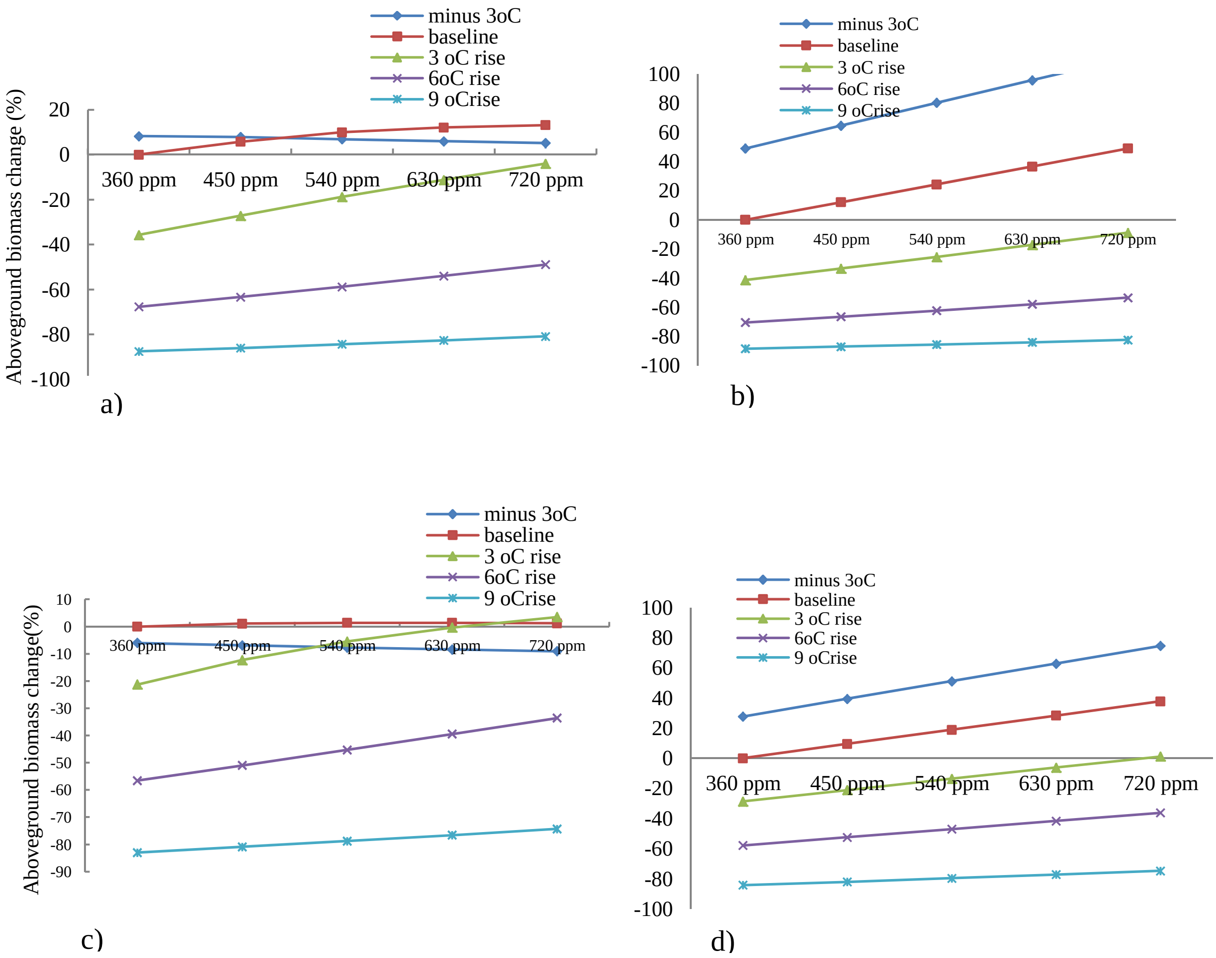

Figure 4 - Effect of temperature, CO_2 and precipitation on aboveground biomass in Gisozi as simulated by LINTUL4 (a) Ynw, (b) Yw (c) Yn and (d) Yp.

