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Research Paper

Calibration and validation of WOFOST model for seven potato (*Solanum tuberosum*) cultivars in India

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ABSTRACT

A crop-growth simulation model WOFOST was calibrated and validated for 7 Indian potato (*Solanum tuberosum* L.) cultivars, namely 'Kufri Arun', 'Kufri Garima', 'Kufri Khyati', 'Kufri Kanchan', 'Kufri Lalit', 'Kufri Sadabahar' and 'Kufri Surya'. The time course data on crop growth and development collected from field experiments at Modipuram (Meerut), Patna, Gwalior and Jalandhar during 2011–12 to 2014–15 were used for calibration and validation of model. The model was calibrated and validated for Indian potato cultivars with reasonable accuracy. Simulated values for emergence and initiation of tuber growth varied between 1 and 5 and 3 and 5 days, respectively, from the measured values, for different cultivars. Variation in final dry-matter yield was maximum in 'Kufri Surya' (7.5%), while the variation in tuber dry-matter yield at maturity was maximum in 'Kufri Arun' (6.9%), which were within the acceptable limits. The indicators of model performance, i.e. the maximum error (ME), root mean square error (RMSE), coefficient of residual mass (CRM) and coefficient of determination (CD) also indicated that the model performance was very satisfactory. The results demonstrated that the WOFOST model can be used for studying and predicting the growth and development of potato crop under Indian situation for popular Indian cultivar.

Key words: Calibration, Crop growth model, Potato, Validation, WOFOST

Potato is one of the most important crops of India. Vast area under potato cultivation lie in the Indo-Gangetic belt which extends from Punjab to West Bengal and accounts for more than 85% of potato production in India. A number of management decisions depend on the crop growth and development, which, in turn, depend on varietal behaviour and climatic conditions. Under the climatic change scenario, the crop growth and development are also affected.

Crop growth models are potential tools to estimate the effects of climate conditions on growth and development of crops. (Eitzinger *et al.,* 2013; Rosenzweigh e*t al.,* 2013). They have been applied as a tool for analysis of yield risk, yield variability, differences among cultivars, planting strategies, study of growth determining factors etc. Crop models are widely used to understand the effects of climate change on crop development, growth and yield. The future climate changes are likely to impact potato productivity in India and therefore, there is a need to assess the impact of changing climate on potato (Singh *et al.,* 2010).

WOFOST (**WO**rld **FO**od **ST**udies) is one of 3 most widely used crop growth models for climate change studies and has been used to assess the effect of climate change on the growth and yield of many crops including wheat, rice, maize, potato, barley, soybean, sugarbeet throughout the world as reported by many workers (Tubiello and Ewert, 2002; Ceglar and Kajfez-Bogataj, 2012; Wolf *et al*., 2010, 2011; Confalonieri *et al*., 2006; Song *et al*., 2005, 2006; Alexandrov and Eitzinger, 2005; Rabbinge and Van Diepen, 2000; Van Diepen *et al*., 1987; Wolf and Van Diepen, 1991, 1994, 1995; Rotter and Van Diepen, 1994; Rotter *et al*., 1995). It is a mechanistic model that simulates the growth and yield of a crop based on eco-physiological processes, with a time step of one

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day. This model has a capability to simulate the effect of various parameters, viz. CO_2, temperature, rainfall and solar radiation on crop growth and development separately, and can take into account their interactions as well.

The model has already been calibrated for 4 Indian potato cultivars (Dua *et al.,* 2014) and has been used for climate change studies (Dua *et al.,* 2013, 2015, 2016). However, a number of new potato varieties are released in India for cultivation in the different agro-climatic zones for different traits. Many of these varieties are gaining popularity and are expected to cover a substantial area under potato in India. However, the behaviour of these varieties is not known under different climatic conditions. In order to study the impact of different climates and future climates on growth and development of these potential varieties, it is imperative to calibrate the crop growth model for the emerging potato cultivars. Keeping these points in view, a study was undertaken to calibrate WOFOST for newly released potato cultivars grown under Indian conditions.

MATERIALS AND METHODS

A field experiment was conducted at 4 regional stations of the ICAR-CPRI, Shimla, Himachal Pradesh during 2011-12 to 2014-15 to generate time course data on crop growth and development. The details are given in Table 1. The observations were recorded on planting, time taken for emergence and tuber initiation, periodic dry-matter accumulation and partitioning of photosynthates, leaf-area index (LAI) and maturity. For tuber initiation, observations were recorded at 2 days interval, starting from 10 days after emergence, while for total and tuber dry-matter yields as well as for leaf-area index (LAI), sampling was done at 10 days interval. Besides, weather parameters, viz. daily minimum and maximum temperature, were also recorded for the duration of experiment.

