Increasing the efficiency of agronomy experiments in potato using INFOCROP-POTATO model

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Summary

This paper reports adaptations of a generic crop model INFOCROP for potato and its application in increasing the efficiency of agronomic experiments in tropical environments. A dataset of 13 experiments consisting of 153 treatments was assembled from an extensive literature search. These experiments were conducted over the period 1976–1999 in diverse Indian locations from 31 °N 75 ° E to 25 ° N 85 ° E. The treatments varied in locations, seasons, planting dates, water and N management and varieties. The duration to tuber initiation in the dataset varied between 25-63 days after planting and tuber yield between 11.0–45.3 t ha^{-1}. Simulated trends of phenological development, growth and tuber yield were in close agreement with the measured with acceptable error. It was concluded that the model was adequate to simulate the effect of various crop management factors to obtain quick results and increase the efficiency of agronomic experiments.

Introduction

The share of developing countries in global output of potato increased from 10.5% in 1961 to 44% in 2002 (Scott, 2002; Khurana & Naik, 2003). The role of potato is now well recognized in human nutrition, food security and national economy of developing countries. Potato is advocated for cultivation in new areas and diversification of traditional cereal-based cropping systems in developing countries,particularly in South Asia where poverty is highly concentrated (Scott, 2002). This requires quantification of adaptation domains, improvement in crop management and efficient utilization of resources. Systematic experimentation on these aspects through traditional methods and tools is costly and time consuming. Using crop simulation models is an alternative approach to increase the efficiency of agronomic experimentation (Kropff et al., 1996; Scott, 2002). Several potato models simulating development and yield have been developed in the past, which perform well under temperate long day conditions (Kabat et al., 1995), but not under the short day tropical conditions (Kooman & Haverkort, 1995). In the tropics, high temperatures in part of the growing seasons and prevailing short day conditions (<11 hrs) strongly affect the development of the crop, growth and yield (Haverkort, 1990; Singh et al., 2001). An-other key reason is that these models do not consider growth and yield loss due to insects, weeds and diseases in the tropical environments.

A generic crop model INFOCROP has been developed in India for simulating growth and yield of annual crop in the tropics (Aggarwal et al., 2004). The model considers the crop growth processes, soil water, nitrogen and carbon dynamics, and crop-pest interactions. The model works adaptively for rice, wheat, maize and millet (Aggarwal et al., 2004). The objectives of this paper are i) describe the adaptations of the INFOCROP model for potato, calibration and validation and ii) demonstrate model application in increasing the efficiency of agronomic experiments.

Materials and methods

Model description

The general structure and details of INFOCROP model is described by Aggarwal et al. (2004). Key features of adaptation of the model for potato (INFOCROP-POTATO) are given here.

Phenological development, growth and tuber yield. The INFOCROP-POTATO simulates the life cycle of potato in three development stages (DS) from planting to emergence, emergence to tuber initiation, and tuber initiation to maturity. The daily rate of phenological development in each of these three stages is a function of thermal time (degreedays), which is modified by sprout length of seed tubers, depth of planting, photoperiod, night temperatures and nitrogen and drought stress experienced by the crop. Low night temperatures favour early tuber initiation (Burt, 1964; Cutter, 1992). The model reduces the thermal time (degreedays) required for tuberization at relatively low temperatures and enhances it at higher temperatures, while growth and development is terminated at exceptionally high temperatures encountered in the tropics. The entire phase from emergence to tuber initiation is considered photosensitive in the model. Short photoperiods favour early tuber initiation (Beukema & van der Zaag, 1990). The model hastens tuber initiation and maturity under nitrogen and drought stress conditions (Beukema & van der Zaag, 1990).

After plant emergence, growth of the crop is calculated as a function of user defined radiation use efficiency (RUE) as affected by various factors. A RUE of 3.5 g MJ^{-1} PAR is used during vegetative and tuber growth (Sale, 1973; Manrique et al., 1991). The effect of crop development stage, temperature, CO_2 concentration and nitrogen and drought stress on RUE is simulated in the model through empirical interpolation functions (Table 1). For long periods after the plant emergence RUE proceeds at a constant rate (Allen & Scott, 1992). However, with age of the crop towards maturity photosynthetic capacity declines to one third of the initial value (Vos & Oyarzun, 1987). No potato crop growth is possible below 2 °C and above 30 °C (van Keulen & Stol, 1995). The miniumum (0–7 °C), optimum (16–25 °C) and maximum (40 °C) temperatures for net photosynthesis are reported (Kooman & Haverkort, 1995). High temperature reduces RUE (Allen & Scott, 1992). There is a direct relationship between nitrogen content in leaves and photosynthesis (Beukema & van der

Table 1. Some important empirical interpolation functions of INFOCROP-POTATO model.