Simulation results for Washington site

The current production system in Washington site is high input as compared to Gisozi site. It was supplied with automated irrigation system and almost optimum amount of nutrient was delivered. Therefore, it was not truly nutrient limited (‘Yn’) and the simulated Yn was closer to Yp (22.2 t ha^{-1} for Yn (Table 6) and 24.6 t ha^{-1} for Yp (Table 11)). The Yp and ‘Yn’ were highest at a combination of low temperature and higher CO_2. Temperature rise negatively affects the crop yield (Figure 5a and Table 6). For instance a temperature rise by 3^{o}C and 6^{o}C from C1W2T2 reduces tuber yield from 22.2 t ha^{-1} to 18.7 t ha^{-1} at C1W2T3 and to 15.2 t ha^{-1} at C1W2T4 respectively (Table 6). However, the effect of CO_2 on Yn and Yp slows with rising CO_2. The rate of tuber yield increase due to change in CO_2 is almost proportional with that of aboveground biomass. The benefit of elevated CO_2 on tuber yield and aboveground biomass was annulled when the temperature rises beyond 3^{o}C.

Table 6 - Effect of CO_2 and temperature change on aboveground biomass (AGB) and tuber yield *(t ha^{-1}) for an irrigated system (Yn) in Washington with respect to baseline CO_2 and 1980 to 2009 daily weather data.)*

	C1 (360 ppm)		C2 (450 ppm)		C3 (540 ppm)		C4(630 ppm)		C5 (720 ppm)	
	Tuber	AGB	Tuber	AGB	Tuber	AGB	Tuber	AGB	Tuber	AGB
T1	24.8	31.0	26.8	33.6	28.0	35.4	28.3	36.2	28.4	36.7
T2	22.2	27.7	23.8	29.9	25.3	31.8	26.7	33.5	27.8	34.8
T3	18.7	23.6	19.9	25.2	21.0	26.5	22.0	27.8	22.9	28.8
T4	15.2	19.2	16.2	20.5	17.1	21.6	17.9	22.6	18.6	23.4
T5	11.6	14.6	12.5	15.7	13.2	16.7	14.0	17.6	14.6	18.4

Water and Nutrient-limited yield for Washington site

The simulated potato yield at Washington was significantly dependent on availability of irrigation water. Switching the automated irrigation system to rainfed production significantly reduces the tuber yield and aboveground biomass of potato production at Washington. The baseline tuber yield and aboveground biomass under rainfed production system (Yw and Ynw) was reduced by more than three-fold when compared with ‘Yn’ (22.1 t ha^{-1} tuber yield and 28 t ha^{-1} dry weight aboveground biomass for Yn at T2W2C1 to 7 t ha^{-1} tuber yield and 12 t ha^{-1} dry weight for aboveground biomass for Yn T2W2C1) (compare Table 6 and Table 12) . Similarly the tuber yield and aboveground biomass at T2W2C1 for Ynw was 7.2 and 11.9 t ha^{-1} respectively. At W2C1 the optimum temperature for Yw was above the baseline temperature (T2) (Yw is shown in Figure 5b and Table 12). The maximum yield was observed at T2W3C5 (combination of baseline temperature, highest precipitation and elevated [CO_2]. The relative tuber yield increase at elevated CO_2 is rapid at high temperatures.

