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Review

Potato, sweet potato, and yam models for climate change: A review

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ABSTRACT

Many crop models have been developed for potato, and a few for sweet potato, and yam. More than 30 potato models, two sweet potato models, and three yam models are described in the literature, and each differ in model structure. Some potato models have been applied to studies of nitrogen fertilizer, irrigation management, and climate change impact, but most of these models have never been validated with field measurements. The nitrogen dynamics of potato models CROPSYSTVB-CSPOTATO, EXpert-N-SPASS, and LINTUL-NPOTATO have been tested with some field data. LPOTCO and AQUACROP are two potato models that have been tested under elevated atmospheric CO_2 conditions. None of the models have ever been tested with high temperature or heat stress data. The most tested and applied potato models include versions of LINTUL and SUBSTOR-Potato. Two sweet potato models, MADHURAM and SPOTCOMS, and two yam models, CROPSYSTVB-Yam and EPIC-Yam had limited field-testing under current climate conditions; however, these sweet potato and yam models are not ready for climate change impact assessments. To prepare potato, sweet potato, and yam models for climate change impact assessments, they need to be (i) calibrated with modern cultivars across agro-climatic zones; (ii) tested and improved with crop physiology and dynamic measurements of phenology, growth, partitioning, and water and nitrogen uptake under different crop management and environments; and (iii) tested and improved with field studies of crop responses to climate factors, including elevated CO_2, water stress, increased temperature, heat stress, and combinations of these. Such extensive model testing and improvement with field experiments require a coordinated international effort and long-term commitment to potato, sweet potato, and yam research.

Contents

1. Introduction

Potato, sweet potato, and yam are among the top 10 most consumed foods in the world (FAO, 2010). Potato (*Solanum tuberosum*) is the most important non-grain crop worldwide, with

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a production of 332 million tons in 2010 (FAO, 2010). Potato originated in the Andean mountains, and from there spread to many regions throughout the world (CIP, 1992). A decade ago, developed countries were the major producers and consumers of potatoes; however, developing countries have recently surpassed developed countries in the production and consumption of potatoes (FAO, 2010).

Sweet potatoes (*Ipomoea batatas*) originated in Central and South America, and east African varieties present characteristics completely different to American varieties (Gichuki et al., 2003). Developing countries, such as China and those in Sub-Saharan Africa have increased the amount of land planted to sweet potato and its production during the last decade. Both regions account for approximately 87% of harvested area of sweet potato in the developing world (Fuglie, 2007). In China, sweet potato has declined as a food crop but increased as animal feed (Fuglie, 2007). Sub-Saharan Africa added approximately two million hectares of sweet potato production in the last decade (FAO, 2010).

Yams (*Dioscorea sp.*) are a multispecies crop, and the most predominant species is water yam (*Dioscorea alata*). Yams are distributed throughout the subtropics and tropics; however, about 93% of the world's production is in west Africa (Asiedu and Sartie, 2010).

Roots and tubers of these crops provide a cheap source of energy and vital nutrients to many people. Therefore, these crops are a main resource for food security, employment, and income in developing countries. While potato is important worldwide (Lutaladio and Castaidi, 2009), sweet potato and yam play key roles in securing food for many households in Africa (Fuglie, 2007; Asiedu and Sartie, 2010).

The anthropogenic emissions of greenhouse gases are expected to increase in the future. Concentrations of CO_2 are projected to increase from 400 ppm to >700 ppm by the end of the century. Elevated CO_2 has been shown to be beneficial for C3 plants such as potato, sweet potato, and yam. Experiments with elevated CO_2 in open-top chambers (OTC) and free air carbon dioxide enrichment (FACE) systems across Europe and United States have shown that potato yields increase under elevated atmospheric CO_2 (Finnan et al., 2008). Other studies indicated that increased temperature may counteract the positive effect of elevated CO_2 in potatoes (Schapendonk et al., 1995). Biswas et al. (1996) showed that sweet potatoes under elevated CO_2 in combination with water stress did not respond to elevated CO_2, while the yield of well-watered plants increased significantly with elevated CO_2. Reports show contradicting results of the effect of water stress on photosynthesis and yield in sweet potatoes, mostly due to large varietal differences. van Heerden and Laurie (2008) reported that in experiments with limited water supply one of the sweet potato varieties showed high drought resistance.

Crop models are a key tool to investigate the impact and potential adaptation options in root and tuber production (Haverkort and Top, 2011). A crop model consists of mathematical equations that describe crop development and growth over time as a function of environmental factors. Crop models use weather data, soil characteristics, and crop characteristics to simulate crop responses under management practices and various environmental conditions. Crop models can be used to anticipate the effects of climate change on root and tuber production.

This paper presents a review of simulation models developed for potato, sweet potato and yam. General physiological differences, structural model differences and limitations, applications in climate change and research gaps are discussed. Most of the reviewed papers describe potato models, less sweet potato and yam models, reflecting the available literature on models and their applications for these crops.

Table 1
Potato, sweet potato and yam crop models.

Model	Reference	Web link
Potato		
APSIM-Potato	(Brown et al., 2011; Lisson and Cotching, 2011)	http://www.mssanz.org.au/modsim2011/B3/brown.pdf
AquaCrop	(Steduto et al., 2009)	http://www.fao.org/nr/water/aquacrop.html
CROPSYST	(Peralta and Stockle, 2002; Stockle et al., 2003)	http://www.bsyse.wsu.edu/CS_Suite/CropSyst/index.html
CROPSYSTVB-CSPOTATO	(Alva et al., 2010)	
CROPWATN	(Karvonen and Kleemola, 1995)	
DAISY	(Heidmann et al., 2008)	
DANUBIA	(Lenz-Wiedemann et al., 2010)	
Expert-N-SPASS	(Gayler et al., 2002)	
INFOCROP-POTATO	(Singh et al., 2005)	http://www.iari.res.in
Ingram-model	(Ingram and McCloud, 1984)	
ISPOTA	(Fishman et al., 1984)	
Johnson-model	(Johnson et al., 1986)	
LINTUL-FAST	(Angulo et al., 2013)	http://models.pps.wur.nl/models
LINTUL-NPOTATO	(Van Delden et al., 2003)	
LINTUL-POTATO	(Kooman and Haverkort, 1995)	
LPOTCO	(Wolf and Van Oijen, 2003)	
NPOTATO	(Wolf, 2002a)	http://models.pps.wur.nl/models
POMOD	(Kadaja and Tooming, 2004)	
POTATO	(Ng and Loomis, 1984)	
POTATOS	(Wolf, 2002a)	http://models.pps.wur.nl/models
Potato Calculator	(Jamieson et al., 2006)	
PotatoSoilWat	(Roth et al., 1995)	
REGCROP	(Gobin, 2010)	
ROTASK 1.0	(Jongschaap, 2006)	
Sands-model	(Sands et al., 1979)	
Sanabria and Lhomme-model	(Sanabria and Lhomme, 2013)	
SCRI-model	(Mackerron and Waister, 1985)	
SIMPOTATO	(Hodges et al., 1992)	
SOLANUM	(Condori et al., 2010)	
SPUDSIM	(Fleisher et al., 2010)	
SUBSTOR-Potato	(Griffin et al., 1993)	http://www.icasa.net/dssat/
SWACROP	(van den Broek and Kabat, 1995)	
WOFOST	(Boogaard and Kroes, 1998)	http://www.wofost.wur.nl
Sweet potato		
MADHURAM	(Somasundaram and Santhosh Mithra, 2008)	
SPOTCOMS	(Santhosh Mithra and Somasundaram, 2008)	
Yam		
CROPSYSTVB-Yam	(Marcos et al., 2011)	
EPIC-Yam	(Srivastava et al., 2012a)	
YAMSIM	(Rodriguez, 1997)	

History of potato models

Crop modeling started approximately 60 years ago (De Wit, 1958), and modeling of potato crops began during the 1980s (Sands et al., 1979; Ingram and McCloud, 1984; Ng and Loomis, 1984;

Fishman et al., 1985; Mackerron and Waister, 1985; Johnson et al., 1986). In the 1990s, potato crop models were linked to dynamic soil-water and soil-nitrogen simulation routines. At this time, they started to be used for systems analysis by exploring management options, including N fertilization, irrigation management, and the impacts of climate variability (MacKerron, 2008). In the 2000s, more potato models were developed and used for a range of systems applications (Table 1).