Function	Axis	Axis name	Corresponding values						
Radiation use efficiency									
RCFDS	x	Development stage	0.0	1.0	1.5	1.75	2.1	–	–
	y	Relative change in RUE	1.0	1.0	1.0	1.0	1.0	–	–
RCFTP	x	Mean day temperature (°C)	0.0	12.0	16.0	18.0	25.0	31.0	50.0
	y	Relative change in RUE	0.0	0.8	1.0	1.0	1.0	0.0	0.0
RCFLN	x	Nitrogen sufficiency	0.0	0.6	0.9	1.0	–	–	–
		Relative change in RUE	0.0	0.4	1.0	1.0	–	–	–
RCFCO2	x	CO_2 (ppm)	300	350	450	550	700	999	–
	y	Relative change in RUE	1.0	1.0	1.1	1.2	1.3	1.35	–
Dry matter partitioning									
FRTTB	x	Development stage	0.0	0.8	1.0	1.62	2.1	–	–
	y	% fraction to roots	0.5	0.2	0.05	.01	0.0	–	–
FLVTB	x	Development stage	0.0	0.8	1.0	1.2	1.6	1.75	2.1
	y	% fraction of shoot to leaf	0.5	0.65	0.65	0.2	0.2	0.05	0.0
FSTTB	x	Development stage	0.0	0.8	1.0	1.1	1.6	1.9	2.1
	y	% fraction of shoot to stem	0.5	0.35	0.35	0.05	0.05	0.0	0.0
Root/shoot ratio									
LLVN	x	Nitrogen sufficiency	0.0	0.2	0.35	0.85	1.0	–	–
	y	Relative change in ratio	1.4	1.4	1.4	1.0	1.0	–	–
LLVST	x	Water sufficiency	0.0	0.5	0.85	1.0	–	–	–
	y	Relative change in ratio	2.0	1.5	1.0	1.0	–	–	–
Root growth									
RTMAX	x	Thermal time from emergence to tuber initiation	300	400	500	700	999	–	–
	y	Maximum root depth (mm)	700	720	750	800	800	–	–
EDPTFT	x	Available soil water fraction	–0.05	0.0	0.15	0.3	0.5	1.0	–
	y	Root activity coefficient	0.0	0.15	0.6	0.8	1.0	1.0	–

Zaag, 1990). The CO_2 concentration and assimilation are positively correlated. Elevated concentrations (double of present concentration) in general leads to increased biomass and yield (10–40%) of potato (van de Geijn & Dijkstra, 1995).

Dry matter partitioning to root, shoot, leaf and stem as a function of development stage (DS) and the root:shoot ratio as affected by nitrogen and drought stress is simulated in the model through empirical interpolation functions (Table 1). The potato plant generally roots rather shallowly 40–50 cm (Beukema & van der Zaag, 1990). Root penetration is linear with time and generally ceases around the time of cessation of leaf appearance (Allen & Scott, 1992). Information available on the effect of nitrogen on the ratios between root and shoot weight under field conditions is scanty (Allen & Scott, 1992). However based on the theory of a functional equilibrium between roots and shoots, it is assumed that the need for high root length densities increases as nitrogen becomes more and more limiting (Brouwer, 1983). Increasing soil moisture deficit from wet to dry soil regime increased the maximum rooting depth and depth of rooting at emergence by 34 and 17%, respectively (Stalham, 1989). Drought, while reducing dry matter production increases the root:shoot ratio indicating a shift in the balance of growth in favour of roots. Roots of plants grown in droughted conditions also tend to be thinner. Both responses enable droughted plants to exploit the available soil moisture more effectively (Vos, 1995). Rooting depth in the model is limited by maximum rooting depth (80 cm) and soil depth and is dependent on a rate that is modified by crop development stage, soil impedance and nitrogen and water stress.

The model calculates all allocations to different plant parts as dry weight. The dry weight of tubers is converted to fresh tuber yield by multiplying with a variety specific fresh: dry weight ratio of the tubers. Number and weight of individual tubers is not simulated.

The leaf area index (LAI) is calculated by multiplying the leaf weight with the pre-defined, specific leaf area (SLA) depending upon age of the crop. The model assumes SLA of 270 $cm^2\ g^{-1}$ after emergence, which increases with age (Singh, 1983; Vos, 1995). Death (senescence) of leaves and stem is simulated through the effect of leaf shading, development stage, temperature and nitrogen and water stress. The model also provides for accumulation of reserves in the stem for tuber growth. Non-leaf green areas such as those of stems also contribute towards photosynthesis and dry matter production. This is indirectly calculated in the model as a function of LAI and development stage.

Soil water and nitrogen balance. The model simulates water and nitrogen balance in three soil layers (Aggarwal et al., 2004). The rate of change in soil water at any given day was calculated by the equation (1).

$$dW = I + Rf + C - E - T - Ic - P - D - R \qquad (1)$$

where, dW is the rate of change in soil water, I is irrigation, Rf is rainfall, C is upward flux of water, E is evaporation from soil surface, T is transpiration of crop, Ic is the rainfall intercepted by the crop, P is percolation, D is drainage and R is runoff.

An important component of soil water balance is evapotranspiration, which includes transpiration loss through the crop canopy and evaporation from the soil surface. A full explanation of calculations of evapotranspiration in the model is given elsewhere (Aggarwal et al., 2004; Allen et al., 1998). Drought stress (DSTRES) was determined as the ratio of actual water-uptake (ATRANS) and potential evapotranspiration (PTRANS) by the equation (2). The drought stress was assigned a value of zero (maximum stress) and linearly approached a value of 1.0 when actual water uptake approached potential evapotranspiration (no stress).

$$DSTRES = ATRANS/PTRANS \quad (2)$$

Nitrogen within a layer is supposed to be uniformly distributed. The model simulates various soil processes such as urea hydrolysis, nitrification, denitrification, immobilization, volatilization, biological N fixation, nitrogen movement and crop uptake (Aggarwal et al., 2004). The processes of mineralization, immobilization, nitrification, denitrification and urea hydrolysis are microbially mediated and can be described by the first order kinetics in common field situations (Stanford & Smith, 1972; Tanji & Gupta, 1978). Soil nitrogen balance was calculated by equation (3):