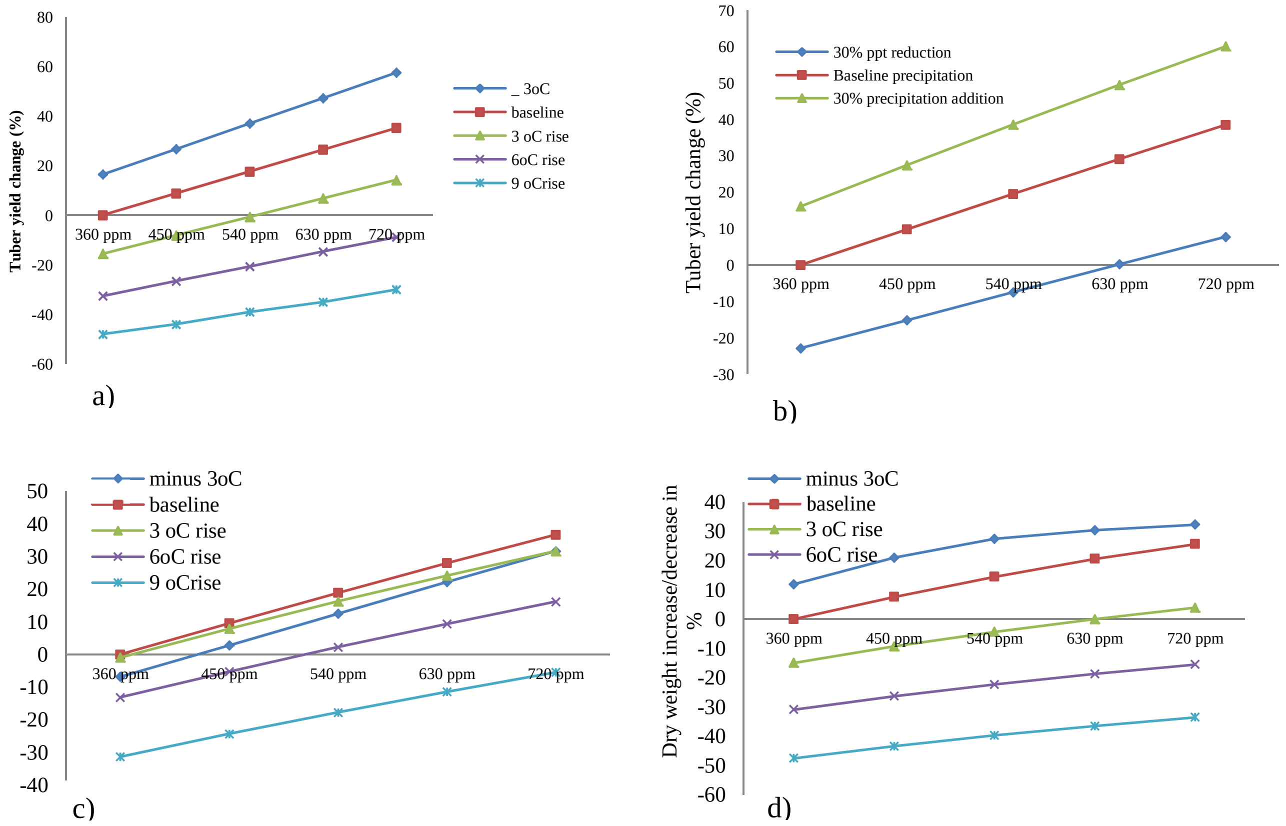

Figure 5 - a) Effect of [CO_2] and temperature on Yp tuber yield for Yp, b) effect of [CO_2] and precipitation on Yw c) Effect of [CO_2] and temperature on tuber yield d) Effect of [CO_2] and temperature on Yn tuber yield in Washington site.

Discussion

Assessing model behaviour with respect to the study sites

The simulation results show that the current temperature is above the optimal for maximal potato production in both Gisozi and Washington sites: the lower the temperature the better the yield. However, for water and nutrient limited yield (Ynw) in Gisozi the maximum tuber yield was obtained at baseline temperature and CO_2 concentration of 540ppm. The severity of Ynw yield loss was intensified at low temperatures (Figure 3a&b). For the Washington site, the tuber yield for both Yn and Yp (more than 22 t ha^{-1} ha dry weight) was more than three-fold of Yw and Ynw (7 t ha^{-1} dry weight), and water availability plays significant role on tuber yield and aboveground biomass. Crop yield increases under elevated [CO_2] in all management systems in Washington. For Washington, the highest yield for Yn and Yp was obtained at low temperature and elevated [CO_2], and for Yw and Ynw it is at a combination of baseline temperature, higher precipitation and elevated CO_2. The result of each study site and the model behaviour is discussed in the next sub-sections.

Gisozi site

At optimum nutrient supply, the maximum yield at Gisozi was obtained at T1, which is in agreement with previous studies (Debrah and Breman, 2003). This suggests that the major underlying cause for low crop yield in Gisozi is nutrient limitation (poor soil fertility). Mueller *et al.* (2012) and Debrah and Breman (2003) indicated that Africa's food production is limited by nutrient supply more than water availability, even in the drought-prone Sahel. The nutrient shortage aggravates in sub-Saharan Africa, like Gisozi, where land, labour productivity rate and average potato tuber yield is lowest (Tittonell and Giller, 2013).