Most potato models were derived from other generic crop or cereal models. For example, the generic crop model LINTUL was adapted into LINTUL-POTATO (Kooman and Haverkort, 1995). SIRIUS (a cereal wheat model) was modified to create the Potato Calculator model (Jamieson et al., 2006). Some potato models are hybrids of generic or other cereal models. For example, DANUBIA is a crop model that combines the cereal crop model CERES and the generic crop model GECROS and was then linked with the soil-water and nitrogen model SOIL-SNT (Lenz-Wiedemann et al., 2010). Potato models have been improved by adding sub-routines to enhance their performance (Haverkort and Top, 2011). For instance, SIMPOTATO (Fig. 1A) was originally adapted from the CERES-maize model (Hodges et al., 1992). The routine of nitrogen uptake of SIMPOTATO was included to transform EXpert-N-SPASS to a potato crop model considering nitrogen (Gayler et al., 2002). Later, SIMPOTATO was combined with CROPSYST to create the CROPSYSVB-CSPOTATO model (Alva et al., 2010). SIMPOTATO was also combined with a two-dimensional soil model (e.g., 2DSOIL) to create the SPUDSIM model (Fleisher et al., 2010). An improved canopy routine from the POTATO model (Ng and Loomis, 1984) has been implemented in the SPUDSIM model (Fleisher et al., 2010) (Fig. 1A). Another example is LINTUL-POTATO (Fig. 1B); this model was modified and adapted for potato cultivars in the Andes and was renamed to SOLANUM (Condori et al., 2010) (Fig. 1B). LINTUL-POTATO was also combined with the NPOTATO model to create LINTUL-NPOTATO (Van Delden et al., 2003).

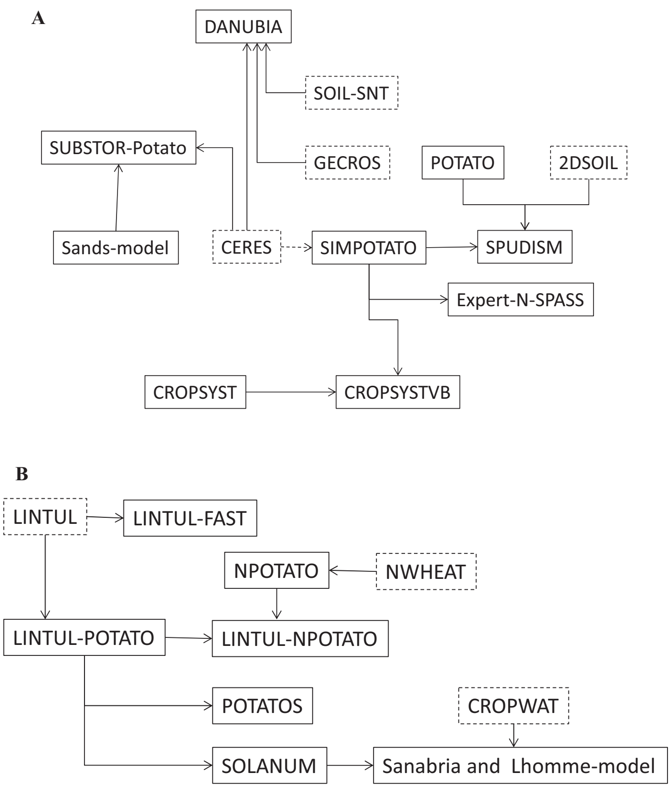

Fig. 1. History of model development for (a) SIMPOTATO and (b) LINTUL models. Potato models represented by solid-line borders and non-potato models represented by dashed-line borders. 2DSOIL (Timlin and Pachepsky, 1997), NWHEAT (Groot and Dewilligen, 1991), CERES (Jones and Kiniri, 1986), SOIL-SNT (Klar et al., 2008), GECROS (Yin and van Laar, 2005), and CROPWAT (Smith, 1992).

Several versions of the LINTUL potato model have been used for climate change studies. Although LINTUL (Hijmans, 2003) does not consider elevated CO_2 effects on crop growth, LINTUL-FAST (LINTUL 2) (Angulo et al., 2013) and LINTUL-POTATO (Kooman and Haverkort, 1995) include these effects. The LINTUL-POTATO model and its modified version named POTATOS consider elevated CO_2 effects based on a literature review (Wolf, 2002a; Haverkort et al., 2013).

The WOFOST model simulates potato crop development, and it was combined with the SIMGRO model, a model simulating the water balance at a regional scale (van Walsum and Supit, 2012). Another generic model parameterized for potato crops is AQUACROP, and it has been linked with an economic optimization model to analyze farm income (Garcia-Vila and Fereres, 2012).

Potato model structures

Crop models can range from simulating potential yields to simulating yields limited by water and nitrogen (van Ittersum et al., 2003). From the models listed in Table 1, three models can simulate potential yield only, 13 models include a water routine, and 14 models include water and nitrogen routines.

In general, crop model routines for potential production include processes of thermal time accumulation, canopy development, tuber induction, dry matter allocation and tuber growth.

Thermal time is estimated by several linear (McMaster and Wilhelm, 1997) and non-linear methods (Sands et al., 1979; Lenz-Wiedemann et al., 2010). The cardinal temperature varies across models. For example, Sands et al. (1979) reported a base temperature (T_b) of 7 °C, but this can vary between 2 °C to 2.8 °C for tuberosum species (MacKerron, 2008). For andigenum species, the base temperature is approximately 0 °C (Hijmans et al., 2003). Furthermore, Streck et al. (2007) suggest that cardinal temperatures tend to change through crop phenology and suggest a T_b of 4 °C for tuber induction and a T_b of 7 °C for tuber bulking.

Two modeling approaches are generally used to simulate canopy development. The simpler approach uses a “big leaf” concept to estimate daily net productivity as the product of potential radiation-use efficiency (RUE) and light interception. A more complex approach estimates diurnal variations in leaf-level photosynthesis, which is scaled to canopy level, and considers carbon losses through respiration and senescence. Differently, AQUACROP uses transpiration efficiency for biomass growth (Vanuytrecht et al., 2011), and the Sands-model considers the tuber growth development as a function of physiological time and radiation (Sands et al., 1979).

