Estimating potato yield with the SUBSTOR model in Québec

M.H. MAHDIAN and J. GALLICHAND

Département des sols et de génie agroalimentaire, FSAA, Université Laval, Québec, QC, Canada G1K 7P4. *Received 25 October 1996; accepted 15 May 1997.*

Mahdian, M.H. and Gallichand, J. 1997. **Estimating potato yield with the SUBSTOR model in Québec.** Can. Agric. Eng. 39:157-164. The growth and development of a crop involve interactions between many physical, chemical, and biological processes. Crop growth models facilitate the study of the effect of these interactions on crop yield. Potato yields simulated by the SUBSTOR model were compared with measured values at Saint-Catherine-de-la-Jacques-Cartier near Québec, QC. A sensitivity analysis was performed to identify the crop input parameters to which SUBSTOR is most sensitive. Results of the sensitivity analysis showed that SUBSTOR outputs related to yield are sensitive to changes in the date of emergence and genetic parameters, especially variations in the degree of determinacy and potential tuber expansion rate. SUBSTOR was calibrated in 1992 and verified in 1993. Results of the simulations show that, on average, SUBSTOR overestimated potato dry yield by 4% in 1992 and underestimated it by 15% in 1993. In 1992 and 1993, maturity dates were simulated accurately, but maximum leaf area index was overestimated. Tuber initiation date was accurately simulated in 1993 and underestimated by 10 days in 1992. Since 1992 and 1993 were wet years, the crop is not likely to have suffered from water stress. However, simulated soil water content was underestimated during the growing season in 1993 that resulted in underestimation of potato yield. Keywords: SUBSTOR, simulation, yield, potatoes, model.

La croissance et le développement d'une culture impliquent l'interaction de plusieurs processus physiques, chimiques et biologiques. Les modèles de croissance peuvent faciliter l'étude de l'effet de ces interactions sur le rendement des cultures. Les rendements de la pomme de terre simulés par le modèle SUBSTOR ont été comparés avec ceux mesurés au champ à Saint-Catherine-de-la-Jacques-Cartier près de Québec, QC. Une analyse de sensibilité a été réalisée pour déterminer les paramètres de croissance auxquels SUBSTOR était sensible. Les résultats de l'analyse de sensibilité ont montré que les sorties du modèle SUBSTOR reliées au rendement, sont sensibles à la variation de la date d'émergence et aux paramètres génétiques, particulièrement le degré de détermination et le taux potentiel de l'expansion des tubercules. SUBSTOR a été calibré en 1992 et testé en 1993. Les résultats de cette simulation montrent que SUBSTOR a sur-estimé de 4% le rendement sec de la pomme de terre en 1992 et l'a sous-estimé de 15% en 1993. En 1992 et 1993, ce modèle a simulé précisément la date de maturité, mais surestimé l'indice de surface foliaire maximum. La date d'initiation de la tubérisation a été simulée précisément en 1993 et sous-estimée de 10 jours en 1992. Puisque 1992 et 1993 furent des années humides, il est peu probable que la culture ait souffert de stress hydrique. Toutefois, en 1993 la teneur en eau a été sous-estimée par SUBSTOR ce qui a résulté en une sous-estimation du rendement de la pomme de terre. Mots clés: SUBSTOR, simulation, rendement, pommes de terre, modèle.

INTRODUCTION

The growth and development of a crop involve interactions between many physical, chemical, and biological processes. Interest in the understanding of these processes has led to interdisciplinary research between plant physiologists, engineers, economists, and meteorologists. This is deemed imperative since the plant system is the synthesis of the physical and biological interactions of its components. Growth models are tools that can facilitate the determination of the effect of these interactions on crop yield and potentially on environmental impacts. Crop growth models range from the strictly empirical types (e.g. Skjelvary 1980) that are simple regression equations relating crop yield to several meteorological and agronomic variables, to highly sophisticated biochemical types (e.g. Curry et al. 1975) that incorporate the detailed phenological and physiological processes of crop growth as influenced by climate. The level of detail required in a given situation depends on the objectives of the study and the purpose for which the crop model will be used.