The tuber yield decreases beyond CO_2 concentration of 540ppm, but the aboveground biomass continues to increase and consequently the HI reduces (Table 7). Similar trend of tuber yield and aboveground biomass reduction was observed for Yn at elevated [CO_2] in Gisozi. In contrary, the highest Yw and Yp (Figure 2&3) was observed at low temperature and high CO_2**.** This indicates that under elevated CO_2 the crop yield was strongly limited by nutrient supply, and not by water availability. Elevated CO_2 increases crop growth during early phases, but once the nutrient uptake fails to match-up with plant growth the crop becomes nutrient limited and the yield reduces. Amthor (2001) showed that in cases of severe nutrient shortage the existing nutrient depletes fast and the vegetative parts start immobilization process at early stage. Africa has the highest nutrient depletion rate, negative nutrient balance (Debrah and Breman, 2003) and lowest fertilizer input per hectare of land. This suggests that nutrient limitation will likely continue to play a significant role in determining the crop yield under elevated CO_2 in continents like Africa. Model studies in other parts of sub-Saharan Africa such as Zimbabwe and Mali on maize and millet yield using agricultural production systems simulator (APSIM) has demonstrated that a part of the yield loss due to climate change effects in the future can be mitigated by smart fertilizer applications (Rurinda *et al.*, 2015; Traore *et al.*, 2017).

At elevated CO_2, and optimum nutrient supply (Yw and Yp) the highest yield was obtained at low temperatures. Potato is a cool climate crop and lower temperature increases length of growing season and consequently increase light interception period. Whereas high temperature reduces light use efficiency (LUE), speeds up plant development, intensifies heat stress, exacerbates water shortage, increases leaf senescence and plant respiration, and reduces CO_2 balance. Supit *et al.* (2010) used Crop Growth Monitoring System for the period 1976–2005, and indicated that for various crops in large areas of Europe the potential yield and biomass decreases with increasing temperatures.

Washington site

Under current production system in Washington nearly optimum nutrient was being supplied and the yield loss from nutrient limitation was almost insignificant. This can be evidenced from the low yield gap between Yn and Yp, and Yw and Ynw. Elevated CO_2 increases crop yield for all production systems (Yn, Yw, Ynw and Yp) in Washington. For Yn, each degree temperature rise drops tuber yield by more than 5% (Table 6). Asseng *et al.* (2013) used 27 ensemble model simulations and observed a comparable wheat yield loss of about 6% for each ^oC increase in global mean temperature.

Although elevated CO_2 improves water use efficiency (WUE), water shortage could dramatically reduce the yield in Washington. In the absence of irrigation water (Yw and Ynw) the effect from water stress is very high, and the yield per unit intercepted light drops drastically. The average tuber yield and aboveground biomass for nutrient limited yield was respectively three-fold and more than two-fold as compared to water limited yield (compare Table 6 and Table 12). The yield difference between rain-fed and irrigated systems is not unexpected since up to ten-fold potato yield variation was reported in some areas in USA including Yakima, Washington (Tubiello *et al.*, 2002). Moreover, the soil in Washington is sandy and excess precipitation drains quickly and only a small proportion of water remains available for the plant. Whereas potato has high tissue water content and is highly sensitive to water shortage. The plant has a shallow and weak root system that is not good at abstracting water from deep soil (Van Loon, 1981).

At higher ambient [CO_2] the potato crop captures more CO_2, and the crop yields increases. However the effect of elevated CO_2, especially on nutrient limited and yield potential, depends on the level of temperature rise. The study of Supit *et al.* (2012) in the southern Europe showed that crops benefit from elevated CO_2 during the initial years (up to the year 2030), but as time progresses increasing temperature reduces the positive effect of CO_2. Higher CO_2 reduces leaf transpiration and stomatal conductance or it increase stomatal resistance (Cure and Acock, 1986).

Higher CO_2 also increases photosynthetic rate by increasing leaf area index (LAI) and light interception (Figure 6). The LAI of potato in Gisozi site increases with increasing CO_2, but reduces with temperature (Figure 6). When the plant is exposed to higher temperature it produces smaller leaves and that consequently reduces total leaf area and LAI-max. Temperature also increases respiration, reduces photosynthesis, and increases plant growth rate and reduces length of growing season. The LAI-max increase by doubling [CO_2] at Gisozi site was observed at ambient and below ambient temperatures. Under the current production system of both Gisozi and Washington sites elevated [CO_2] improves light use efficiency (LUE), water use efficiency (WUE), nitrogen use efficiency (NUE) and nitrogen nutrition index (NNI) or effect of nitrogen stress (Table 7). The increased [CO_2], therefore, improves photosynthesis by increasing carbon gain, improving water use efficiency and reducing transpiration. Elevated [CO_2] also improves NUE, and also the NNI, the ratio of actual nitrogen concentration and critical nitrogen concentration in the plant. The extent of soil moisture improvement under elevated [CO_2] depends on transpiration and soil evaporation improvement.