Photoperiod and temperature play a key role in crop development and trigger tuber induction in potato crops (Jackson, 1999). Temperature thresholds and photoperiod sensitivity vary widely with potato species (Kooman and Haverkort, 1995). Some of the first crop models for potato accounted for photoperiod sensitivity in simulating the tuber growth (Regel and Sands, 1983; Ng and Loomis, 1984), but most models developed in the 1980s described tuber induction and development only as a function of temperature (Ingram and McCloud, 1984; Mackerron and Waister, 1985). This temperature function together with a function of photoperiod sensitivity were included in models developed in the 1990s (Griffin et al., 1993; Kooman and Haverkort, 1995). However, in APSIM-potato, photoperiod affects only the leaf appearance (Brown et al., 2011).

A potato yield is often calculated as the proportion of biomass allocated to tubers (harvest index – HI), and some models consider a partitioning process to different organs. For instance, in the

Potato Calculator model, the biomass partitioning is determined using simple rules. Initially, all biomass is assigned to the shoots. From tuber initiation until maximum canopy, 75% of new biomass is assigned to tubers and 25% to the canopy. After maximum canopy cover, all new biomass is translocated to tubers, with an additional remobilization of biomass from stems to tubers (Jamieson et al., 2009).

Sands et al. (1979) proposed a model that presents the most detailed potato phenology. This model describes planting, emergence, tuber initiation, start of tuber growth, maximum bulking rate, cessation of bulking, and tuber maturity or skin-hardening. Some models simulate the emergence of potatoes (EXpert-N-SPASS and SIMPOTATO), emergence to flowering (EXpert-N-SPASS and DANUBIA), emergence to tuber initiation (SUBSTOR-Potato, SIMPOTATO, LINTUL-POTATO), emergence to canopy expansion (Mackerron and Waister, 1985) or the period of tuber initiation to maximum canopy cover (Jamieson et al., 2009). In the case of EXpert-N-SPASS and SUBSTOR-Potato, the calculation of the tuberization rate begins when emergence is reached and when photoperiod and temperature requirements are met. Flowering often does not have an effect on tuberization (Sands et al., 1979), and flowering could be absent in some cultivars.

The components of the soil–water balance vary across models, as some models did not initially consider precipitation (Fishman et al., 1985). Main components of the water balance considered include soil–water dynamics and evapotranspiration. The water dynamics in the soil profile are usually simulated by the tipping bucket approach or the Richards equation (Table 2). Both methods simulate a one-dimensional movement of water. The SPUDSIM model is the only potato model that simulates soil–water dynamics in two dimensions (Fleisher et al., 2010).

Soil organic matter (SOM) dynamics are often simulated using different SOM pools and different decomposition rates, and these can vary across models (Table 3). For example, the DAISY model has two general pools (e.g., soil organic matter and added organic matter). EXpert-N-SPASS has three pools (e.g., litter, manure, and humus); LINTUL-NPOTATO also has three different pools (e.g., crop, manure, and wastewater solids).

The number of cultivar parameters varies among crop models, and not all published models provide this information. Some parameters are estimated from other crops, while some parameters are calculated from experiments or adopted from other models (Roth et al., 1995; Peralta and Stockle, 2002; Lenz-Wiedemann et al., 2010).

Some model use weekly climate input data (Sands et al., 1979), while most models use daily weather input data. SPUDSIM and DANUBIA are the only models that simulate the water, carbon, and nitrogen fluxes as well as the energy balance at hourly time steps (Fleisher et al., 2010; Lenz-Wiedemann et al., 2010). The DAISY potato model can simulate crop development and growth using daily solar radiation, air temperature, and precipitation, and can use hourly inputs for vapor pressure and wind speed. The POTATO model uses a sine function to calculate hourly temperature based on daily average and amplitude temperature (Ng and Loomis, 1984).

Models differ in the description of crop development, including the way they consider abiotic factors. Several models consider abiotic factors, including nitrogen, water, frost, heat, and drought (Jefferies, 1993; Gayler et al., 2002; Hijmans et al., 2003; Heidmann et al., 2008; Fleisher et al., 2010). However, biotic factors such as weed, pest, or diseases are often not considered.

A crop model combined with pest and disease models could allow to study integrated pest and disease management and estimate yield losses due to these factors (Haith et al., 1987; Rouse, 1988). For example, the Johnson-model was developed (Johnson et al., 1986) to link three pest and disease sub-models (potato leafhopper, early blight, and Verticillium wilt) (Johnson, 1992). The model PotatoSoilWat based on the Johnson-model was combined with a virus epidemic model (Nemecek et al., 1995). A single-plant potato model based on the structure of SUCROS was linked to a subroutine of *Verticillium dahliae* (Termorshuizen and Rouse, 1993). Another potato model, INFOCROP-POTATO, applied a constant yield loss due to pest and diseases of 10–12% annually (Singh et al., 2005).

Potato model testing with experimental data

A crop model can become a good representation of reality if it reproduces observed data with acceptable accuracy. A range of statistical indicators has been used to quantify model accuracy (Gayler et al., 2002; Condori et al., 2010; Fleisher et al., 2010; Gobin, 2010). The root mean square error (RMSE) (Wallach and Goffinet, 1987) is used (sometimes calculated from other indicators if available) to compare the accuracy in simulating field measurements across models. These results are summarized in Table 3 as relative RMSE (RRMSE). Note that Table 3 provides the performance of models for specific cultivars or specific geographical regions for which they were validated. However, a better way to compare the performance of models would be a model intercomparison study with standardized inputs (Rosenzweig et al., 2012). Such a study was performed in 1995 with five potato models (Kabat et al., 1995). The models that performed best in this comparison for a dry treatment were WOFOST, followed by SWACROP and CROPWATN (Fig. 2).

Some of the models that do not supply a quantifiable error estimate have nevertheless been used for specific application, and these include CROPSYST, POMOD, NPOTATO, and APSIM- potato. Under current climate conditions, the variation of the RRMSE across models is less than 32%, often based on a single validation study. However, in the case of the SUBSTOR-Potato model, the RRMSE ranged between 14% and 51%, using information across several studies. The DAISY model was tested at six sites across Europe, and the RRMSEs ranged from 1% to >30% (Heidmann et al., 2008).

Only LPOTCO and AQUACROP models were tested for components of future climate change, including the effect of elevated CO_2 on yield. For the LPOTCO model (Fig. 3), the coefficient of determination was provided ($R^2 = 0.65$) (Wolf and Van Oijen, 2003). The AQUACROP model showed a RRMSE of 11–30%.

Crop nitrogen uptake was validated for the CROPSYSTVB-CSPOTATO model (15%), the EXpert-N- SPASS model (9.6%), and the LINTUL-NPOTATO model (22–29%) (Gayler et al., 2002; Van Delden et al., 2003; Alva et al., 2010).

Most potato models have been tested in specific locations with some exceptions. Angulo et al. (2013) used the LINTUL FAST model and addressed uncertainties of the simulations using various calibration methods; they also suggested an improvement with multi-location experimental datasets to enhance the performance of the model at regional levels. The DAISY potato model was calibrated across contrasting experiments in Europe and suggested key crop parameters to be changed at a regional level (Heidmann et al., 2008).

Potato model applications

Table 4 considers four applications of potato crop models, including crop productivity, nitrogen management, irrigation management, and the impacts of climate change on productivity. Potato model applications for crop productivity included yield estimates (Travasso et al., 1996; St'astna et al., 2010), yield-gap analysis (Caldiz and Struik, 1999), modeling tuber size (Nemecek et al., 1996), studying the impact of a frost-tolerant cultivar

Table 2

Modeling approaches for potato, sweet potato and yam.