$$SOLN = APPLN + RAINN + IRRIGN + ORGNN + NBIOL - NDOWN - NUPTK - DENIT - VOLATN \quad (3)$$

where, SOLN is the soil N balance in a particular soil layer, APPLN is applied N through fertilizers, RAINN, IRRGN, ORGN and NBIOL are the inputs through rainfall, irrigation, organic matter and biological N fixation, respectively, NDOWN is the movement of N to other soil layers, NUPTK is the uptake of N, and DENIT and VOLATN are the losses of N due to denitrification and volatilization, respectively. Nitrogen stress (NSTRES) was determined based on the potential (ANCRPT) and current levels (ANCR) of N in different plant parts by the equation (4). N stress effect was assigned a value of zero (maximum N stress) when actual mobilizable nitrogen is zero, and linearly approached a value of 1.0 when actual nitrogen approached the potential/maximum value of crop nitrogen (no N stress),

$$NSTRES = ANCR/ANCRPT \quad (4)$$

Crop pest interaction. Globally the losses in potato crop due to diseases and pests have been estimated as 12 and 7%, respectively. In tropical conditions in India total pest damage accounts for 10–20% of the total produce annually. The assessment of crop losses due to pests in the model is based on pest damage mechanism. Various categories of damage mechanisms encompass reduction in germination and plant stand, competition for resources (light water and nutrients), reduction in assimilation rate, assimilate consumption, tissue consumption and hampering of water and nutrient uptake (Rabbinge et al., 1994). Accordingly different pests can be broadly categorized as germination reducers, stand removers, light stealers, assimilation rate reducers, assimilate sappers, tissue consumers and turgor reducers. A single pest may be involved in more than one damage mechanism. Thus, for quantifying damages all the possible damage mechanisms of a pest were hypothesized and prioritized followed by establishing empirical relationship between pest incidence and tuber yield losses. The most important damage mechanisms of a pest were coupled to the crop growth model at appropriate plant growth processes level (Aggarwal et al., 2004). The model does not simulate the pest dynamics at present, therefore, pest incidence is provided as input. Important potato pests considered by the model are aphids, leaf defoliating beetles and caterpillars, cutworms, and early and late blight diseases.

Model input requirements. Daily weather data needed for the model are minimum and maximum air temperature (°C), solar radiation (KJ m^{-2} d^{-1}) vapour pressure (kPa), wind speed (m s^{-1}) and rainfall (mm). Required inputs about soil are depth (mm), organic carbon (%), soil texture (sand, silt, clay %), bulk density and NH_4-N and NO_3-N content in three soil layers. The crop management data needed are seed rate, sprout length of seed tubers, date of planting and harvesting, depth of planting, amount and date of fertilizers applied, amount and date of irrigation applied.

Output and verifiable variables. The standard output comprises dry weight of roots, stem, leaves and tuber fresh yield, leaf area index (LAI), rooted depth, N uptake by crop, soil water and N, evapotranspiration, N and drought stress. Development stage, accumulated thermal time and emission of greenhouse gases are other important outputs.

Time step and programming language. The time step of the model is one day. The INFOCROP-POTATO is written in FORTRAN SIMULATION TRANSLATOR (FST) language (van Kraalingen et al., 1994).

Calibration

Calibration of various model parameters, interpolation functions and genetic coefficients is essential to simulate a crop/variety accurately. The model requires as many as nine following genetic coefficients:
TTGERM – Thermal time from planting to plant emergence (degreedays).
TTVG – Thermal time from plant emergence to tuber initiation (degreedays).
TTGF – Thermal time from tuber initiation to maturity (degreedays).
TGMBD – Base temperature from planting to plant emergence (°C).
TVBD – Base temperature from plant emergence to tuber initiation (°C).
TGBD – Base temperature from tuber initiation to maturity (°C).
TPOPT – Optimal temperature for phenological development (°C).
TMAX – Temperature above which the rate of development becomes zero (°C).
RGRPOT – Index of early growth (unit less index of early vigour, scale 1–5).

The detailed time course data on growth and development required for the calibration of the model and genetic coefficients of Indian potato varieties was not avail-

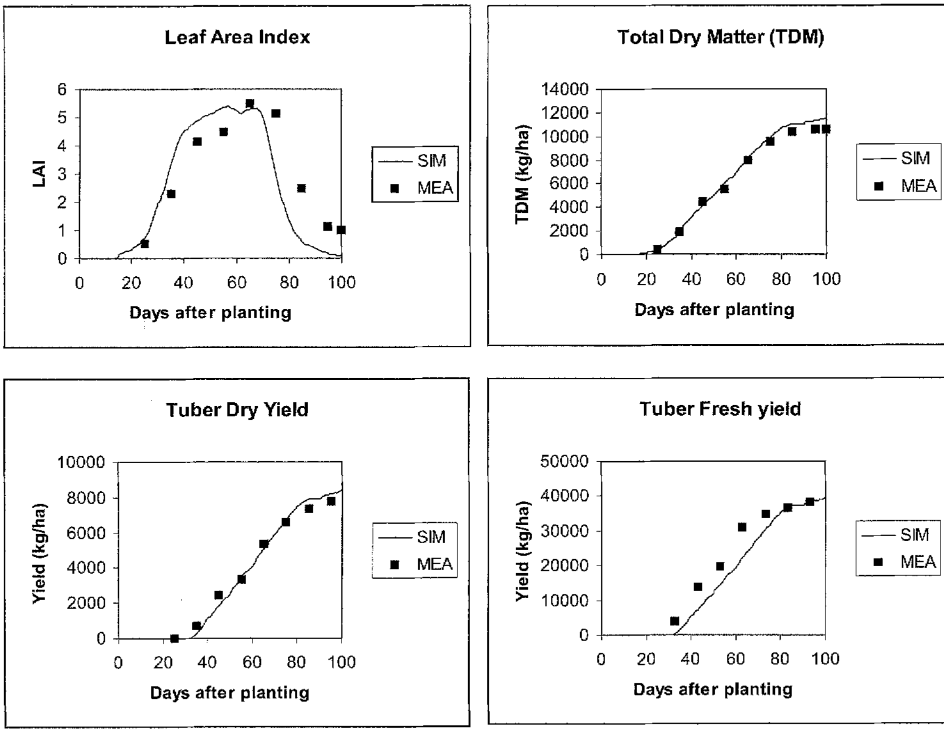

Fig. 1. Measured (MEA) growth and yield attributes compared with the simulated (SIM) by INFOCROP-POTATO model for an early maturing variety (Kufri Chandramukhi) grown under potential conditions at Jalandhar.