Table 7 - Harvest Index, Transpiration, LUE, WUE, NUE and NNI at different CO_2 for current production systems in Gisozi and Washington.

Water & Nutrient limited Gisozi							Nutrient limited Washington					
[CO_2] in ppm	HI	Trans	LUE	WUE	NUE	NNI	HI	Tran	WUE	LUE	NUE	NNI
360	0.73	171.7	1.38	3.32	77.46	0.64	0.79	410.6	57.7	2.07	81.2	0.74
450	0.71	172.7	1.44	3.55	78.48	0.59	0.79	405.4	58.0	2.23	81.8	0.72
540	0.70	172.6	1.49	3.72	79.48	0.54	0.79	399.5	59.1	2.37	82.5	0.70
630	0.68	170.8	1.52	3.82	80.20	0.49	0.79	392.8	60.8	2.51	83.4	0.68
720	0.66	169.2	1.54	3.88	80.51	0.44	0.79	385.1	60.3	2.63	84.7	0.65

Abbreviations: HI – harvest index, LUE – light use efficiency, WUE-water use efficiency, NUE-nitrogen use efficiency, NNI –nitrogen nutrition index

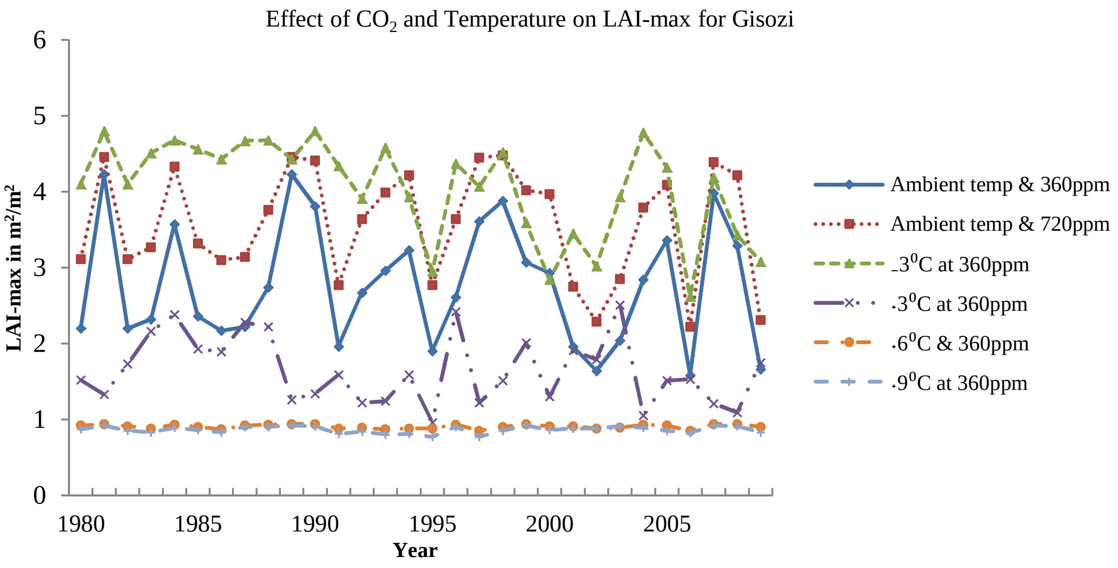

Figure 6 - Simulated values of LAI at combinations of different temperatures changes and [CO_2] levels.General discussion on the model

Calibrating a model for rainfed production in developing countries such as the Gisozi site in Burundi was a difficult process. This is mainly due to poor data quality and existence of few measured parameters. There is also no independent model data for model validation to further increase the reliability and confidence of prediction, and thus, the scenario analysis of this study is based on direct use of fully calibrated model. However, since the rationale of the study is to understand how climate change affects crop production, and not to simulate the exact actual yield, the calibrated model was sufficient to understand what climate change does to crop production systems in the study areas.