WOFOST is a dynamic, explanatory model which estimates the growth of an annual crop, given a set of specific soil and weather conditions. It simulates crop growth with time steps of 1 day, based on knowledge of processes at a lower level of integration; however, some parts of the model are descriptive and/or static. The simulation of crop growth is based on eco-physiological processes, under the assumption that optimum management practices are applied. The major processes are phenological development, CO_2 assimilation, transpiration, respiration, dry-matter formation and partitioning of assimilates to the various organs. The WOFOST calculates potential production and 2 levels of limited production: water-limited and nutrient-limited production (Boogaard *et al*., 1998). However, under the present study, the model was calibrated for the crop grown under best management, i.e. water and nutrients, were not limited and the weeds, diseases and pests were kept under complete check. This model was calibrated for potato cultivars, viz. 'Kufri Arun', 'Kufri Garima', 'Kufri Khyati', 'Kufri Kanchan', 'Kufri Lalit', 'Kufri Sadabahar' and 'Kufri Surya'. The important characteristics of these varieties are given in Table 2.

Weather data

Various input weather parameters used by WOFOST crop growth model are daily irradiance (KJ/m^2), minimum and maximum temperature (ºC), early morning vapour pressure (kPa), mean wind speed (m/s) and precipitation (mm/d). However, for potential production estimation, model uses only the radiation and temperature data.

Daily minimum and maximum temperature recorded in the experimental fields and solar radiation was worked out employing Hargreaves-Samani equation which is reported to be the best suited for Indian Conditions (Samani, 2000).

Calibration

Various crop parameters selected for the calibration of WOFOST are given in Table 3. Values/ functions of these parameters were revised within the range actually observed and reported in literature in order to obtain a good agreement between measured and simulated values of crop growth and development of different potato cultivars. The WOFOST is used with the graphic user interface, WOFOST Control Centre (WCC). It has a special rerun table through which different model parameters can be selected and their values may be modified. With the help of rerun facility, the effect of the change in values of different parameters in the model output can be quantified individually and jointly as well.

For validation, independent date sets, other than those used to calibrate the model, were used which were obtained from the field experiments. The evaluation of model performance was done using statistical indicators; maximum error (ME), root mean square error (RMSE), coefficient of residual mass (CRM), modeling efficiency (EF) and coefficient of determination (CD). Kabat *et al*. (1995) described the formulae for calculating these model parameters.

RESULTS AND DISCUSSION

Calibration

For calibration of WOFOST model, 7 Indian potato cultivars were selected, viz. 'Kufri Arun' (110–120 days), 'Kufri Garima' (90–100 days), 'Kufri Khyati' (90–110 days), 'Kufri Kanchan' (80–95 days), 'Kufri Lalit' (120–130 days), 'Kufri Sadabahar' (110–120 days) and 'Kufri Surya' (100–110 days). These are the potato cultivars recommended for Indo-Gangetic plains, north-eastern and north-western hills and plateau region of India (Table 1).

Model calibration is adjustment for the parameters of a system, so that the simulated results reach a pre-determined level, usually that of an observation (Jame and Cutforth, 1996). It is required to apply a model under a specific situation since models usually do not perform satisfactorily outside the domain in which they are developed (Sinclair and Seligman, 2000). The model parameters were selected and the calibration of WOFOST model for potato varieties was done following the procedure described by Wolf (2003). A stepwise approach was followed for calibration. The model was calibrated in 3 steps: (i) total length of growing period and phenological development stages, followed by (ii) light interception and total biomass production and finally (iii) assimilate distribution among various crop organs. Crop data file ‘‘POT705’’ available in WOFOST model version 7.1.2 was used for calibration studies, this file has a set of default parameters which are applied for crop-growth monitoring with agrometeorological model in the European Commission. The parameters selected for calibration of model for our study were: AMAXTB, DTSMTB, TMNFTB, DVS, EFFTB, FLTB, FOTB, FSTB, SLATB, SPAN, TBASEM, TEFFMX, TSUMEM, TSUM1 and TSUM2. The details of these parameters are given in Table 3.