There is little information on the application of potato growth models in Eastern Canada. These models have the potential to help farmers to optimize field operations and minimize costs. Several computer models simulating crop growth have been developed since 1975 (Curry et al. 1975; Arkin et al. 1976; Baker and Horrocks 1976; Morgan et al. 1980; Wilkerson et al. 1983; Stewart and Dwyer 1986). Some models are specific to potatoes and include SUBSTOR (Hodges et al. 1989), SWACROP (Feddes et al. 1978), POTATO (Ewing et al. 1990), and that of Ng and Loomis (1984). Many of these models have the potential to be used as crop management or research tools. SUBSTOR is a CERES (Crop Environment REsearch Synthesis) crop growth model (IBSNAT 1989) and uses the same hydrological and nitrogen dynamic subroutines as other CERES models. The effects of climate, soil, and plant parameters and of nitrogen and water deficits are included in simulating potato growth. SUBSTOR can quantify the biomass of leaves, stems, tubers, and roots, leaf area index, emergence date, and maturity date. The objectives of this research were to evaluate the capabilities of SUBSTOR for simulating the yield of Kennebec potato variety at an experimental location near Québec, QC and to carry out a sensitivity analysis to study the impact of the input of plant and genetic parameters on the yield component of this model.

MATERIALS AND METHODS

Experimental site and measurements

The experiment was carried out at Saint-Catherine-de-la-Jacques-Cartier near Québec, QC. For this study, SUBSTOR was run using data from the 1992 and 1993 growing seasons in two adjacent potato fields. The Kennebec potato variety was planted in mid-May and harvested in mid-September of both years. Because of crop rotation, the same field could not be used for the two successive years. There were 8 plots in 1992 and 12 plots in 1993. The soils were similar in the two fields. The texture was loamy sand in the upper 300 mm over sand at greater depths. Watertable depth was monitored and was always deeper than 2500 mm in both 1992 and 1993 (which precluded upward capillary flow). Climatic variables measured at the experimental site with an automated weather station included hourly values of air temperature, global radiation, and rainfall. Table I summarizes the climatic data obtained during these two years. Rainfall during the growing seasons was 634 mm in 1992 and 584 mm in 1993. These values were higher than those of potential evapotranspiration calculated by the Priestly and Taylor (1972) method for the same period (490 mm for 1992, 458 mm for 1993). Rooting depth, leaf area index (LAI), and above ground biomass were measured during both growing seasons. Final tuber yield was evaluated by sampling on an area of 20 m^2 in each of the 20 plots. Fresh tubers were dried at 70°C to constant mass. Maturity date was that corresponding to no significant increase in tuber yield. Tuber initiation dates were taken as those on which 50% of the plants had at least one tuber greater than or equal to 10 mm in diameter. Nitrogen fertilization was based on soil measurements and recommendations of the Québec Ministry of Agriculture (CPVQ 1992) that resulted in applications of 175 kg/ha in 1992 (128 kg/ha on May 20 and 47 kg/ha on June 29), and 309 kg/ha in 1993 (121 kg/ha on May 18 and 188 kg/ha on June 25).

Model description

Version 2.0 of SUBSTOR was used in this study as this was the version available at the start of the project in 1992. The plant growth component is described in detail in Griffin et al. (1991). The crop production function of SUBSTOR has two components, plant and soil. The plant component incorporates processes of net photosynthesis, leaf area expansion, root distribution, light interception, stage of tuber development, the effect of nitrogen and water stress on development, tuber dry matter production, and plant uptake of nitrogen. The soil component includes water movement (infiltration, runoff, and drainage), evapotranspiration, nitrogen transformation and movement, soil temperature, and the release of mineral nitrogen through mineralization of crop residue and organic matter. The accumulation and partitioning of biomass and the phenological development of a potato crop are influenced by several factors. The most important are environmental and include temperature, photoperiodicity, and intercepted radiation. The simulation of potato growth in various environments and the effect of varietal differences must take these variables into account. SUBSTOR uses a zero to one relative temperature function based on mean daily air temperature to simulate the response of different plant organs and processes over a wide temperature range. The relative temperature function increases from zero at a base temperature of 2 to 5°C to a plateau value of one at 15 to 25°C, then decreases to zero at temperatures of 33 to 35°C. The potato growing season is divided into five phenological stages defined by pre-planting, planting, sprout germination, emergence, tuber initiation, and maturity.