Model	Leaf area/light interception[a]	Light utilization[b]	Yield formation[c]	Tuberization[d]	Root distribution over depth[e]	Environmental constraints involved[f]	Type of water stress[g]	Water dynamics[h]	Evapotranspiration[i]	Soil CN-model[j]	Process modified by elevated CO_2[k]	No. cultivar parameters	Climate input variables[l]	Model relative[m]	Model type[n]
Potato															
APSIM-Potato	S	RUE	Prt	T	EXP	W/N	S	C/R	PT/PM	CN/P(2)/B	RUE	7	R/Tx/Tn/Rd	C/S	P
AquaCrop	S	TE	HI/B	T	EXP	W	E/S	C	PM	n.a.	TE	2	R/Tx/ETo		P
CropSyst	S	RUE	HI/B	T	EXP	W/N	E	R	PT/PM	N/P(3)/B	RUE/TE	20	R/tx/tn/Rd/e	E	P
CropSystVB-CSPotato	S	RUE	HI/B	T/DL	EXP	W/N	E	R	PT/PM	-	n.a.	n.a.	R/tx/tn/Rd/e	E/C	P
CROPWATN	S	P-R	B/Prt	T	-	W/N	-	R	PM	N/P(1)	n.a.	10	Rd/Tavg/Cl		P
DAISY	D	P-R	B/Prt	T/DL	-	W/N	E	R	PT	CN/P(2)/B	F	-	R/Ta/Rd/e	S	R
DANUBIA	D	P-R	B/Prt	T/DL	CA	W/N	E/S	R	PM	N/P(2)/B	F	18	RH/Ta/Rd/e/W/atC0$_2$	C/G	P
Expert-N-SPASS	D	P-R	B/Prt	T/DL	EXP	W/N	E/S	R	PM	CN/P(3)/B	n.a.	15	R/Tx/Tn/Rd/RH/W	C/S	P
INFOCROP-POTATO	S	RUE	HI/B	T/DL	EXP	W/N/H	E	C	PM/PT	CN/P(2)/B	RUE/TE	22	R|/Tx/Tn/Rd/W/e	S	P
Ingram-model	S	P-R	B/Prt	T	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	-	Rd/Tx/Tn		P
ISPOTA	D	P-R	B/Prt	T	-	W	-	-	-	n.a.	n.a.	20	Rd/Tx/Tn/R/Rdu/Pe		P
Johnson-model	S	RUE	B/Prt	T	n.a.	W**	n.a.	n.a.	n.a.	n.a.	n.a.	16	Rd/Tx/Tn		P
LINTUL-FAST	-	RUE	Prt	T	EXP	W	E	C	PM	CN/P(3)	RUE	4	R/Tx/Tn/Rd/RH	L	R
LINTUL-NPOTATO	S	RUE	HI/B	T/DL	EXP	W/N	S	C	P	CN/P(2)	RUE/TE	-	R/Tx/Tn/Rd/e/W	L	P
LINTUL-POTATO	S	RUE	HI/B	T/DL	-	W	-	C	PM	n.a.	RUE/WUE	-	R/Tx/Tn/Rd/e/W	L	P/R
LPOTCO	S	RUE	HI/B	n.a.	n.a.	W	n.a.	n.a.	PM	n.a.	RUE	-	R/Tx/Tn/Rd/e/W	L	P/R
NPOTATO	D	P-R	B/Prt	T	n.a.	W/N	-	C	PM	N/P(2)	F	5	R/Tx/Tn/Td/Rd/W	S	P/R
POMOD	S	P-R	B/Prt	-	-	W	E	C	G	n.a.	n.a.	-	R/Ta/Rd		
POTATO	S	P-R	B/Prt	T/DL	-	W	-		PM	n.a.	n.a.	-	Rd/Ta/dTa/Td/W/RH		P
POTATOS	S	RUE	B/Prt	T/DL	n.a.	W	-	C	PM	n.a	RUE/TE	-	R/Tx/Tn/Td/Rd/W	L	P/R
Potato Calculator	S	RUE	B/Prt	T	EXP	W/N	E	C	P/PT	N/P(1)	n.a.	-	R/Tx/Tn/Rd/e/W	I	P
PotatoSoilWat	S	RUE	B/Prt	T	-	W	-	-	PM	-	-	31	R/Tn/Tx//Rd/W/RH		P
REGCROP	S	RUE	HI/B	T	-	W	-	-	PM	n.a.	n.a.	20	R/Tn/Tx/Td/Rd/W/RH		R
ROTASK 1.0	S	RUE	-	-	-	-	-	C	-	N/P(2)	-	9	R/Tn/Tx/Rd/W/RH/nR	G	
Sanabria and Lhomme-model	S	RUE	HI	T	n.a.	W	n.a.	C	PM	n.a	RUE	21	R/Tn/Tx/Rd/W/RH	L	P

Table2 (*Continued*)

Model	Leaf area/light interception[a]	Light utilization[b]	Yield formation[c]	Tuberization[d]	Root distribution over depth[e]	Environmental constraints involved[f]	Type of water stress[g]	Water dynamics[h]	Evapotranspiration[i]	Soil CN-model[j]	Process modified by elevated CO_2[k]	No. cultivar parameters	Climate input variables[l]	Model relative[m]	Model type[n]
Sands-model	S	n.a.	HI/B	T/DL	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	10	Rd/Tx/Tn		P
SCRI-model	S	RUE	HI/B	T	n.a.	W***	n.a	n.a.	n.a.	n.a.	n.a.	n.a.	Rd/Tx/Tn		P
SIMPOTATO	S	RUE	HI/B	T/DL	EXP	W/N	E/S	C	P/PT	CN/P (2)	-	-	R/Ta/Rd	C	P
SOLANUM	S	RUE	HI/B	T	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	10	Rd/Tx/Tn	L	P
SPUDSIM	D	P-R	B/Prt	T	CA	W	E/S	R	PM	n.a.	F	13	R/Tx/Tn/Rd/e	C	P
SUBSTOR-Potato	S	RUE	HI/B	T/DL	EXP	W/N	E/S	C/R	PT	CN/P (3)/B	RUE/TE	7	R/Tx/Tn/Rd/RH/W	C	P
SWACROP	S	P-R	B/Prt	T	-	W		R	PM/PT/MAK	n.a.	n.a.	-	Rr/Ta/sRH/W/C/CR		P
WOFOST	D	P-R	B/prt	T/DL	LIN	W/N*	E/S	C	P	P(1)	F	3	R/Tx/Tn/Rd/e/W	S	G
Sweet potato															
MADHURAM	D	P-R	B/prt	T/DL	n.a.	W/N/K	E/S	-	PT	n.a.	n.a.	-	R/Tx/Tn/H/RHn/RHx/S		P
SPOTCOMS	D	P-R	B/prt	T/DL	n.a.	W/N/K	E/S	-	PT	n.a.	n.a.	-	R/Tx/Tn/H/RHn/RHx/S		P
Yam															
CROPSYSTVB-YAM	S	RUE	HI/B	T/DL	LIN	W/N	-	C/R	PT/PM	-	n.a.	-	R/Tx/Tn/Rd/e	E	P
EPIC-yam	S	RUE	HI/B	T/DL	EXP	W/N	E	C	PT/PM	N/P (5)/B	RUE/TE	31	R/Tx/Tn/Rd/e	E	R
YAMSIM	D	P-R	-	-	-	-	-	-	-	-	-	-		S	P

*Nitrogen-limited yields can be calculated for given soil nitrogen supply and N fertilizer applied, but model has no N simulation routines.