able. Therefore, it was obtained through independent field experiments conducted with 10 most popular potato varieties, grown under potential conditions during autumn 1998 to 2000 at Central Potato Research Station, Jalandhar (31 ° N 75 ° E) and Patna (25 ° N 85 ° E) in northern plains of India (unpublished data). Calibration of the model parmeters, functions and genetic coefficients was done by repeated iterations until a close match between simulated and measured phenology, growth and yield was obtained. Calibration results for an early maturing variety Kufri Chandramukhi is given (Fig. 1). The calibrated genetic coefficients of 10 most popular Indian potato varieties are given (Table 2). These genetic coefficients estimated and calibrated from independent and exclusive data set other than the validation data set were used in the subsequent validation and application.

Validation

A large number of experiments have been done in India where the effect of different agro-ecological factors such as nitrogen, irrigation, season, weather, planting dates and variety has been studied on growth and yield of potato. Through an extensive lit-

Table 2. Estimated and calibrated model genetic coefficients of some Indian potato varieties.

Varieties[a]	TTGERRM	TTVG	TTGF	TGMBD	TVBD	TGBD	TPOPT	TMAX	RGRPOT
K. Ashoka	260	280	650	4	4	4	25	35	5
K. Chanramukhi	275	290	750	4	4	4	25	35	4
K. Jyoti	315	325	790	4	4	4	25	35	4
K. Badshah	320	360	850	4	4	4	25	35	4
K. Pukhraj	275	275	850	4	4	4	25	35	5
K. Jawahar	315	360	800	4	4	4	25	35	5
K. Bahar	240	230	800	4	4	4	25	35	5
K. Sutlej	315	330	850	4	4	4	25	35	5
K. Lalima	325	370	850	4	4	4	25	35	3
K. Sindhuri	325	440	950	4	4	4	25	35	3

[a] Suffix K refers to potato breeding station at Kufri, Shimla, India.

erature search, 13 experiments were selected where inputs required for the model simulation were available. This database included experiments from Indo-Gangetic plains, which contributes 80% of the potato produced in India (Khurana & Naik, 2003) and had locations varying from Jalandhar (31 ° N 75 ° E) in the west to Patna (25 ° N 85 ° E) in the east (Table 3). These experiments were conducted between 1976 and 1999. There was a wide variation in the mean temperatures during potato growing seasons at these locations; maximum temperature varied from 10.2 to 37.1 °C, whereas minimum temperatures varied from 1.0 to 28.0 °C across locations and seasons. Depending upon the experiment, radiation varied from 3.6 to 22.9 MJ m^{-2}.

These experiments consisted of 153 treatments. Each treatment was different either in location or season or planting date or variety or in N or water management. The database consisted of 10 popular varieties; the duration to tuber initiation of these varieties ranged from 25 to 63 days after planting depending upon the location and season. Tuber yield varied from 11.0 to 45.3 t ha^{-1}. The weather data for these locations was collected from the concerned research stations. The representative soil profiles were taken from literature. Management practices relating to dates of planting, plant population, spacing, seed rate, harvesting, and N and irrigation as measured in the different treatments were used in the simulation.

Model efficiency

Model efficiency was evaluated by calculating maximum error (ME), residual mean square error (RMSE), coefficient of residual mass (CRM), model efficiency (EF) and coefficient of determination (CD $\neq R^2$ of conventional statistics) as described by Kabat et al. (1995). The R^2 of the conventional statistics was also calculated for estimating the linearity between measured and simulated values of development, growth and yield.

Efficiency of agronomic experiments

Model application in increasing the efficiency of agronomic experiments was demonstrated by comparing the results and the recommendations to potato arising

Table 3. Characteristics of the locations and brief details of experiments included for validation and application of the INFOCROP-POTATO model in tropical Indo-Gangetic plains.

Location (lat., long.)	Experiment no.	Year	No. of treatments	Duration to tuber initiation (days after planting)	Yield, t ha^{-1} range	Temperature °C, range		Solar radiation MJ m^{-2}, range	Data source
						maximum	minimum		
Jalandhar (31 °N, 75 °E)	Ex-1	1980, 81	6	26–63	11.0–45.3	10.2–36.5	1.0–21.0	3.6–20.9	Mehta et al., 1988
	Ex-2	1982, 83	5	29–31					Anon., 1983, 84
	Ex-3	1986, 87	14	30–36					Singh, 1993
	Ex-4	1992, 93	6	30–32					Trehan et al., 1998
	Ex-5	1998, 99	10	30–60					Marwaha & Sandhu, 2002
Modipuram (29 °N, 78 ° E)	Ex-6	1977–80	4	25–33	15.0–35.2	13.0–37.1	4.5–28.0	7.2–22.9	Verma et al., 1985
	Ex-7	1981, 82	15	25–31					Upadhya & Sharma, 1987
	Ex-8	1981	9	25–34					Birhman & Verma, 1988
Pantnagar (28 °N, 79 °E)	Ex-9	1977	8	30–33	15.2–40.2	14.9–32.3	2.4–20.4	6.8–19.3	Tripathi & Mishra, 1984
	Ex-10	1981, 82	6	29–38					Singh & Singh, 1987
Patna (25 °N, 85 °E)	Ex-11	1976-80	24	29–38	15.6–40.4	16.4–35.3	4.8–23.0	5.8–21.4	Singh et al., 1986
	Ex-12	1977, 78	16	29–31					Singh & Grewal, 1983
	Ex-13	1982, 83	30	26–38					Kushwah et al., 1989

Data range for yield, temperature and solar radiation is over the experiments and seasons.