Generally the model evaluation using the potato varieties under changing temperature, precipitation and CO_2 levels was fairly adequate in mimicking field observations when assessed with graphical comparisons, RMSE, MBE and *d*-index. For Gisozi site the simulated result of the tuber yield (*d-index*=0.897, MBE=8%, RMSE= 33%) and aboveground biomass (*d-index*= 0.439, MBE=10%, RMSE= 33%). There are very few sampling points in Gisozi site because the data collection started late due to logistics issues. The observed tuber yield and aboveground biomass at the Gisozi site (Figure 2 a and b) shows a much different trajectory of decline due to delayed harvest time (maturity was exceeded and harvest was delayed), and that also attributed to the relatively low *d-index* value, and high MBE and RMSE. Whereas, for Washington site there is good fit between simulated and observed tuber yield and aboveground biomass (MBE and RMSE of 13% and 17% for tuber yield respectively, and 18% and 20% for aboveground biomass respectively). The Wilmott's coefficient of agreement (*d-index*) for Washington also showed very good agreement between predicted and observed values of tuber yield *d-index*=0.993) and aboveground biomass (*d-index*=0.987).

The RMSE indicates the square root of the average of squared differences between prediction and actual observations. Therefore the error by RMSE is usually magnified due to summing up of squared positive and negative error values. The positive MBE indicates that the model over predicted yields. At the Gisozi site RUE (2.2 g DM/MJ PAR) is lower than the commonly used value of 2.7 or 2.8 g DM/MJ PAR for the same and many other potato genotypes grown in other regions. The RUE deviation is most likely attributed to low nitrogen supply that led to low leaf protein required for Rubisco production, and that consequently leads to lower photosynthesis. RUE can also be affected by spatial variation, environmental condition (temperature, precipitation and radiation) and leaf damage from pests or heavy rainfall. The RUE efficiency variation is in agreement with Kooman and Rabbinge (1996) who studied several late and early maturing potato varieties in The Netherlands and suggested that the RUE difference between years is larger than RUE among cultivars.

However, it should be noted that models are simplification of reality and only attempts to account for the most important factors that influence yield. In this regard LINTUL4 is a simple model and it depicts crop growth and development with low data requirement and with essential crop growth processes. LINTUL4 model has shown much improvement compared to its predecessors (Spitters, 1990; Wolf, 2012). Yet some of the following aspects of LINTUL4 can be improved:

- The simulation results at both sites suggest that higher temperature reduces tuber yield and aboveground biomass. However, the rate of reduction for tuber yield at present study is less than or equal to that of aboveground biomass at high temperatures and between consecutive [CO_2] (Table 5, 6, 7, 8-12). This means that the harvest index increases or remains the same at higher temperature. This proportional reduction of tuber yield and aboveground biomass depicts that the model fails to simulate tuberization inhibition and diversion of assimilate to foliar parts (above ground biomass) at higher temperature, which is at the cost of tubers (Haverkort and Verhagen, 2008).
- The water and nutrients available for the plant was included by using a bucket model on a daily time step (van Ittersum *et al.*, 2003). The movement of water and nutrients into and out of the bucket between soil layers along potential gradient, and soil water table fluctuation, and dynamics of fluxes for temporal resolution of less than a day was not considered (Diepen *et al.*, 1989).
- LINTUL predicts crop yield with a limited data requirement and is a less complex model. It simulates the response of a potato crop to water availability, temperature rise and change in CO_2 satisfactorily. However, the actual farm setting is affected by a complex mixture of stresses from both climate and non-climate factors, and further improvement is needed on the role of C:N ratio on organic matter decomposition, water and nutrient balance part of the model. Furthermore, the CO_2 effects are assumed to be independent of the nitrogen status of the crop which in reality is not the case.

Conclusion

The present study investigated how tuber yield and aboveground biomass of a potato crop in a high resource input Washington and low resource input Gisozi responds to changes in temperature, CO_2 and precipitation by using LINTUL4 model, and assessed the model behaviour. The results show climate change has dire consequences on potato production in both Gisozi and Washington. Though rainfall shortage is a challenge during extreme events, nutrient availability will remain to be the major limiting factor for potato production in Gisozi. The effect of nutrient limitation exacerbates under elevated CO_2, and therefore, under the continued nutrient depletion and increasing atmospheric CO_2, the availability of nutrients will continue to play a significant role for potato production in Gisozi. For high input Washington the current production is limited by temperature rise. The yield increase as a result of global warming reported in some temperate regions like northern Europe (Hijmans, 2003; Supit *et al.*, 2012) is not expected in Washington. The increased CO_2 partially compensates for the effect of temperature rise on the potential yield but does not have a proportionately larger effect at higher temperature.