*The model uses soil water potential as input data and does not have water balance model.

***The model uses soil water deficit and does not have a water balance model.

- not available, n.a not applicable

[a] S, simple approach (e.g., LAI); D, detailed approach (e.g., canopy layers).

[b] RUE, radiation use efficiency approach; P-R, gross photosynthesis–respiration; TE, transpiration efficiency biomass growth.

[c] HI, fixed harvest index; B, total (aboveground) biomass; Prt partitioning during reproductive stages; HI_mw, harvest index modified by water stress.

[d] T, temperature; DL, photoperiod (day length); O, other water/nutrient stress effects considered.

[e] LIN, linear, EXP, exponential, SIG, sigmoidal, CA, carbon allocation.

[f] W, water limitation; N, nitrogen limitation; K, potassium limitation.

[g] E, actual to potential evapotranspiration ratio; S, soil available water in root zone.

[h] C, capacity approach; R, Richards approach.

[i] P, Penman; PM, Penman-Monteith; PT, Priestley-Taylor; TW, Turc-Wendling; MAK, Makkink; HAR, Hargreaves; SW, Shuttleworth and Wallace (resistive model), Gojsa and Bibic.

[j] CN, CN model; N, N model; P(x), x number of organic matter pools; B, microbial biomass pool.

[k] RUE, radiation use efficiency; TE, transpiration efficiency; WUE, water use efficiency; F, Farquhar model.

[l] Cl, cloudiness; R, rainfall; nR, nitrogen concentration in precipitation; Tx, maximum daily temperature; Tn, minimum daily temperature; Ta, average daily temperature; Td, dew point temperature; dTa, daily temperature amplitude Rd, radiation; H, sunshine hours; e, vapor pressure; RH, relative humidity; RHn, minimum relative humidity; RHx, maximum relative humidity; W, wind speed; CR, canopy resistance; Rdu rainfall duration; Pe, pan evaporation; S, soil moisture content; at CO_2, atmospheric CO_2.

[m] C, CERES; L, LINTUL; E, EPIC; G, GECROS; S, SUCROS; I, SIRIUS.

[n] P, point model; G, global or regional model (regarding the main purpose of model).

Table 3
Relative RMSE (RRMSE) for potato, sweet potato and yam model–observation comparisons.

Models	Yield		LAI	N				Water			References
	Ambient CO_2	Elevated CO_2		N fertilizer	soil N mineralization	N uptake	N leaching	Drainage	Water uptake	Irrigation	
Potato											
APSIM-Potato											
AquaCrop	2%	11–30%[#]									(Vanuytrecht et al., 2011)
CROPSYST											(Peralta and Stockle, 2002)
CROPSYSTVB-CSPOTATO	12%					15%					(Alva et al., 2010)
CROPWATN											
DAISY	1->30%										(Heidmann et al., 2008)
DANUBIA	1.6[*]		0.97								(Lenz-Wiedemann et al., 2010)
Expert-N-SPASS	9.31%					9.63%					(Gayler et al., 2002)
INFOCROP-POTATO	11%			19%							(Singh et al., 2005)
Ingram-model	10–27%										(Ingram and McCloud, 1984)
ISPOTA	8–32%[**]										(Fishman et al., 1984)
Johnson-model											
LINTULS-FAST	1.13–2.65[*]										(Angulo et al., 2013)
LINTUL-NPOTATO	1.08–1.19[*]		0.567		27.6–33.5	21.6–28.6					(van Delden et al., 2001)
LINTUL-POTATO											
LPOTCO											
NPOTATO											(Wolf, 2002a)
POMOD											(Kadaja and Tooming, 2004)
POTATO	19%										(Ng and Loomis, 1984)
POTATOS											
Potato Calculator	8.7[*]						31.22%				(Jamieson et al., 2009)
PotatoSoilWat											
REGCROP	6.74[*]										(Gobin, 2010)
ROTASK 1.0											
Sanabria and Lhomme-model											
Sands-model											
SCRI- model											
SIMPOTATO	16%			37%			111%	65%		19%	(Hodges et al., 1992)
SOLANUM	0.74–1.48[*]										(Condori et al., 2010)
SPUDSIM	14%										(Fleisher et al., 2010)
SUBSTOR-Potato	14.7–47–51%										(Kabat et al., 1995; Travasso et al., 1996; St'astna et al., 2010)
SWACROP	10%[**]										(van den Broek and Kabat, 1995)
WOFOST	16%[**]										(Boogaard and Kroes, 1998)
Sweet potato											
MADHURAM	1.14–4.17[*]										(Santhosh Mithra and Somasundaram, 2008)
SPOTCOMS	2.88–3.92[*]										(Santhosh Mithra and Somasundaram, 2008)
Yam											
CROPSYSTVB-Yam	0.5[*]		0.3[*]								(Marcos et al., 2011)
EPIC-yam	8.78–25-38%										(Srivastava and Gaiser, 2010; Srivastava et al., 2012a)
YAMSIM											

[#] Based on FACE experimental data.
[*] Only absolute RMSE were available ($t\,ha^{-1}$).
[**] Includes above-below biomass production ($t\,ha^{-1}$).

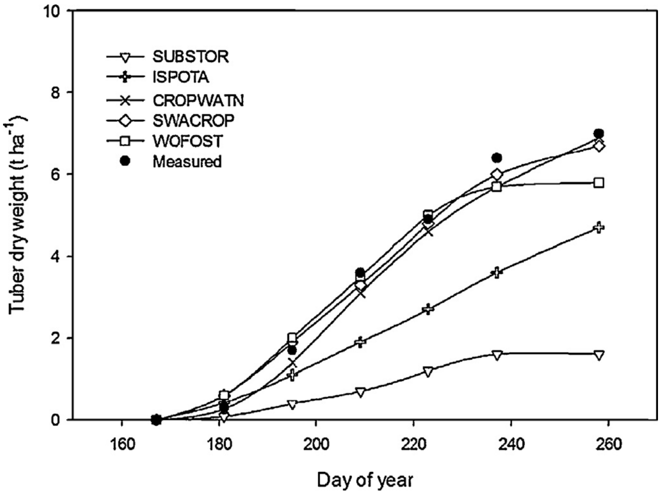

Fig. 2. Measured and simulated cumulative potato tuber dry weight predicted by models for a 1987 dry treatment. Reproduced from Kabat et al. (1995).

(Hijmans et al., 2003), modeling the response to drought (Jefferies, 1993), identifying the relevance of genotype by environmental interaction for assisting breeding for drought-tolerant genotypes (Spitters and Schapendonk, 1990; Haverkort and Kooman, 1997) and optimizing farm income from potato cropping (Garcia-Vila and Fereres, 2012).

Models for nitrogen management were used to assess nitrogen uptake and nitrogen leaching and to estimate nitrogen crop requirements. Ten of the reviewed models have been used in simulation experiments on N management; however, only five of these models were validated with field experimental N fertilizer data (CROPSYSTVB-CSPOTATO, SIMPOTATO, LINTUL-NPOTATO, SIMPOTATO, Potato Calculator, and EXpert-N-SPASS). Five potato models have been used to assess nitrogen leaching, and only two of them were validated with N leaching data (SIMPOTATO and Potato Calculator). Other potato model applications included simulation studies to optimize manure application to avoid nitrogen losses and to estimate the rate of nitrogen mineralization (Peralta and Stockle, 2002; Van Delden et al., 2003).