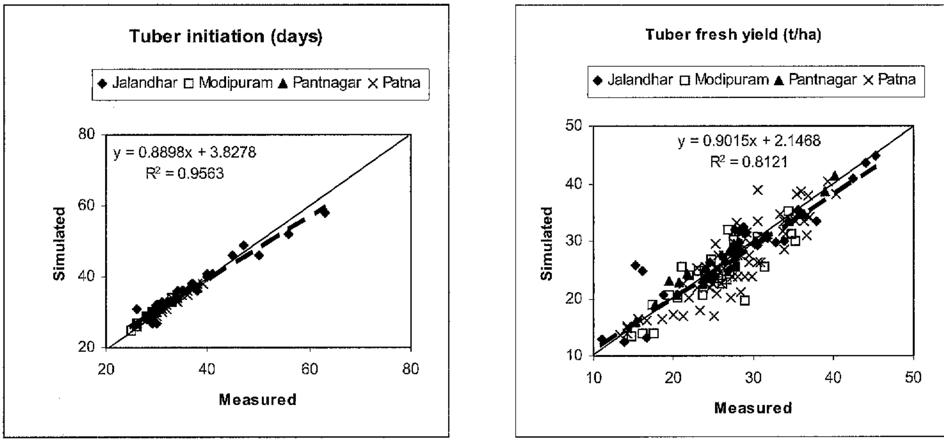

Fig. 2. Comparison between measured and simulated duration to tuber initiation (days after planting) and yield across datasets varying in locations, seasons, weather, planting dates, variety and N and water management. Also shown are 1:1 line (solid line) and line of regression (dashed) between simulated and measured values).

from simulated responses with those from the measured responses in different experiments on agronomic factors. Our measured dataset (Table 3) included experiments on planting dates (Anon., 1983, 1984; Birhman & Verma, 1988), fertilizer N application (Kushwah et al., 1989; Singh, 1993; Trehan et al., 1998; Upadhayay & Sharma, 1987), water management (Singh & Grewal, 1983; Tripathi & Misra, 1984) and genotype × environment interaction (Birhman & Verma, 1988; Marwaha & Sandhu, 2002; Singh & Singh, 1987; Verma et al., 1985). Additionally few simulations were also done under potential conditions. These simulations under potential conditions are briefly described here.

Simulations were done for 8 dates of planting at 10 days interval commencing from Julian dates 258 (15th September) to 328 (24th November) for a randomly selected set of 5 consecutive years at each of 4 locations Jalandhar, Modipuram, Patna and Kalyani. Each simulation continued till maturity or 46 Julian day (15th February) of the following year, whichever occurred earlier. The Julian date 46 is the last date of harvesting the main season potato to facilitate planting of rotational crops (Kushwaha & Govindakrishnan, 1993). The planting date maximizing tuber yield was considered as optimum.

Economically possible potato growing period was identified by simulations for serial plantings at 15 days interval commencing from 1st September through the year to following 15th August under potential conditions till maturity in each case for two locations Jalandhar (31 °N 75 °E) and Kalyani (22 °N 88 °E) widely contrasting in agro-climate.

Table 4. Statistical indicators of INFOCROP-POTATO model performance.

Indicators	Simulated outputs						
	Emergence (DAP)	Tuber initiation (DAP)	MAX LAI (m^2 m^{-2} ground)	TDM (kg ha^{-1})	Tuber dry yield (kg ha^{-1})	Tuber fresh yield (t ha^{-1})	Maturity (DAP)
ME	2	5	2.8	1837	1098	10.5	11
RMSE(%)	5.1189	3.8704	13.687	10.655	9.3094	11.0170	4.2638
CRM	0.0093	–0.0067	–0.104	–0.019	–0.035	0.0198	–0.013
EF	0.9497	0.9501	0.9245	0.8305	0.915	0.7956	0.8772
CD	1.2438	1.2055	0.8929	0.8557	0.8478	0.9926	0.7075
R^2	0.9582	0.9563	0.6395	0.7320	0.9619	0.8121	0.9346

DAP - days after planting; TDM - total dry matter; MAX LAI - maximum leaf area index .

Results and discussion

Phenological development

Correct estimation of tuber initiation date is crucial for the success of potato crop simulation models. Measured tuber initiation date varied from 25 in an early to 63 days after planting in a late maturing variety. The measured and simulated tuber initiation date showed good agreement: R^2=0.95 (Fig. 2) with acceptable errors (Table 4). The root mean square error (RMSE) was 10.4% of the mean of measured values. The tuber initiation takes place between 26–40 days after planting (DAP) in autumn planted crops and between 50–63 DAP in spring planted crops depending upon varieties (Marwaha & Sandhu, 2002; Mehta et al., 1988). Emergence and maturity are the other phenological events of importance in potato growth and development. Within our validation data set a strong linear relationship between measured and simulated values was obtained for both emergence and maturity (Table 4).

Leaf area and total dry matter

The measured maximum leaf area index (MAXLAI) in treatments varying in seasons, weather, locations, N and water management, planting dates and varieties, ranged from 2.5 to 7.8. The simulated MAXLAI was linearly correlated (R^2=0.64) with measured values. The RMSE for the MAXLAI was 13.7% of the mean of measured values (Table 4). Similarly the measured total dry matter (TDM) yield in different treatments ranged from 3630 to 14484 kg ha^{-1}. The simulated TDM by the model was linearly correlated (R^2=0.73) with measured values. The RMSE for the TDM was 10.6% of the mean of measured value (Table 4).