Total length of growing period and phenological development stages

In WOFOST model, total growth period of potato has been divided into 3 phenological development states: 1, planting to emergence; 2, emergence to initiation of tuber growth; and 3, initiation of tuber growth to physiological maturity. The total length of the crop-growth period and phenological development stages were calibrated by making changes in the thermal time parameter in these developmental stages. Keulon and Stol (1995) reported that for calibration of growing period, the base temperature taken for temperature sum was 2ºC, as no potato growth is possible below this temperature. For calibration of phenological development stages, model parameters used were DTSMTB, TBASEM, TSUMEM, TSUM1 and TSUM2.

Among the 7 cultivars for which model was calibrated, ‘Kufri Kanchan’ required the minimum thermal time (290 ºC) to emerge, while ‘Kufri Lalit’ required the maximum (380ºC). This cultivar also exhibited the maximum thermal time from emergence to tuber initiation (390ºC), however, the thermal time for tuber initiation to maturity was the least (935ºC) for this cultivar.

Light interception and total biomass production

In WOFOST, the amount of biomass production depends on the irradiation intercepted by the crop canopy. The model parameters which were used for simulation of leaf-area index (LAI) and total biomass production were: AMAXTB, TMNFTB, DVS, EFFTB, SLATB and SPAN. These 5 parameters were modified to model leaf-area index (LAI) and total biomass production.

Assimilate distribution among various crop organs

The allocation of biomass produced to different plant organs is a function of phenological development stage in WOFOST. During initial growth stage, larger proportion

Table 1. Details of field experiments conducted to generate genetic coefficient

Station	Geographical location	Cultivars	Year	Dates of planting (dd/mm/yy)
Modipuram (Meerut)	29.0677° N, 77.7080° E	‘Kufri Sadabahar’	2011–12	17 Oct 11, 27 Oct 11, 6 Nov 11
			2012–13	15 Oct 12, 25 Oct 12, 5 Nov 12
		‘Kufri Khayati’	2011–12	17 Oct 11, 27 Oct 11, 6 Nov 11
			2012–13	15 Oct 12, 25 Oct 12, 5 Nov 12
		‘Kufri Garima’	2013–14	25 Oct 13, 4 Nov 13, 13 Nov 13
			2014–15	17 Oct 14, 27 Oct 14, 5 Nov 14
Patna	25.5941° N, 85.1376° E	‘Kufri Kanchan’	2011–12	31 Oct 11, 10 Oct 11, 20 Nov 11
			2012–13	31 Oct 12, 9 Nov 12, 19 Nov 12
		‘Kufri Arun’	2011–12	31 Oct 11, 10 Nov 11, 20 Nov 11
			2012–13	31 Oct 12, 9 Nov 12, 19 Nov 12
		‘Kufri Lalit’	2013–14	29 Oct 13, 7 Nov 13, 16 Nov 13
			2014–15	31 Oct 14, 10 Nov 14, 20 Nov 14
		‘Kufri Sindhuri’	2013–14	29 Oct 13, 7 Nov 13, 16 Nov 13
			2014–15	31 Oct 14, 10 Nov 14, 20 Nov 14
Gwalior	26.2183° N, 78.1828° E	‘Kufri Surya’	2012–13	22 Sep 12, 1, 11 and 21 Oct 12, 1 Nov 12
			2013–14	20 and 30 Nov 13, 10, 20 and 30 Nov 13
Jalandhar	31.3260° N, 75.5762° E	‘Kufri Surya’	2013–14	25 Sep 13, 5 Oct 13, 15 Oct 13
			2014–15	28 Sep 14, 7 Oct 14, 15 Oct 14

of total biomass is allocated to roots and of above-ground biomass to leaves and then stems. The partitioning of assimilates to leaves decreases and to storage organ (tubers) increases, as the growth progresses. The partitioning factors FLTB, FOTB and FSTB were altered to calibrate the model for allocation of assimilates to various plant organs, depending on DVS (development stage).

The modified values of some of the important parameters during the course of calibration are given in Table 4.

Calibration results showed a closed match between simulated and observed values of total dry-matter yields of all the 7 varieties, which varied from 1.3% ('Kufri Khyati') to 7.5% ('Kufri Surya'), and are within acceptable limit (Table 5). The tuber dry-matter yield was simulated more accurately than total dry-matter yield as the variation of simulated values ranged from 0.1% ('Kufri Lalit') to 6.9% ('Kufri Arun') at maturity, thus showing a strong correlation. The model simulated values of tuber dry-matter yield for 'Kufri Arun', 'Kufri Khyati' and 'Kufri Surya' were less than the observed values, while 'Kufri Garima', 'Kufri Kanchan' and 'Kufri Sadabahar' had higher simulated values than the observed one.