The time of tuber initiation is often estimated by extrapolation of linear tuber bulking rate back to the time axis (Sands et al. 1979). In SUBSTOR, the timing of tuber initiation is a function of cultivar response to both temperature and photoperiodicity. Therefore, timing of tuber initiation is based on the threshold temperature above which tuber initiation is inhibited, on the predominance of daily minimum temperature over daily mean or maximum temperature and on photoperiodicity. For the latter, dimensionless genetic coefficient (P2) links the effect of photoperiodicity to tuber initiation. Potential tuber growth rate is calculated by an equation that relates maximum tuber growth rate (genetic coefficient G3) to temperature. Actual tuber growth rate is based on potential tuber growth rate, soil water deficit, and nitrogen deficit. Leaf growth is a function of soil water deficit and nitrogen deficit, the genetic coefficient for maximum leaf expansion rate (G2), the relative temperature, and plant density. Stem growth is calculated as 75% of leaf growth and root growth is estimated by a function related to stem and leaf growth.

The effect of soil water content on plant development is accounted for by two soil water deficit indices. These water stress indices represent the relationship between the maximum transpiration rate and the maximum water uptake rate

Table I: Summary of climatic data during the growing season (May 15 to September 15)

Variable	1992				1993			
	Avg	Min	Max	Total	Avg	Min	Max	Total
Maximum daily temperature (°C)	21.8	7.0	31.0	-†	22.7	9.0	33.1	-
Minimum daily temperature (°C)	10.1	-3.0	18.0	-	10.6	-1.4	19.7	-
Solar radiation ($MJ \cdot m^{-2} \cdot d^{-1}$)	18.1	2.6	31.0	-	15.9	1.2	28.7	-
Precipitation (mm)	-	-	-	634	-	-	-	584

† not applicable

Table II: Plant parameters required by SUBSTOR

Parameter	Description	Units
IEMERG	Date of emergence	julian date
PLANTS	Plant population	plants /m^2
SDEPTH	Seeding depth	cm
SPRLAP	Sprout length at planting	mm
SEEDRV	Reserve of carbohydrates in the tuber at planting	g

from the soil. One index describes the effect of water stress on photosynthesis and the other relates the effect of water stress to expansion growth and serves as a modifier for development rates and partitioning of biomass. Both indices are dimensionless and vary from 1.0 for no water stress, to 0.0 for extreme water stress.

Model formulation and calibration

For all simulations, the portion of the soil profile simulated by SUBSTOR was the upper 1250 mm which was divided into 15 soil compartments ranging in depth from 50 to 150 mm. Soil parameters were calibrated at each site as described in Mahdian and Gallichand (1995). SUBSTOR requires the specification of five plant parameters and five genetic parameters. The specified plant parameters are presented in Table II. Values for plant parameters can be easily obtained by field measurements and therefore do not need calibration. Genetic parameters, however, are difficult to specify because they are particular to the potato variety used, and may depend on the climatic conditions of the region where the model will be used. Genetic parameters are presented in Table III, along with upper and lower bound values found in the literature. The five genetic parameters were calibrated using measured values from the 8 plots of 1992. Results from the 12 plots of 1993 were used for verification. Calibration was performed by minimizing the objective function which was based on three plant parameters:

$$O = \sum_{i=1}^{8} \left[\left(\frac{Y_O - Y_S}{Y_O} \right)_i^2 + \left(\frac{LAI_O - LAI_S}{LAI_O} \right)_i^2 + \left(\frac{TID_O - TID_S}{TID_O} \right)_i^2 \right] \quad (1)$$

where:

O = objective function,

Y = dry yield (kg/ha),

LAI = maximum leaf area index (m^2/m^2),

TID = tuber initiation date (julian date),

o, s = indices for observed and simulated values, respectively, and

i = index for plot number.

At each step of the optimization, SUBSTOR was run for the 8 plots, the objective function computed, and the genetic parameters adjusted to minimize O. Least square optimization of O was performed using the program of Doherty (1993) and was set for the optimized parameters to stay within the bounds shown in Table III. Considering the amount of nitrogen applied in 1992 and 1993, we assumed that there was no nitrogen deficiency and SUBSTOR was run in the corresponding mode. SUBSTOR was driven by daily values of rainfall, minimum and maximum temperature, and global radiation.