Tuber yield

The measured tuber fresh yield in our datasets varied from 11.0 to 45.3 t ha^{-1}. The measured and simulated tuber fresh yield showed good agreement: R^2=0.81 (Fig. 2) with acceptable errors (Table 4). The root mean square error (RMSE) was 11.0% of

Table 5. Effect of planting date on tuber yield of potato at maturity in Indo-Gangetic plains.

Experiment no.	Varieties	Location	Tuber yield (t ha^{-1}) Dates of planting (Julian days)					Recommended planting date (Julian)	Reference
			258	268	278	288	298		
Measured data set									
Ex-2	K. Chandramukhi	Jalandhar	15.6	24.3	26.9	27.5	27.3	288	Anon., 1983,1984
Ex-8	K. Chandramukhi	Modipuram	-	-	23.2	26.6	24.0	288	Birhman & Verma, 1988
	K. Bahar		-	-	21.1	27.1	27.6	298	
	K. Lalima		-	-	26.2	25.7	27.5	298	
Simulated data set									
Ex-2	K. Chandramukhi	Jalandhar	21.5	25.6	27.1	27.5	25.2	288	-
Ex-8	K. Chandramukhi	Modipuram	-	-	24.9	23.3	24.1	298	-
	K. Bahar		-	-	25.6	24.2	25.6	298	
	K. Lalima		-	-	22.6	23.7	25.9	298	

the mean of measured values. Similarly the measured tuber dry yield also showed strong linear relationship (R^2=0.96) with the simulated tuber dry yield. The RMSE for the tuber dry yield was 9.3% of the mean of measured values (Table 4).

Model efficiency
The model efficiency (EF) as given by Kabat et al. (1995) indicates whether model predictions provides a better estimate of the measurements than the average of the observed values. The maximum value of EF is one (1). If EF becomes less than zero, the model predicted values are worse than simply using the observed mean (Kabat et al., 1995). The model efficiency (EF) within our validation data set ranged from 0.79 to 0.96 for different development, growth and yield attributes of potato (Table 4). Similarly the residual mean square error (RMSE) ranged from 4.2 to 13.7% of mean of measured values indicating small error of estimation. The coefficient of residual mass (CRM) ranged from –0.104 to 0.0198 showing only slight error of under and over estimation. The coefficient of determination (CD$\neq R^2$ of conventional statistics) ranged from 0.70 to 1.24. This parameter (CD$\neq R^2$ of conventional statistics) describes the ratio between the scatter of simulated values and the scatter of measured values; as such indicates how the dynamics in measured and simulated values agree (Kabat et al., 1995). The R^2 (coefficient of determination of conventional statistics) ranged from 0.64 to 0.96 showing close linear agreement between the measured and simulated values (Table 4).

Efficiency of agronomic experiments
Optimizing planting date. The recommended optimum planting dates were similar in both simulated and measured data set in all cases except one, where it varied only by 10 days (Table 5). The optimum planting date for the main season crop of potatoes from simulations under potential conditions was 284, 298, 306 and 324 at Jalandhar, Modipuram, Patna and Kalyani, respectively (Table 6). The results are commensurate with reported optimum period of planting for each location (Gaur & Pandey, 1994; Grewal & Jaiswal, 1990; Kushwaha & Govindakrishnan, 1993, 2003).

Identifying economically possible potato growing periods. Identifying economically possible potato growing periods accurately is of vital importance in any new area where potato needs to be introduced. Farmers are also interested in growing short duration early and late crop of potato to catch high market prices. The tuber yield from this short duration early and late planted crops may be low, but give satisfactory economic returns due to high prices they command in the market. The choice of planting and harvesting of these crops will depend upon the duration of the crop and yield obtained to suitably fit in the crop rotations of a particular region. An efficient simulation model should effectively and quickly answer these questions.

The national average tuber yield of potato in India is 18 t ha^{-1} (Khurana & Naik, 2003), while potential tuber yield is calculated as 45 t ha^{-1} (Kushwaha & Govindakrishnan, 1993; van der Zaag, 1982). In India economically feasible tuber yield is obtained if available growing period from planting to maturity/harvest is about 70 days

Table 6. Simulated tuber yield (t ha^{-1}) of main winter potato crop planted on different dates at various locations in Indo-Gangetic plains for an early maturing variety Kufri Chandramukhi under potential conditions.