Seven varieties for which model was calibrated had differences in phonological development and physiological growth in terms of dry-matter accumulation and partitioning, which is reflected in different values of calibrated parameters for these varieties. While 'Kufri Kanchan' had the longest maturity ('TSUM2-1055'), 'Kufri Lalit' had

Table 2. Important characteristics of potato cultivars used for calibration studies

Variety	Characteristics
'Kufri Arun'	A medium-maturing, main-season, high-yielding table potato variety, suitable for cultivation in north Indian plains. Its tubers are red, oval with shallow to medium eyes and creamy-light yellow flesh, and having good keeping quality.
'Kufri Garima'	A medium-maturing, main-season, high-yielding table-purpose potato variety, suitable for cultivation in Indo-gangetic plains and plateau regions having field resistance to late blight with light yellow, ovoid tubers with shallow eyes and light yellow flesh.
'Kufri Khyati'	A high-yielding-early-maturing white tuber variety having moderate resistance to late blight and is for cultivation in plains of India. It possesses moderate resistance to late blight and is suitable for high-cropping intensity.
'Kufri Kanchan'	It is a red tuber potato cultivar, resistant to wart disease and late blight. It is a medium-maturing cultivar, with good cooking and keeping qualities.
'Kufri Lalit'	This variety is resistant to late blight with red-peel, yellow flesh, round, medium deep-eyed tubers. This variety was identified for cultivation in Indo-Gangetic plains.
'Kufri Sadabahar'	A medium-maturing, main-season, high-yielding potato variety, suitable for cultivation in Uttar Pradesh. White tuber, oblong with shallow eyes and white flesh with field resistance to late blight.
'Kufri Surya'	An early-maturing, heat-tolerant and hopper-burn resistant potato variety with oblong tuber, white smooth skin and pale yellow flesh. This variety is meant for early (September) planting in north-western plains and for *rabi* and *kharif* plantings in peninsular India. It can also be grown in the main crop season in north-western and west-central plains.

Table 3. Description and units of WOFOST parameters revised for calibration

Parameter	Description	Unit
AMAXTB	Maximum leaf CO_2 assimilation rate as a function of development stage of the crop	kg/ha/hr.
DTSMTB	Increase in thermal time as function of average temperature	ºC
DVS	Development stage of crop	-
EFFTB	Initial light-use efficiency of CO_2 assimilation of single leaves as function of daily temperature	(kg/ha/hr)/(J/m^2/s); ºC.
FLTB	Fraction of above-ground dry-matter increase partitioned to leaves as a function of development stage	kg/kg
FOTB	Fraction of above-ground dry-matter increase partitioned to storage organs as a function of development stage	kg/kg
FRTB	Fraction of total dry-matter increase partitioned to roots as a function of development stage	kg/kg
FSTB	Fraction of above-ground dry-matter increase partitioned to stems as a function of development stage	kg/kg
SLATB	Specific leaf area as a function of development stage	ha/kg
SPAN	Life span of leaves growing at 35ºC	days
TBASEM	Lower threshold temperature for emergence	ºC
TEFFMX	Maximum effective temperature for emergence	ºC
TMNFTB	Reduction factor of gross assimilation rate as function of low minimum temperature	-; ºC
TSUMEM	Thermal time from sowing to emergence	ºC
TSUM1	Thermal time from emergence to initiation of tuber growth	ºC
TSUM2	Thermal time from initiation of tuber growth to maturity	ºC

the earliest ('TSUM2 935') (Table 4). Although varieties had same patterns in total and tuber dry-matter yield (Figs 1 and 2), 'Kufri Surya' was observed to be an early bulker followed by 'Kufri Arun', with a slower bulking rate towards the maturity. However, in case of other varieties, after initial phase of slow growth, a consistent increase was observed till maturity (Figs 1 and 2).

Validation

A model needs to be validated in order to evaluate its accuracy in terms of desired output parameters, which in our case are phonological growth period and total and tuber dry-matter yields. The validation results, which show the comparison of measured and simulated results, showed variation of 1 day ('Kufri Surya') to 5 days ('Kufri Garima') in plant emergence and 3 days ('Kufri Arun', 'Kufri Kanchan', 'Kufri Sadabahar') to 5 days ('Kufri Lalit') in crop maturity, which are within the satisfactory limits (Table 5).