Sensitivity analysis

A sensitivity analysis was performed to study the impact of genetic and plant parameters on SUBSTOR biological outputs. The sensitivity analysis was done with average soil and plant parameters, using 1993 climatic data. Input base values were assigned to each input parameter. These input base values were selected as average values of crop parameters; genetic input base values are shown in Table III. Using input base values and climatic data, the model was run and output base values were determined. Output base values for SUBSTOR consisted of the tuber initiation date (TID), maturity date (MD), total dry yield (TDY), maximum leaf area index (LAI), and dry mass of above ground biomass (AGB). Once the input and output base values were defined, two variations were imposed on each input parameter (except temperature sensitivity and date of emergence): base value +50% and base

Table III: Genetic parameters required by SUBSTOR

Parameter	Description	Units	Input base value	Calibrated value	Bound values
G2	Potential leaf expansion rate	$cm^2 \cdot m^{-2} \cdot d^{-1}$	1200	1900	360-2000†
G3	Potential tuber expansion rate	$g \cdot m^{-2} \cdot d^{-1}$	14	11.7	5.4-21.0†
PD	Degree of determinancy	-	0.5	0.6	0.0-1.0‡
P2	Photoperiod sensitivity	-	0.6	0.7	0.4-0.8‡
TC	Temperature sensitivity	^oC	18	18	14-21†

† Manrique et al. (1990)
‡ Ritchie (1992)

value -50%. For temperature sensitivity (TC), variations were limited to 20% of the base value because potatoes cannot grow optimally if air temperature is less than 14 °C. The date of emergence (IEMERG) was fixed at 164 (julian date) with a variation of 10 days. The model was run separately for each input parameter to obtain the modified output values. Variations in the output values were quantified, on a percentage basis, using the maximum absolute difference between the modified and output base values:

$$Dmax = \left[\frac{\max(\,|M_{val} - B_{val}|\,,\,|M_{val} + B_{val}|)}{B_{val}} \right] x\ 100 \quad (2)$$

where:

M_{val} = modified value, and

B_{val} = base value.

Values of *D*max were averaged by input parameters (*D*max1) and by output variables (*D*max2).

RESULTS AND DISCUSSIONS

Sensitivity analysis

Values of *D*max, presented in Table IV, show that the degree of determinancy (PD), potential tuber expansion rate (G3), and date of emergence (IEMERG) are the most sensitive plant parameters, with average *D*max1 values of 18, 17, and 11, respectively. These parameters are used to define the different components of yield in SUBSTOR. The model is less sensitive to potential leaf expansion rate (G2, *D*max1 = 7), photoperiod sensitivity (P2, *D*max1 = 5), sowing depth (SDEPTH, *D*max1 = 5), temperature sensitivity (TC, *D*max1 = 4), and plant population (PLANTS, *D*max1 = 2). Sprout length (SPRLAP) and carbohydrate reserves in the tuber at planting (SEEDRV) did not have any effect on the crop production variables. On average, above-ground biomass (AGB) and maximum leaf area index (LAI) were affected by plant and genetic parameters having *D*max2 values of 12. Total dry yield was less affected (TDY, *D*max2 = 9); whereas the effect on the other parameters (TID, and MD) was negligible. Except for the date of emergence, which can be easily observed in the field, plant parameters did not have important effects on SUBSTOR plant outputs. However, the model is much more sensitive to the genetic parameters that cannot be easily measured and are not readily available in the literature, especially for potato varieties that are not extensively used.