Year	Date of planting (Julian days)								Optimum planting date (Julian day)
	258	268	278	288	298	308	318	328	
Jalandhar (31 °N 75 °E)									
1985	34.4	35.6	32.4	29.9	22.1	12.3	4.2	0.0	268
1986	34.3	34.4	30.5	27.5	27.8	33.8	28.9	22.9	308
1987	24.2	33.7	39.2	43.0	41.5	41.4	34.7	24.6	288
1988	33.5	34.2	36.1	33.9	29.0	21.2	10.6	2.7	278
1989	31.7	34.7	35.6	34.9	33.2	37.9	31.7	22.3	278
Mean	31.6	34.5	34.8	33.8	30.7	29.3	22.0	14.5	284
Modipuram (29 °N 77 °E)									
1993	31.5	35.5	33.6	33.9	36.4	37.6	37.3	28.0	308
1994	32.0	31.7	33.7	29.7	30.7	32.0	36.9	28.5	318
1995	0.0	34.5	35.4	32.7	29.2	34.3	36.8	30.0	318
1996	27.3	36.9	40.8	40.6	38.7	40.8	36.0	24.7	278
1997	21.1	29.4	26.6	27.2	24.6	27.7	22.5	22.7	268
Mean	22.4	33.6	34.0	32.8	31.4	34.5	33.9	26.8	298
Patna (25 °N 85 °E)									
1975	10.3	31.5	45.5	49.3	48.4	48.6	48.9	42.3	288
1976	21.6	29.2	34.5	41.2	40.8	40.1	46.6	46.0	318
1977	29.9	31.7	33.8	38.0	42.5	41.9	46.5	42.9	318
1978	29.9	33.7	36.8	40.8	43.5	43.2	41.7	40.9	298
1979	18.2	25.4	30.7	35.1	40.7	47.7	44.7	46.5	308
Mean	22.0	30.3	36.3	40.9	43.2	44.3	45.7	43.7	306
Kalyani (22 °N 88 °E)									
1996	21.9	27.6	35.6	43.2	42.7	43.0	46.0	46.6	328
1997	19.1	26.7	29.0	32.0	31.0	33.7	32.9	32.8	308
1998	0.0	13.1	26.9	30.6	32.9	32.2	30.8	34.1	328
1999	12.9	21.9	28.7	30.9	28.7	27.7	29.6	37.2	328
2000	4.7	19.6	32.4	39.7	42.8	44.1	46.0	48.2	328
Mean	11.7	21.8	30.5	35.3	35.6	36.1	37.1	39.8	324

or more (Kushwaha & Govindakrishnan, 2003). Thus, growing period of about 70 days or more giving tuber yield ranging between national average and potential yield, may help identify the economically possible growing period. The simulations accurately identified the economically possible growing period of potato for two locations widely contrasting in agro-climate (Table 7). At Jalandhar situated in north-western plains of India the crop planted between September to February matured in 66–118 days after planting (DAP) giving potential tuber yield ranging between 18.3–58.0 t ha^{-1} (Table 7). Plantings done from March to August either failed to initiate tubers or give yield of any consequence. While, at Kalyani situated in eastern plains of India the crop planted between October to January matured in 67–88 DAP giving potential tuber yield ranging between 21.4–52.3 t ha^{-1}. Plantings done from

Table 7. Simulated results by INFOCRO-POTATO for identifying economically feasible potato growing period in Indo-Gangetic plains for an early maturing variety K. Chandramukhi under potential conditions at Jalandhar (JAL) and Kalyani (KAL), year 2000–01.

Date of planting	Emergence (DAP)		Tuber initiation (DAP)		Maturity (DAP)		Tuber yield (t ha^{-1})		TDM (kg ha^{-1})	
	JAL	KAL	JAL	KAL	JAL	KAL	JAL	KAL	JAL	KAL
1 September	12	12	31	30	67	63	21.5	1.0	6676	436
15 September	12	12	30	34	72	70	26.9	5.3	7774	1358
1 October	13	11	32	31	88	74	38.4	27.3	11120	7321
15 October	14	12	28	30	107	80	37.7	40.1	10540	11578
1 November	17	14	27	28	111	87	40.6	45.7	11295	12651
15 November	23	16	36	26	118	87	47.7	48.0	13119	12613
1 December	32	21	57	31	117	88	52.9	52.3	14209	13793
15 December	41	21	57	34	110	86	52.5	50.4	15522	14516
1 January	31	25	42	35	97	80	58.0	44.6	15864	12250
15 January	28	22	40	33	88	74	49.4	38.0	14659	10981
1 February	27	21	37	30	80	67	33.0	21.4	10709	8270
15 February	25	19	35	32	66	59	18.3	6.4	6605	2790
1 March	21	15	33	29	51	39	4.2	0.0	2912	421
15 March	18	14	Nil	Nil	Nil	Nil	0.0	0.0	200	31
1 April	13	11	Nil	Nil	Nil	Nil	0.0	0.0	31	59
15 April	11	11	Nil	Nil	Nil	Nil	0.0	0.0	22	46
1 May	11	11	Nil	Nil	Nil	Nil	0.0	0.0	25	29
15 May	10	11	Nil	Nil	Nil	Nil	0.0	0.0	26	48
1 June	11	11	Nil	Nil	Nil	Nil	0.0	0.0	24	36
15 June	11	11	Nil	Nil	Nil	Nil	0.0	0.0	24	31
1 July	11	11	36	Nil	40	Nil	0.0	0.0	1341	47
15 July	12	11	Nil	Nil	Nil	Nil	0.0	0.0	279	41
1 August	12	12	Nil	Nil	Nil	Nil	0.0	0.0	27	40
15 August	11	11	33	33	70	57	9.4	0.5	2533	324

DAP - days after planting; TDM - total dry matter yield.

mid February to September either failed to initiate tubers or give yield of any consequence (Table 7).

Results showed that warmer climatic conditions at Kalyani through the year restricted the economically possible potato-growing period from October to March compared to the relatively cooler climate of Jalandhar, where the growing period extended from September to April (Table 7). In India after hot spell during summer the temperatures become congenial progressively from north-west towards north-central and finally eastern plains (Kushwaha & Govindakrishnan, 2003). Longer possible growing period allows three crops of potato early, main and spring possible in north-western plains, while only two crops early and main is possible in eastern plains (Kushwaha & Govindakrishnan, 1993, 2003).

Nitrogen stress

Measured tuber yield ranged from 11.0 to 45.3 t ha^{-1}, whereas simulated tuber yield

Table 8. Comparison of recommended fertilizer N based on measured and simulated response.