The amount of irrigation required by a potato crop is linked to nitrogen uptake and leaching, e.g., N leaching is often related to the amount of irrigation (Hodges, 1998; Peralta and Stockle, 2002; Lisson and Cotching, 2011). The potential to reduce nitrogen fertilizer and irrigation without compromising productivity has been explored with the Potato Calculator model (Jamieson et al., 2006).

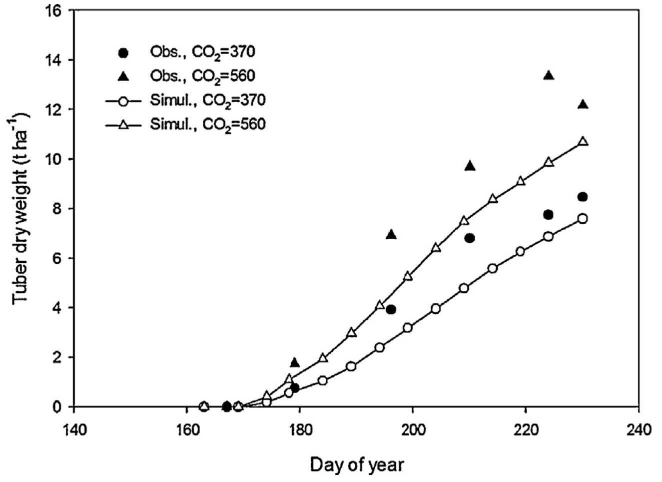

Fig. 3. Measured and simulated cumulative potato tuber dry weight (cv. Bintje) for a FACE experiments with ambient (370 μmol mol^{-1}) and elevated atmospheric CO$_2$ (560 μmol mol^{-1}) at Rapolano, Italy; observed (Obs) and simulated (Simul) using the LPOTCO model. Reproduced from Wolf and Van Oijen (2003).

Potato models have also been used to explore the impacts of climate change on potato production. The SCRI-model (Mackerron and Waister, 1985) was used to study the impact of temperature change on potato production in Scotland over the last 60 years. This study showed that 23–26% of yield increase was due to a temperature increase (Gregory and Marshall, 2012). Note that models were initially developed to simulate the growth and development of crops in current climate conditions and were not intended for use in studies of climate change. Nevertheless, many potato models have included CO$_2$ effect on crop growth (e.g., INFOCROP-POTATO, WOFOST, CROPSYST, SUBSTOR-Potato, LINTUL-FAST, LINTUL-POTATO, LPOTCO, NPOTATO, Sanabria and Lhomme-model), but not all of them were tested with experimental data (Table 3).

Potato models were also applied in climate change studies at various geospatial scales, including grid points, extrapolated grid points to various administrative units, and downscaled or interpolated grid points (Fig. 4). In simulation experiments for the United States (Tubiello et al., 2002) and Europe (Supit et al., 2012; Angulo et al., 2013) grid points were extrapolated to administrative units. Interpolated grids were used for regional studies in Washington state, USA (Stockle et al., 2010), Western India (Kumar et al., 2011), England (Davies et al., 1997) and were also used at a global scale (Hijmans, 2003). Most regional and global model applications suggest future climate change will cause current production areas to shift toward cooler regions (Tubiello et al., 2002; Hijmans, 2003; Supit et al., 2012).

Simulation studies on climate change impact that did not consider the effects of elevated CO$_2$ suggested higher yield losses (Davies et al., 1997; Hijmans, 2003; Gobin, 2010; Stockle et al., 2010; Saue and Kadaja, 2011; Angulo et al., 2013) compared to simulation studies with potato models that include a CO$_2$ effect (Stockle et al., 2010; Angulo et al., 2013). However, when all studies with and without considering a CO$_2$ effect on crop growth were compared, the lower simulated yield reductions with considering changes in atmospheric CO$_2$ concentrations seemed to be an artifact of the different models, cultivars, climate change scenarios and growing environment used in these studies (Fig. 4).

Simulation studies with models including CO$_2$ effects suggested a 7% yield increase by 2020 in Washington state, USA, due to an increase in the growing period and the benefits from elevated CO$_2$ (Stockle et al., 2010). A change in potato yields from +5 to −4% was simulated for 2030 for Western India (Kumar et al., 2011). For Europe and the United States, an average potato yield increase was simulated with climate change by 2050 (Tubiello et al., 2002; Wolf, 2002b; Wolf and Van Oijen, 2003; Angulo et al., 2013). In Ireland, future potato production would depend on the water availability in irrigated areas by 2055 (Holden et al., 2003). For this region, maintaining current production will require 150–300 mm of additional irrigation (Holden and Brereton, 2006). By 2080, an 8% yield reduction has been suggested for Washington state, USA, despite considering an extended growing period as an adaptation strategy (Stockle et al., 2010). For 2090, simulation experiments suggested a yield decline in southern Europe, an unchanged yield in central Europe, and a yield increase in northern Europe (Supit et al., 2012). In the highland tropic of Peru, Sanabria and Lhomme (2013) reported a yield increase between 28% and 29% by 2085. In most cases, elevated atmospheric CO$_2$ concentrations will mitigate negative climate change impacts by 2050, but by the end of the century the increase in temperature will override any positive effects of elevated CO$_2$ on potato production. In addition, the simulation results also depend on the adaptation strategies, the

Table 4
Applications of potato, sweet potato and yam models.

Model	Productivity	Nitrogen management	Irrigation management	Climate change			References
				CO_2	T	adaptation	
Potato							
APSIM-Potato		x					(Lisson and Cotching, 2011)
AquaCrop	x		x				(Garcia-Vila and Fereres, 2012)
CROPSYST		x	x	x	x	x	(Peralta and Stockle, 2002; Stockle et al., 2010)
CROPSYSTVB-CSPOTATO		x					(Alva et al., 2010)
CROPWATN							
DAISY		x	x				(Jensen et al., 1994; Dolezal et al., 2007)
DANUBIA		x					(Lenz-Wiedemann et al., 2010)
Expert-N-SPASS		x	x				(Gayler et al., 2002)
INFOCROP-POTATO	x	x		x	x		(Singh et al., 2005; Govindakrishnan et al., 2011; Kumar et al., 2011)
Ingram-model							
ISPOTA							
Johnson- model	x						(Johnson, 1992; Nemecek et al., 1996)
LINTUL-FAST				x	x		(Angulo et al., 2013)
LINTUL-NPOTATO	x	x					(Van Delden et al., 2003)
LINTUL-POTATO	x			x	x	x	(Hijmans, 2003; Hijmans et al., 2003; Haverkort et al., 2013)
LPOTCO					x	x	(Wolf and Van Oijen, 2003)
NPOTATO				x	x		(Wolf, 2002b)
POMOD	x				x	x	(Saue and Kadaja, 2009b; Saue and Kadaja, 2009a; Saue and Kadaja, 2011; Sepp and Saue, 2012)
POTATO							
POTATOS				x	x		(Wolf, 2002b)
Potato Calculator	x	x					(Jamieson et al., 2009)
PotatoSoilWat	x						(Nemecek et al., 1996)
REGCROP					x		(Gobin, 2010)
ROTASK 1.0							
Sanabria and Lhomme-model				x	x		(Sanabria and Lhomme, 2013)
Sands-model							
SCRI-model	x				x		(Peiris et al., 1996; Davies et al., 1997; Gregory and Marshall, 2012)
SIMPOTATO		x	x				(Han et al., 1995; Hodges, 1998)
SOLANUM							
SPUDSIM							
SUBSTOR-Potato	x	x	x	x	x	x	(Travasso et al., 1996; Mahdian and Gallichand, 1997; Shae et al., 1999; Tubiello et al., 2002; Holden et al., 2003; Snapp and Fortuna, 2003; Stoorvogel et al., 2004; Holden and Brereton, 2006; Brassard and Singh, 2007; St'astna et al., 2010; Daccache et al., 2011)
SWACROP			x				(Mahdian and Gallichand, 1996; Utset et al., 2000)
WOFOST				x	x		(Supit et al., 2012; van Walsum and Supit, 2012)
Sweet potato							
MADHURAM							
SPOTCOMS							
Yam							
CROPSYSTVB-Yam	x						(Marcos et al., 2011)
EPIC-Yam					x	x	(Srivastava et al., 2012a; Srivastava et al., 2012b)
YAMSIM							