It was observed that simulated total dry-matter yield was very close to the observed value during initial phase. Simulated value lied almost on the observed value (Figs 1,2) up to 70 days in case of 'Kufri Sadabahar', 'Kufri Khyati' and 'Kufri Surya' and up to 100 days in 'Kufri Lalit' and 'Kufri Kanchan'. The tuber dry-matter yield of tuber simulated up to 60 days was more than observed value in 'Kufri Garima', however, after 70 days it was below the observed value but at harvesting it was almost similar to observed value (–1.6%).

The dry-matter yield of tuber was simulated almost

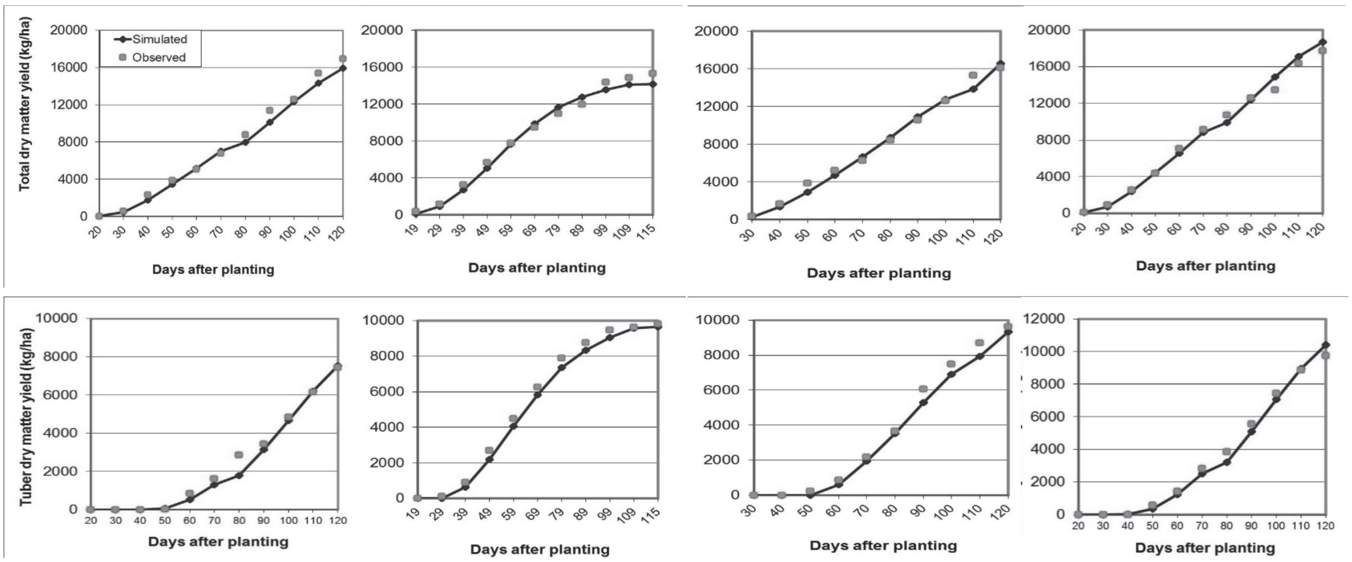
Table 4. Values of some important model parameters used in calibration of WOFOST for different potato cultivars

Parameter	Default values	Cultivar															
		'Kufri Arun'				'Kufri Garima'				'Kufri Khyati'				'Kufri Kanchan'			
TSUMEM	170.	335.				340.				310.				290.			
TSUM1	200.	380.				340.				280.				330.			
TSUM2	1800.	1010.				1015.				1025.				1055.			
DTSMTB	0.00, 0.00 2.00, 0.00 13.0, 11.0 30.0, 28.0	0.00, 0.00 2.00, 0.00 13.00, 11.00 30.00, 28.00 35.00, 33.00															
AMAXTB	0.00, 30.00 1.57, 30.00 2.00, 0.00	0.00, 35.00 1.35, 35.00 2.00, 1.00				0.00, 35.00 1.45, 35.00 2.00, 1.00				0.00, 40.00 1.50, 40.00 2.00, 1.00				0.00, 30.00 1.50, 30.00 2.00, 01.00			
TMNFTB	0.00, 0.00 3.00, 1.00	0.0, 0.00 5.0, 1.00															
Dry matter partitioning	(Range)	DVS	FLTB	FSTB	FOTB	DVS	FLTB	FSTB	FOTB	DVS	FLTB	FSTB	FOTB	DVS	FLTB	FSTB	FOTB
FLTB	(0.8 – 0)	0.00	0.80	0.20	0.00	0.00	0.80	0.20	0.00	0.00	0.80	0.20	0.00	0.00	0.80	0.20	0.00
FSTB	(0.2 – 0)	1.00	0.80	0.20	0.00	1.00	0.80	0.20	0.00	1.00	0.80	0.20	0.00	1.00	0.80	0.20	0.00
FOTB	(0.0 – 1.0)	1.25	0.35	0.00	0.65	1.25	0.35	0.00	0.65	1.40	0.28	0.00	0.72	1.35	0.40	0.00	0.60
		2.00	0.00	0.00	1.00	2.00	0.00	0.00	1.00	2.00	0.00	0.00	1.00	2.00	0.00	0.00	1.00