Yet it is possible to suggest recommendation for the study areas based on the results of this study. The yield loss due to climate change in Gisozi can be reduced by using optimum amounts of nutrients. Nutrients reduce the negative effects of CO_2 and will increase crop yield (win-win scenario). This was also demonstrated in other SSA (Rurinda *et al.*, 2015; Traore *et al.*, 2017). Moreover, to cope with rising temperature, using potato cultivars that are adapted to the condition is recommended. Harahagazwe *et al.* (2012) suggested that potato genotypes from International Potato Centre (CIP) are adapted to tropical regions and lowland parts of the world are good alternatives to mitigate the adverse effects of temperature rise in traditionally potato producing areas in Burundi and elsewhere. Similarly for the Washington site using optimum irrigation and using appropriate crop management practices (planned or autonomous crop adaptation) should be considered.

Abbreviations: [CO_2]– atmospheric carbon dioxide concentration; T – 24-hour minimum / maximum air temperature; AGB – aboveground biomass; W – daily rainfall; Yp – Potential Yield; Yw – water limited yield; Ynw – nutrient and water limited yield; Yn – nutrient limited yield

Declaration

Ethical approval and consent to participate: not applicable

Consent for publication: not applicable

Availability of data and materials: the datasets used for analysis during the current study was available with the AgMIP project and the authors.

Competing interest: the authors declare no conflicts of interest

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Appendix

Table 8 - Effect of temperature and [CO$_2$] on tuber yield and aboveground biomass (AGB) of potato on nutrient limited yield (Yn) in Gisozi

Simulated absolute dry matter weight of tuber yield and AGB in *t ha^{-1}* (Yn)										
	C1 (360 ppm)		C2 (450 ppm)		C3 (540 ppm)		C4(630 ppm)		C5 (720 ppm)	
	Tuber	AGB	Tuber	AGB	Tuber	AGB	Tuber	AGB	Tuber	AGB
T1	6.2	10.2	5.9	10.1	5.5	10.0	5.3	9.9	5.0	9.9
T2	8.0	10.8	7.8	11. 0	7.6	11.0	7.4	11.0	7.1	11.0
T3	6.8	8.5	7.5	9.5	8.1	10.2	8.44	10.7	8.6	11.2
T4	3.7	4.7	4.2	5.3	4. 7	5.9	5.2	6.6	5.7	7.2
T5	1.4	1.8	1.5	2.1	1.7	2.3	1.9	2.5	2.1	2.8

Table 9 – Tuber yield and aboveground biomass (AGB) in t ha^{-1}for Water Limited yield (Yw) in Gisozi

	C1		C2		C3		C4		C5	
	Tuber	AGB	Tuber	AGB	Tuber	AGB	Tuber	AGB	Tuber	AGB
T1W1	10. 3	13.9	11.4	15.5	12.6	17.1	13.7	18.6	14.9	20.2
T1W2	11.5	15.3	12.7	16.9	13.9	18.5	15.1	20.1	16.3	21.75
T1W3	12.1	16.0	13.4	17.6	14.6	19.3	15.8	20.9	17.0	22.5
T2W1	6.6	9. 1	7.4	10.2	8.3	11. 4	9.2	12.5	10.1	13.7
T2W2	7.76	10.3	8.7	11.5	9.6	12.8	10.6	14.0	11.6	15.3
T2W3	8.36	10.9	9.3	12. 2	10.3	13.5	11.3	14.8	12.3	16.11
T3W1	3.8	5.3	4.3	6.0	4.9	6.7	5.5	7.5	6.1	8.3
T3W2	4.5	6.0	5.1	6.8	5.8	7.6	6.4	8.5	7.1	9. 4
T3W3	4.95	6.5	5.6	7.3	6.3	8. 2	7.0	9.1	7.7	10.0
T4W1	1.9	2.7	2.2	3.1	2.4	3.4	2.7	3.9	3.1	4.3
T4W2	2.2	3.0	2.5	3.4	2.8	3.9	3.2	4.39	3.6	4.8
T4W3	2.4	3.3	2.7	3.7	3.1	4.1	3.5	4.69	3.9	5.1
T5W1	0.7	1.1	0.8	1.2	1.0	1.3	1.0	1.5	1.1	1.6
T5W2	0.8	1.2	0. 9	1.3	1.0	1.5	1.1	1.6	1.2	1.8
T5W3	0.8	1.2	1.0	1.4	1.1	1.6	1.2	1.7	1.3	1.9