chosen emission scenario (SRES), and the type of global circulation model (GCM) used. For example, Tubiello et al. (2002) used two GCMs for rainfed conditions in the United States; the Canadian Centre Climate Model Scenario (CCGS) suggested an increase in potato yield, and the Hadley Centre Model Scenario (HGCS) suggested a decrease in yield. Another simulation study with a potato model suggested a reduction of the growing season with climate change (Holden and Brereton, 2006; Stockle et al., 2010). Adaptation strategies include using later-maturing cultivars in the temperate regions (Stockle et al., 2010; Saue and Kadaja, 2011), short-maturity cultivars in the highland tropics (Sanabria and Lhomme, 2013), shifting growing seasons (Tubiello et al., 2002; Hijmans, 2003; Franke et al., 2013), and using drought (Sanabria and Lhomme, 2013) or heat-tolerant cultivars (Hijmans, 2003). Hijmans (2003) created a heat tolerant cultivar by increasing the upper sensitivity temperature thresholds for tuber bulking in the model by two degrees. The simulation results with this new cultivar showed that heat-tolerant cultivars could increase potato production by approximately 5% under future climate change scenarios by 2020 and 2050. Under optimal irrigated conditions, models showed that a consequence of elevated CO_2 is that crops have improved water use efficiency (Holden and Brereton, 2006; Supit et al., 2012) and reduced nitrogen fertilizer requirements (Holden and Brereton, 2006). In contrast, Brassard and Singh (2007) pointed out that a larger amount of nitrogen will be required with climate change. The positive effect of CO_2 could also be counterbalanced by the lack of available water in rainfed and irrigated systems (Holden et al., 2003; Supit et al., 2012). Across all available potato models, the LINTUL model, its various versions, and the SUBSTOR-Potato model are the most widely used potato models (Table 4 and Fig. 4).

Studies of climate change using GCM encounter challenges related to the temporal and geospatial resolution of the input data. Usually GCMs represent areas over 1° by 1° (~111 by 111 km at the equator) or higher. GCMs have been downscaled to higher resolution to improve the coarse resolution in potato modeling.

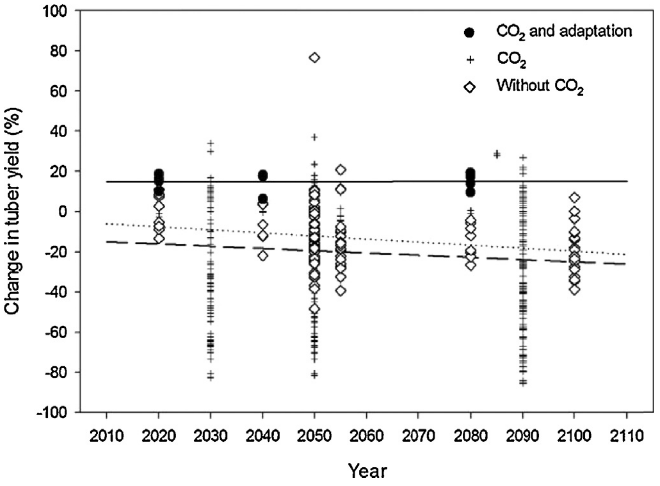

Fig. 4. Simulated climate change impacts using potato crop models and considering an elevated CO_2 effect (Tubiello et al., 2002; Holden et al., 2003; Brassard and Singh, 2007; Stockle et al., 2010; Daccache et al., 2011; Kumar et al., 2011; Supit et al., 2012; Haverkort et al., 2013; Sanabria and Lhomme, 2013) (463 data points, $y = -0.1115x + 209.1$, $r^2 = 0.009$, diamonds, dashed line), without considering an elevated CO_2 effect (197 data points, $y = -0.1519x + 299.28$, $r^2 = 0.03$, plus-signs, dotted line) (Hijmans, 2003; Brassard and Singh, 2007; Saue and Kadaja, 2011) and with an adaptation strategy (later maturing cultivars) and considering an elevated CO_2 effect (Stockle et al., 2010) (12 data points, $y = 0.0024x + 10.073$, $r^2 = 0.0002$, filled circles, full line).

A resolution of 50 km by 50 km was used for WOFOST (Supit et al., 2012). Statistical weather generators have been used for climate data inputs for potato modeling studies (Supit et al., 2012), and a simple linear interpolation method was also used (Hijmans, 2003).

Sweet potato models

Two crop simulation models have been reported for sweet potato, MADHURAM (Somasundaram and Santhosh Mithra, 2008) and SPOTCOMS, which is the MADHURAM model with a modified canopy algorithm (Santhosh Mithra and Somasundaram, 2008). The MADHURAM model simulates photosynthesis across canopy layers to calculate direct and diffused sunlight interception. It simulates three phenological stages, crop growth, and yield by considering water, potassium, and nitrogen limitations. For sweet potato, potassium is the most important macro element and determines the number of tubers produced. Compared to MADHURAM, SPOTCOMS is a simpler model, although the canopy development includes branching (Santhosh Mithra and Somasundaram, 2008). In both MADHURAM and SPOTCOMS, the phenology stages are determined by growing degree days (GDD), with a base temperature of 8 °C, an optimum temperature of 25 °C, and a maximum temperature of 38 °C. The value of the base temperature appears low as sweet potato is cropped in subtropical and tropical regions. Other research suggests a base temperature of 12 °C (C. Gavilan, pers. comm., 2012).

The SPOTCOMS and MADHURAM provided absolute RMSE of 2.88–3.99 Mg DM ha^{-1} and 1.14–4.17 Mg DM ha^{-1} for a validation with measured data.

There are no published model applications for these two sweet potato models. However, the growing degree concept from these sweet potato models has been used to simulate the harvest dates for sweet potatoes in Louisiana, USA (Villordon et al., 2009).

Yam models

Three simulation models have been reported for yam (*D. alata*), including YAMSIM, CROPSYSTVB-Yam and EPIC-Yam. YAMSIM is based on the SUCROS model and estimates potential crop growth (Rodriguez, 1997). CROPSYSTVB-Yam uses the phenology routine from a potato model (Streck et al., 2007), but modified (Marcos et al., 2009) and integrated for CROPSYSTVB-Yam (Marcos et al., 2011). The EPIC-Yam model was based on cassava (Srivastava and Gaiser, 2010). While YAMSIM applies a detailed photosynthesis routine, CROPSYSTVB-Yam and EPIC-Yam use a RUE approach and consider water and nitrogen limitations.