TSUMEM	380.				335.				355.			
TSUM1	390.				320.				265.			
TSUM2	935.				1045.				980.			
DTSMTB	0.00, 0.00 2.00, 0.00 13.00, 11.00 30.00, 28.00 35.00, 33.00											
AMAXTB	0.00, 35.00 1.42, 35.00 2.00, 1.00				0.00, 35.00 1.43, 35.00 2.00, 1.00				0.00, 35.00 1.40, 35.00 2.00, 1.00			
TMNFTB	0.0, 0.00 5.0, 1.00											
Dry matter	DVS	FLTB	FSTB	FOTB	DVS	FLTB	FSTB	FOTB	DVS	FLTB	FSTB	FOTB
partitioning	0.00	0.80	0.20	0.00	0.00	0.80	0.20	0.00	0.00	0.80	0.20	0.00
	1.00	0.80	0.20	0.00	1.00	0.80	0.20	0.00	1.00	0.80	0.20	0.00
	1.20	0.30	0.00	0.70	1.35	0.38	0.00	0.62	1.15	0.40	0.00	0.60
	2.00	0.00	0.00	1.00	2.00	0.00	0.00	1.00	2.00	0.00	0.00	1.00

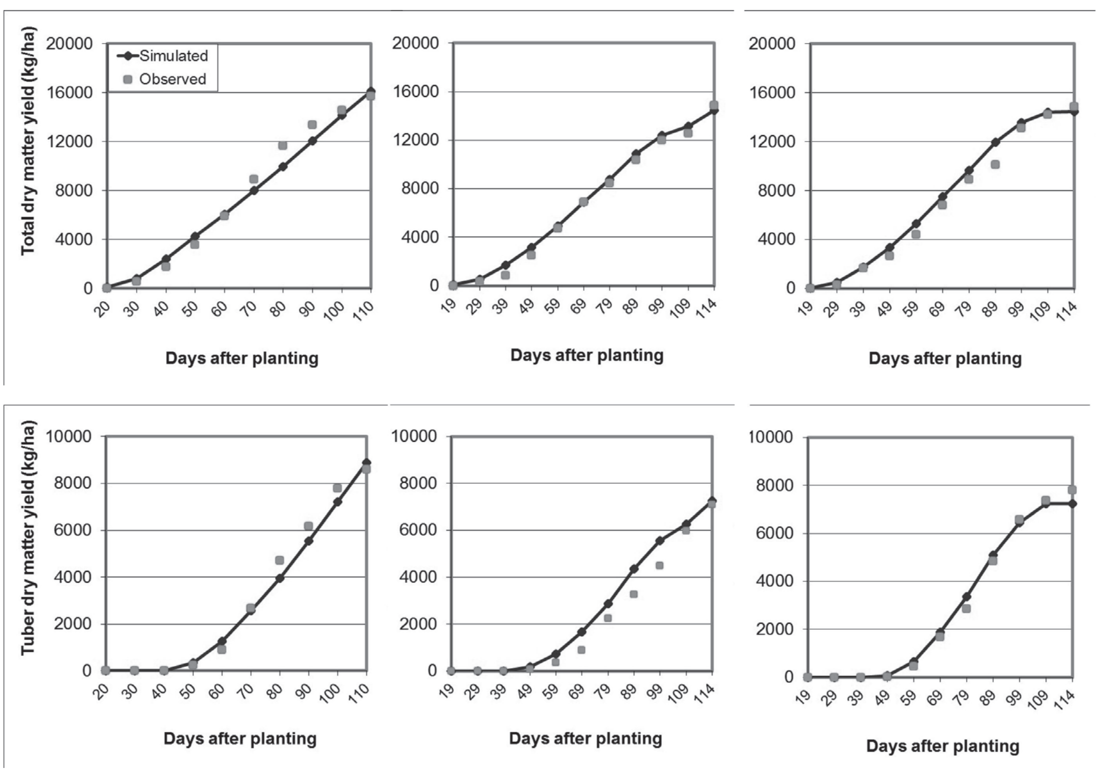
perfectly in case of ‘Kufri Surya’, ‘Kufri Khyati’ and ‘Kufri Arun’ up to the maturity. However, simulated tuber dry-matter yield of ‘Kufri Sadabahar’, ‘Kufri Lalit’, ‘Kufri Garima’ and ‘Kufri Kanchan’ at maturity were very close to the observed value, showing deviation ranging from 0.1% to 2.5% only. The highest dry-matter yield of tuber was simulated in ‘Kufri Khyati’, while these parameters were lowest for ‘Kufri Arun’ and ‘Kufri Kanchan’.