Table IV: Sensitivity of SUBSTOR to genetic and plant parameters

	*D*max (%)					
Parameters	TID	MD	TDY	LAI	AGB	*D*max1†
Genetic parameters						
G2	0	0	0	30	7	7
G3	0	0	50	0	37	17
PD	3	2	11	28	45	18
P2	2	0	5	16	2	5
TC	2	0	4	13	1	4
Plant parameters						
SEEDRV	0	0	0	0	0	0
SPRLAP	0	0	0	1	0	0
IEMERG	6	0	20	16	11	11
PLANT	0	0	1	8	2	2
SDEPTH	3	0	1	7	15	5
*D*max2‡	2	0	9	12	12	

† *D*max1: *D*max values averaged by input parameters
‡ *D*max2: *D*max values averaged by output variables

Model evaluation

Calibrated genetic parameter values, shown in Table III, are well within the bounds reported by Manrique et al. (1990) and Ritchie (1992) for potatoes. This suggests that the calibrated values obtained by optimization do not form an artificial combination of parameter values since none of the parameters was constrained by either bound. Measured and simulated dry yields are presented in Table V. The Québec Ministry of Agriculture reports an average regional fresh yield of 21.5 t/ha (MAPAQ 1994). Assuming a ratio of dry to fresh mass of 20%, the corresponding regional dry yield is 4300 kg/ha which is lower than our average measured yield of 6680 and 6912 kg/ha in 1992 and 1993. These higher yields can be due to the wet weather during those two growing seasons. In 1992, measured dry yield averaged 6680 kg/ha (ranging from 5810 to 8180) compared to 6959 kg/ha (from 6537 to 7059) for simulated yield. This represents an average overestimation of 4% by SUBSTOR. For the verification year (1993), the simulated yield averaged 5878 kg/ha (ranging from 5737 to 5990), while measured yield was 6912 kg/ha (from 5200 to 7930), an underestimation of 15%. In 1992, the difference between measured and simulated dry yields was not significant at the 0.05 probability level (Student t test), whereas it was significant in 1993. Table V also shows that standard deviations of simulated dry yield (188 kg/ha in 1992, 91 kg/ha in 1993) are lower than those observed (710 and 730 kg/ha). Although for 1992 and 1993, SUBSTOR was run at each site separately, the lower standard deviation of simulated yield means that SUBSTOR was unable to consider some soil or physiological processes that influenced yield production.

Imprecision of yield estimate by SUBSTOR might be attributed to three main classes of error: 1) insufficient fertilization, 2) imprecision of simulated soil water content, and 3) some inadequacies in the crop growth subroutines of SUBSTOR. Inadequate fertilizer amounts would have caused nitrogen deficiencies in the root zone and resulted in larger simulated yields than measured yields attributable to our use of the optimum fertilization option of SUBSTOR. However, in 1993, simulated yields were

Table V: Measured and simulated dry yield (kg/ha)

Year	n†	Average			STD		Min		Max	
		Mea‡	Sim§	Diff	Mea	Sim	Mea	Sim	Mea	Sim
		(kg/ha)		(%)	(kg/ha)					
1992	8	6680	6959	4	710	188	5810	6537	8180	7059
1993	12	6912	5878	-15	730	91	5200	5737	7930	5990