Experiment no.	Varieties	Location	Applied N (kg ha^{-1})	Recommended N (kg ha^{-1})		Reference
				measured	simulated	
Ex-3	K. Chandramukhi	Jalandhar	0-300	200	226	Singh, 1993
	K. Badshah		0-300	260	245	
Ex-4	K. Chandramukhi	Jalandhar	0-300	266	216	Trehan et al., 1998
Ex-7	K. Chandramukhi	Modipuram	0-200	160	152	Upadhayay & Sharma, 1987
	K. Bahar		0-200	200	185	
	K. Lalima		0-200	200	208	
Ex-13	K. Chandramukhi	Patna	0-200	200	202	Kushwaha et al.,1989
	K. Lalima		0-200	190	250	
	K. Jyoti		0-200	200	232	
	K. Bahar		0-200	200	225	
	K. Sindhuri		0-200	176	264	
	K. Badshah		0-200	200	255	
Mean				204	221	

ranged from 12.9 to 44.6 t ha^{-1} in response to applied incremental N rates from 0 to 300 kg ha^{-1} (Table 8). The response in the measured data set in most cases was linear up to 200 kg N ha^{-1}. The response in the simulated data set was also linear to the initial incremental levels of N followed by a plateau with little or no increase in tuber yield, where the plateau in response represents the biological optima of N requirement (Bartholomew, 1972; Waugh et al., 1973). The recommended optimum N in the measured dataset ranged from 160 to 266 kg ha^{-1}, while in the simulated dataset it ranged from 152 to 264 kg ha^{-1} (Table 8). It may be noted that in the measured dataset the recommended N in many cases was restricted to 200 kg ha^{-1} the highest dose of N tried showing higher actual requirement. No such limitation was there in the simulated dataset and more realistic estimates were obtained. In the Indo-Gangetic plains the fertilizer N requirement of potato varies from 180 to 240 kg ha^{-1} based on multilocational field trials conducted for 20 years (Gaur & Pandey, 1994).

Drought stress
In our subset of measured database on drought stress treatments, the stress varied widely based on leaf water potential (–2.5, –5.0, –7.5 bar), IW/CPE (irrigation water: cumulative pan evaporation) ratio (1.0, 1.25, 1.50), irrigation at 9 days interval and at 75% available soil moisture (Tripathi & Misra, 1984). In the other experiment, four levels of irrigation applied at cumulative pan evaporation (15, 20, 25, 30 mm) were tested at four levels of applied N (0, 60, 120, 180 kg ha^{-1}) to study the water × N interaction (Singh & Grewal, 1983). In these treatments measured tuber yield ranged from 13.3 to 36.7 t ha^{-1}, whereas simulated tuber yield ranged from 13.8 to 34.6 t ha^{-1}. Same recommendations for scheduling irrigation were obtained from both measured and the simulated datasets (data not presented).

Genotype × environment interaction. The relative performance of high yielding improved indigenous potato genotypes across locations in Indo-Gangetic plains was determined using the model. The simulated ranking of the genotypes under similar water-nitrogen limiting conditions showed reasonable agreement with the measured rankings with few exceptions (Table 9). Some variability in ranking may be attributed to smaller differences in yield of genotypes at a particular location. Small differences between many of the genotypes at a location observed in the measured data set are difficult to simulate because of inaccuracies in measurement of model inputs and because such differences are generally beyond crop model resolution.

Conclusions

The principal objective of this study was to adapt a generic model INFOCROP for potato and demonstrate its application in increasing the efficiency of agronomic experiments for obtaining reliable results quickly for resource management in diverse tropical and subtropical regions of the world. The model simulated the trends in phenological development and tuber yield in diverse field experiments fairly accurately under tropical conditions in India. Simulations under similar water-nitrogen limiting

Table 9. Genotype × environment interaction of indigenous potato varieties in the Indo-Gangetic plains.

Experiment No.	Varieties	Location	Tuber yield (t ha^{-1}) and ranking		Reference
			Measured	Simulated	
Ex-5	K. Bahar	Jalandhar	35.7 (2)	35.4 (1)	Marwaha & Sandhu, 2002
	K. Chandramukhi		31.8 (4)	31.1 (5)	
	K. Jyoti		37.9 (1)	33.9 (2)	
	K. Lauvkar		33.9 (3)	32.3 (3)	
	Gulmarg Special		34.4 (5)	32.0 (4)	
Ex-6	K. Chandramukhi	Modipuram	17.3 (4)	18.5 (4)	Verma et al., 1985
	K. Bahar		22.0 (2)	23.4 (2)	
	K. Sheetman		19.4 (3)	21.6 (3)	
	K. Lalima		24.8 (1)	26.6 (1)	
Ex-8	K. Chandramukhi	Modipuram	24.6 (3)	24.1 (2)	Birhman & Verma, 1988
	K.Bahar		25.3 (2)	25.3 (1)	
	K.Lalima		26.5 (1)	24.0 (3)	
Ex-10	K. Chandramukhi	Pantnagar	19.6 (6)	25.6 (6)	Singh & Singh, 1987
	K. Dewa		32.2 (5)	32.9 (5)	
	K. Badshah		38.6 (2)	35.8 (2)	
	K. Sutlej		33.3 (4)	34.6 (3)	
	K. Jawahar		40.6 (1)	37.2 (1)	
	K. Sindhuri		35.1 (3)	34.1 (4)	

Values in parentheses indicate variety ranking based on tuber yield in each experiment.

conditions were demonstrated to yield similar recommendations regarding resource management options. These options were about planting date, identifying economically possible potato growing period at a location, N fertilization, irrigation and varieties in different agro-environments. The treatments in this study varied widely in location, weather, seasons, soil, dates of planting and harvesting, irrigation and N fertilization. Considering these it can be concluded that model performance was satisfactory and adequate to simulate the effects of agro-climate and various management inputs resulting in increased efficiency of agronomic experiments.

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