The highest total and tuber dry matter yield of ‘Kufri Khyati’ among all the 7 cultivars may be attributed to higher maximum leaf CO_2 assimilation rate (AMAXTB) (Table 4), the yield of ‘Kufri Kanchan’ was the least due to the lowest AMAXTB value. ‘Kufri Arun’, which had a slightly higher AMAXTB value than ‘Kufri Kanchan’



‘Kufri Sadabahar’ ‘Kufri Surya’ ‘Kufri Lalit’ ‘Kufri Khyati’

Fig. 1. Validation results of simulated and measured dry-matter yields of different potato cultivars



‘Kufri Garima’ ‘Kufri Kanchan’ ‘Kufri Arun’

Fig. 2. Validation results of simulated and measured dry-matter yields of different potato cultivars

showed the similar trend as of 'Kufri Kanchan' in terms of total and tuber dry-matter yield, as though the value of AMAXTB was higher, it was maintained up to smaller period (DVS 1.35; least among all the cultivars) as compared to 'Kufri Kanchan' (DVS 1.5). The most important parameter of our interest, i.e. dry-matter yield of tuber was simulated well in case of all the varieties and were within the range of ± 6.9%, while another important parameter, total dry matter yield, was also simulated well with the highest variation of 7.5% in 'Kufri Surya'.

A model can only be used if it can make predictions with a reasonable accuracy. In order to evaluate model, statistical parameters are used. Model performance can be evaluated by comparing simulated parameters with the observed values. For evaluating the performance of WOFOST for potato varieties, model simulated periodic total and tuber dry-matter yields were compared with the data obtained from the field studies, using statistical parameters. The Maximum Error (ME) values, which show the maximum difference between observed and simulated values, ranged from 227.0 ('Kufri Lalit') to 852.0 kg/ha ('Kufri Kanchan') for total dry-matter yield and from 171.0 ('Kufri Khyati') to 1,089.0 kg/ha ('Kufri Kanchan') for total tuber yield (Table 6). The ME was < 7% for total tuber yield and < 8.3% for tuber dry-matter yield of their maximum values, except for 'Kufri Kanchan', which had a ME of about 15% of the maximum tuber dry-matter yield. However, as far as the final tuber yield is concerned, the difference between measured and simulated tuber dry matter yield was about 2.2% for 'Kufri Kanchan'.

The Root Mean Square Error (RMSE), which indicates the overage magnitude of error in terms of percent over- or under-estimation by the model with respect to the mean of observed values, varied from 2.6 ('Kufri Lalit' – total dry matter yield) to 10.5 ('Kufri Sadabahar'-tuber dry -matter yield) for dry-matter yields (Except for 'Kufri Kanchan', which had a value of 25.8% with respect to tuber dry-matter yield). The co-efficient of residual mass (CRM) which shows whether model over-estimated (-) or under-estimated (+) the parameters, indicated that WOFOST under-estimated the total dry matter yields of 'Kufri Arun', 'Kufri Garima', 'Kufri Lalit', 'Kufri Sadabahar' and 'Kufri Surya', and tuber dry-matter yields of 'Kufri Arun', 'Kufri Garima', 'Kufri Khyati', 'Kufri Sadabahar' and 'Kufri Surya' (Table 6). However, these values were very near to the desired value of zero. Similarly, the modelling efficiency (EF) values, which indicate whether model predictions proved a better estimate of the measurements from the average values of the observed values and the coefficient of determination (CD) indicator, which describes the ratio between the scatter of predicted values and the scatter of observations (Kabat *et al.,*1995) – both of these indicators showed that model performance was satisfactory for both the parameters (total and tuber yield dry matter yield) for all the varieties, as these values were very near to the ideal value of 1. All these statistical indicators thus indicated that WOFOST has simulated the total and tuber dry matter yields very satisfactorily and accurately and the model can be used with much reliability.