Table 10 - Effect of temperature and [CO_2] change on potential yield (Yp) in Gisozi

Potential yield change from baseline in t ha^{-1}										
	C1 (360 ppm)		C2 (450 ppm)		C3 (540 ppm)		C4(630 ppm)		C5 (720 ppm)	
	Tuber	AGB	Tuber	AGB	Tuber	AGB	Tuber	AGB	Tuber	AGB
T1	15.578	20.411	16.970	22.284	18.360	24.155	19.748	26.023	21.136	27.891
T2	12.432	15.985	13.580	17.503	14.718	19.012	15.852	20.516	16.982	22.017
T3	9.041	11.389	9.994	12.605	10.931	13.807	11.851	14.991	12.755	16.159
T4	5.366	6.752	6.058	7.612	6.751	8.476	7.439	9.336	8124	10.194
T5	1.931	2.528	2.216	2.884	2.514	3.256	2.822	3.641	3.140	4.037

Table 11 - Effect of CO_2 and temperature on aboveground biomass (AGB) and tuber yield of Yp (in percent and t/ha) with respect to baseline climate of 360^{o}C and 1980 to 2009 weather data, Washington.

Absolute dry matter weight of Yp in t ha^{-1}										
	C1 (360 ppm)		C2 (450 ppm)		C3 (540 ppm)		C4(630 ppm)		C5 (720 ppm)	
	Tuber	AGB	Tuber	AGB	Tuber	AGB	Tuber	AGB	Tuber	AGB
T1	28.7	35.6	31.2	38.7	33.7	41.9	36.2	45.1	38.7	48.3
T2	24.6	31.0	26.8	33. 8	28.9	36.5	31.1	39.3	33.3	42. 1
T3	20.5	26.5	22.3	28.9	24.1	31.2	26. 0	33.6	27.8	36.0
T4	16.6	21.6	18.0	23.5	19.5	25.5	21.0	27.4	22.4	29.4
T5	12.7	16.6	13.8	18.1	15.0	19.6	16.1	21.1	17.2	22.6

Table 12 - Effect of precipitation, temperature and CO_2 on nutrient limited yield (Yn) in Washington

Water-limited potato yield, Washington										
	C1		C2		C3		C4		C5	
	Tuber	AGB	Tuber	AGB	Tuber	AGB	Tuber	AGB	Tuber	AGB
T1W1	4.4	9.1	4.9	10.1	5.4	11.0	5.9	12.0	6.4	13.0
T1W2	6.0	11.1	6.7	12.2	7.4	13.4	8.0	14.5	8.7	15.6
T1W3	7.3	12.5	8.1	13.8	8.9	15.1	9.7	16.4	10.4	17.6
T2W1	5.6	10.0	6.1	11.0	6.7	11.9	7.2	12.9	7.7	13.8
T2W2	7.2	11.9	7.9	13.0	8.6	14.1	9.3	15.2	10.0	16.2
T2W3	8.4	13.2	9.2	14.4	10.0	15.6	10.8	16.8	11.5	17.9
T3W1	6.0	10.1	6.5	11.0	7.1	11.9	7.6	12.7	8.2	13.5
T3W2	7.5	11.8	8.2	12.8	8.9	13.8	9.5	14.7	10.1	15.6
T3W3	8.5	12.9	9.3	14.0	10.0	15.0	10.7	16.0	11.4	17.0
T4W1	5.6	9.0	6.2	9.8	6.7	10.6	7.2	11.4	7.7	12.1
T4W2	6.9	10.3	7.5	11.3	8.2	12.1	8.8	13.0	9.4	13.8
T4W3	7.7	11.2	8.4	12.2	9.1	13.1	9.8	14.0	10.4	14.9
T5W1	4.7	7.2	5.2	7.9	5.7	8.6	6.2	9.3	6.6	10.0
T5W2	5.6	8.2	6.2	9.0	6.8	9.8	7.3	10.5	7.8	11.2
T5W3	6.2	8.8	6.9	9.7	7.5	10.5	8.0	11.3	8.6	12.1

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