EPIC-Yam and CROPSYSTVB-Yam require daily precipitation, maximum and minimum temperature, solar radiation, and wind speed. For CROPSYSTVB-Yam model testing showed an absolute RMSE of 0.6 Mg DM ha^{-1} for total biomass, 0.5 Mg DM ha^{-1} for tubers, and 0.3 for LAI (Marcos et al., 2011). For EPIC-Yam the RRMSE for yield was between 8.9% and 38% (Srivastava et al., 2012a).

EPIC-Yam is part of the generic crop model EPIC. The model accounts for nutrients (N, P, and K) and pesticide dynamics. EPIC-Yam requires improvements in simulating phenology and model calibration is currently restricted to a few cultivars (Srivastava and Gaiser, 2010). Two model applications have been reported with EPIC-Yam and included studies of the effect of fallow duration on yam productivity and the impact of climate change. The effect of fallow is important because many farmers prefer to plant yam as the first crop after the fallow (Srivastava et al., 2012a). For a climate change study, EPIC-Yam only considered the effect of temperature and rainfall, even though EPIC-Yam accounts for a CO_2 effect on RUE and ET (Srivastava et al., 2012b). The simulation study showed a yield reduction by 2050. The simulated yield reduction was higher for a Ferruginous soil (sandy type, 33% yield reduction) than for a Ferralitic soil (clay type, 18% yield reduction) (Srivastava et al., 2012b).

Model development and data improvement

Overall, model improvements often resulted in a new model name (Fig. 1); consequently many potato models share a similar structure with some changes (Table 2). In the case of sweet potato, a canopy algorithm improvement of the MADHURAM model led to the SPOTCOMS model.

The number of publications on potato model improvements is relatively small compared to the number of applications. Topics of model improvements include temperature response functions and canopy dynamics. Most models consider a linear temperature response of potato crop development (McMaster and Wilhelm, 1997). A non-linear temperature function is included in the Sands-model, DANUBIA and SUBSTOR-Potato (Sands et al., 1979; Griffin et al., 1993). Both functions were compared with measured data and suggested that the non-linear function performed better (Yuan and Bland, 2005; Streck et al., 2007).

The model Rotask 1.0 integrates the use of remote sensing data. In this model, the simulated LAI and canopy nitrogen were replaced with values obtained from remote sensing. The LAI was estimated using a vegetation index (Normal Weighted Difference Index–NDVI and Weighted Difference Vegetation Index–WDVI), and the canopy nitrogen was estimated from the red edge position (indicator of chlorophyll and nutrient content) (Jongschaap, 2006). The use of the remote sensing data improved the accuracy of simulated results (Jongschaap, 2006).

Limitation of models for climate impact studies

Crop modeling depends on physiological experimentation under non-stress and stress conditions, for a range of growing conditions. However, most potato, sweet potato and yam models lack any detailed model testing under stress conditions (i.e., high temperature, heat and drought) and elevated atmospheric CO_2

concentrations. Model applications also highlighted the importance of modern cultivars adapted to agro-climatic zones, and therefore, models need to be calibrated with modern cultivars for climate change impact studies. Simulation studies that suggest new crop traits for climate change adaptation [e.g., earliness for heat tolerance (Levy et al., 1991)] need to be tested with such cultivars in field experiments. The SCRI-model was used to study drought effects on crop growth. Drought is a major abiotic stress in many potato cropping systems, and this model evaluated possible adaptation strategies, although it had never been tested with experimental drought stress data (Jefferies, 1993).

The models AQUACROP and LPOTCO use elevated atmospheric CO_2 data for model testing from OTCs and FACE experiments carried out under non-stress conditions (De Temmerman et al., 2002; Magliulo et al., 2003). There are only few data sets available for potato crops and elevated CO_2 and some of them are limited to closed chambers (Fleisher et al., 2008; Fleisher et al., 2013). There are no such experiments for sweet potato and yam.

In general, potato models have been tested in higher latitudes with some improved cultivars of tuberosum sub species adapted to long-day conditions. The INFOCROP-POTATO, SOLANUM, and Sanabria and Lhomme-model were developed for subtropical and tropical conditions, respectively. Only SOLANUM was calibrated for other potato species commonly planted in tropical regions (Condori et al., 2010). Using a model developed in the temperate region (e.g., SUBSTOR-Potato) for the tropics assumes no variation of the growing period; however, cultivars of temperate regions tend to have a shorter growing period when introduced to the tropics (Kooman et al., 1996; Condori et al., 2010). Conversely, a model developed in the tropics (SOLANUM) assumes no photoperiod sensitivity when used in temperate regions; however, most cultivars of the tropics do not form tubers under long-day conditions. Hence, potato models tend to be geographic and cultivar specific (Griffin et al., 1993), which limits their use across latitudes (MacKerron, 2004). Despite this limitation, a version of the LINTUL model has been used to explore the effects of climate change on global potato production (Hijmans, 2003).

Linking crop modeling with pest modeling has received little attention so far. Modeling biotic factors, such as spatial and temporal dissemination, dispersion, infection, or infestation, is complex. Thus, some of the available pest or disease models only describe a limited part of a potato system. For example, EPIVIT is a virus epidemic model that predicts the percentage of infected tubers (Bertschinger et al., 1995); LATEBLIGHT is a fungal disease model that predicts the percentage of foliar damage (Andrade-Piedra et al., 2005); and ILCYM is a tuber moth pest model that describes the number of generations of potato tuber moth (Sporleder et al., 2004). The effects of climate change on disease risk or the dynamic of the population of insects have also been explored (Sparks et al., 2010; Kocmankova et al., 2011; Jonsson et al., 2013; Kroschel et al., 2013), but not yet linked with dynamic potato crop models. Linking biotic stress models with crop models could improve the yield estimates in climate change impact assessments.

Potato, sweet potato and yam model shortcomings and future directions

Crop models for potato, sweet potato and yam have not received the same attention in model testing and improvement as models for grain crops (White et al., 2011). Crop physiological knowledge, detailed field experimental data and agronomic research are rare for these crops, especially for sweet potato and yam. As a consequence, major field experimentations for modeling improvements are needed for potato, sweet potato and yam.

There is an urgent need to develop a substantial research program to prepare for the challenges of climate change on potato, sweet potato and yam. Such a research program requires an international research consortium of several institutes and universities with a long-term commitment. Such a program should combine physiological studies on high temperature, heat stress, CO_2 and water stress responses for all three crops. This research program should also include physiological analysis that quantifies differences of conventional and modern stress tolerant (water and heat stress tolerant) cultivars and seek to better understand and improve physiological-sound aboveground and below-ground biomass relationships. Such a program would also entail studies on local agronomic adaptation, including phenology, crop growth dynamics, water and N uptake, crop N dynamics, and partitioning. Collecting and making available detailed dynamic data on crop development and growth under a range of field conditions, management strategies and different environments can help to serve as the basis for agronomic decision-making and as a foundation for model testing, model improvement, and model application at local, regional and global scales.

Crop models can be robust means to assess the impacts of climate change and potential adaptations if the models are well tested and proven to reproduce field-based experiments, including variations in climate change factors. Many potato crop models have not or received limited testing with experiments, and there are only few sweet potato and yam models with restricted field evaluation and none of them were tested under climate change conditions.

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