The calibration and validation of WOFOST crop growth model was done for potato crop. The model simulated crop growth, biomass production and distribution over the course of growing period in 7 Indian potato cultivars falling under different classes of maturity, viz. 'Kufri Arun', 'Kufri Garima', 'Kufri Khyati', 'Kufri Kanchan', 'Kufri Lalit', 'Kufri Sadabahar' and 'Kufri Surya'. The

Table 5. Comparison of measured and simulated values of some important parameters of potato cultivars

Parameter	'Kufri Arun'			'Kufri Garima'			'Kufri Khyati'			'Kufri Kanchan'		
	Mea.	Sim.	Diff.	Mea.	Sim.	Diff.	Mea.	Sim.	Diff.	Mea.	Sim.	Diff.
Emergence (days)	23	20	3 days	22	17	5 days	16	18	2 days	22	17	5 days
Tuber initiation (days)	48	45	3 days	45	41	4 days	42	38	4 days	43	40	3 days
Total dry-matter yield (kg/ha)	14,875	14,439	2.9%	17,200	16,921	1.6%	18,976	19,238	1.3%	14,730	14,305	2.9%
Tuber dry-matter yield (kg/ha)	7,789	7,244	6.9%	9,510	9,641	1.3%	11,200	10,906	2.6%	7,087	7,258	2.4%

Mea, Measured; Sim, simulated; Diff., difference

Parameter	'Kufri Lalit'			'Kufri Sadabahar'			'Kufri Surya'		
	Mea.	Sim.	Diff.	Mea.	Sim.	Diff.	Mea.	Sim.	Diff.
Emergence (days)	21	23	2 days	23	20	3 days	15	16	1 days
Tuber initiation (days)	45	50	5 days	48	45	3 days	28	32	4 days
Total dry-matter yield (kg/ha)	16,600	16,921	1.9%	17,854	16,919	5.2%	15,327	14,176	7.5%
Tuber dry-matter yield (kg/ha)	9,630	9,641	0.1%	8,225	8,437	2.5%	9,823	9,647	1.7%

Mea, Measured; Sim, simulated; Diff., difference

Table 6. Statistical indicators of performance of WOFOST model

Parameter	Optimum value	'Kufri Arun' Total DM yield (kg/ha)	'Kufri Arun' Tuber DM yield (kg/ha)	'Kufri Garima' Total DM yield (kg/ha)	'Kufri Garima' Tuber DM yield (kg/ha)	'Kufri Khyati' Total DM yield (kg/ha)	'Kufri Khyati' Total DM yield (kg/ha)	'Kufri Kanchan' Tuber DM yield (kg/ha)	'Kufri Kanchan' Total DM yield (kg/ha)	'Kufri Lalit' Tuber DM yield (kg/ha)	'Kufri Lalit' Total DM yield (kg/ha)	'Kufri Sadabahar' Tuber DM yield (kg/ha)	'Kufri Sadabahar' Tuber DM yield (kg/ha)	'Kufri Surya' Total DM yield (kg/ha)	'Kufri Surya' Tuber DM yield (kg/ha)
ME		436.0	545.0	605.0	698.0	1414	171	852.0	1089	227.0	308.0	274.0	267.0	798.0	534.0
RMSE	0	10.016	8.902	4.583	4.774	6.669	5.455	6.938	25.812	2.600	4.504	7.539	10.493	7.558	6.475
CRM	0	0.066	0.013	0.003	0.034	–0.010	0.043	–0.047	–0.184	0.010	–0.020	0.055	0.035	0.027	0.055
EF	1	0.980	0.998	0.996	0.999	0.990	0.955	0.992	0.987	0.998	0.999	0.988	0.997	0.984	0.995
CD	1	1.001	0.966	0.920	0.977	0.898	0.996	1.031	1.114	1.020	1.026	1.093	0.953	1.010	0.937

ME, Maximum error; RMSE, root mean square error; CRM, coefficient of residual mass; EF, modelling efficiency; DM, dry-matter; CD, coefficient of determination

model predicted values corresponded well with measured values. Thus, WOFOST model can be used for studying and predicting the dynamics of crop growth and biomass yield of potato cultivars under changing environmental conditions in India.

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