† Number of plot-years
‡ Measured
§ Simulated

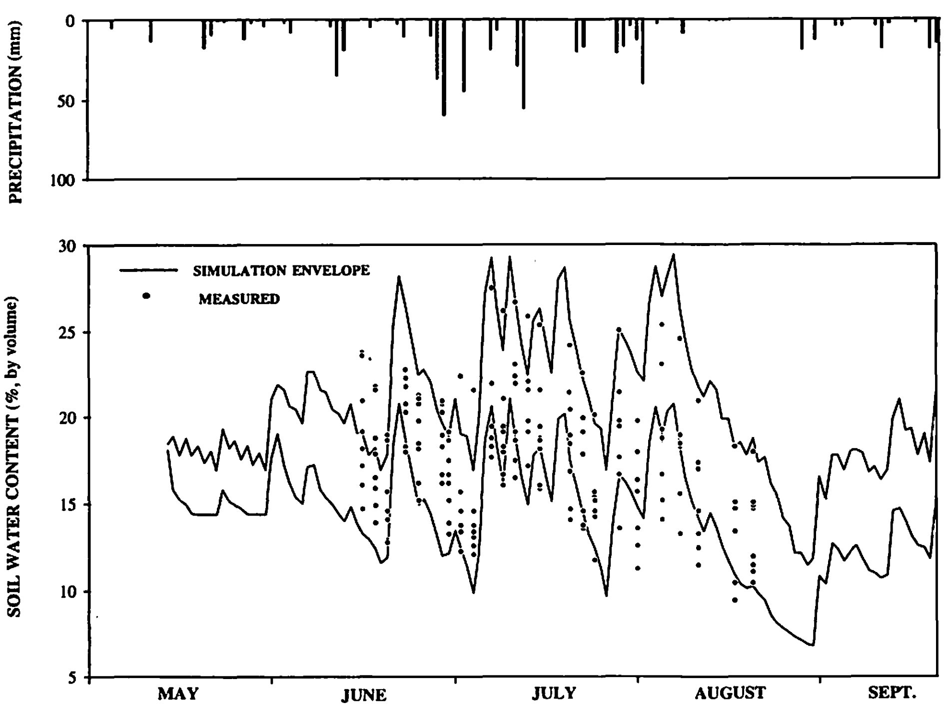

Fig. 1. Measured and simulated soil water content in the root zone for 8 plots in 1992.

lower than observed ones by 15% on average and nitrogen fertilization was adequate (309 kg/ha) since it was based on soil testing. This rules out insufficient fertilization as the cause of model inaccuracy.

Accuracy of soil water content simulation might explain, in part, the difference between observed and simulated yield. Figures 1 and 2 show measured and simulated soil water content in the root zone (0-450 mm) for 1992 and 1993, respectively. In both figures, measured values from all sites appear as dots whereas for simulated values, only the upper and lower envelopes of the 8 (1992) or 12 (1993) curves are shown. Figure 1 shows, with few exceptions, that measured values were within the simulation envelope. In this case, we would expect observed and simulated water stresses to be similar and consequently, the yields to be close. This was observed with an average difference between simulated and measured yields of only 4% in 1992. For 1993, however, Fig. 2 shows that many points lie outside the simulation envelope, especially during July. Moreover, most of the outlying points are above the upper boundary of the envelope. This implies that, for a part of the season where biomass production is very rapid due to high radiation and temperature, SUBSTOR underestimated water content. This underestimation must have resulted in unrealistic water stress that would have reduced simulated yield. This is what was observed for 1993 when SUBSTOR underestimated yield by 15%.

For the growth component, we found that the leaf area index (LAI) curve simulated by SUBSTOR, when using the optimized genetic parameters, did not match with observed values (Fig. 3). The leaf surface intercepts light and absorbs carbon dioxide in the processes of photosynthesis. Photosynthesis and dry matter production of a plant are proportional to the surface of its leaves. Figure 3 shows that there is a discrepancy between measured and simulated LAI values during the growing season for both years. SUBSTOR was modified to accept measured LAI values. Keeping all other parameters unchanged, use of the observed LAI resulted in average simulated dry yields of 6385 kg/ha in 1992 and 5747 kg/ha in 1993, which correspond to an underestimation of 3% in 1992 and 17% in 1993. Using measured LAI values did not result in improved performance of SUBSTOR.

Besides yield, other biological outputs from SUBSTOR were examined. Table VI presents observed and simulated values of tuber initiation date, maturity date, total fresh yield, dry mass of the above ground biomass, and maximum leaf area index for 1992 and 1993. Table VI shows that the maturity date was accurately simulated by SUBSTOR with a

Table VI: Average values of biological outputs measured and simulated by SUBSTOR (8 plots in 1992 and 12 plots in 1993)

Description	Output	1992			1993		
		Avg	Min	Max	Avg	Min	Max
Tuber initiation date (julian date)	Observed	204	204	204	198	198	198
	Simulated	194	194	194	198	197	200
Maturity date (julian date)	Observed	260	260	260	256	256	256
	Simulated	260	260	260	256	256	256
Total fresh yield (t/ha)	Observed	32.2	28.2	39.0	33.1	26.3	39.9
	Simulated	35.0	32.7	35.3	29.0	28.7	30.0
Above ground biomass (kg/ha	Observed	NA†	NA	NA	5266	4592	6318
	Simulated	7017	6778	7240	3627	3227	4086
Maximum leaf area index	Observed	4.5	2.3	7.6	5.7	3.3	6.6
	Simulated	7.5	7.3	8.2	7.0	6.8	7.2

† not available

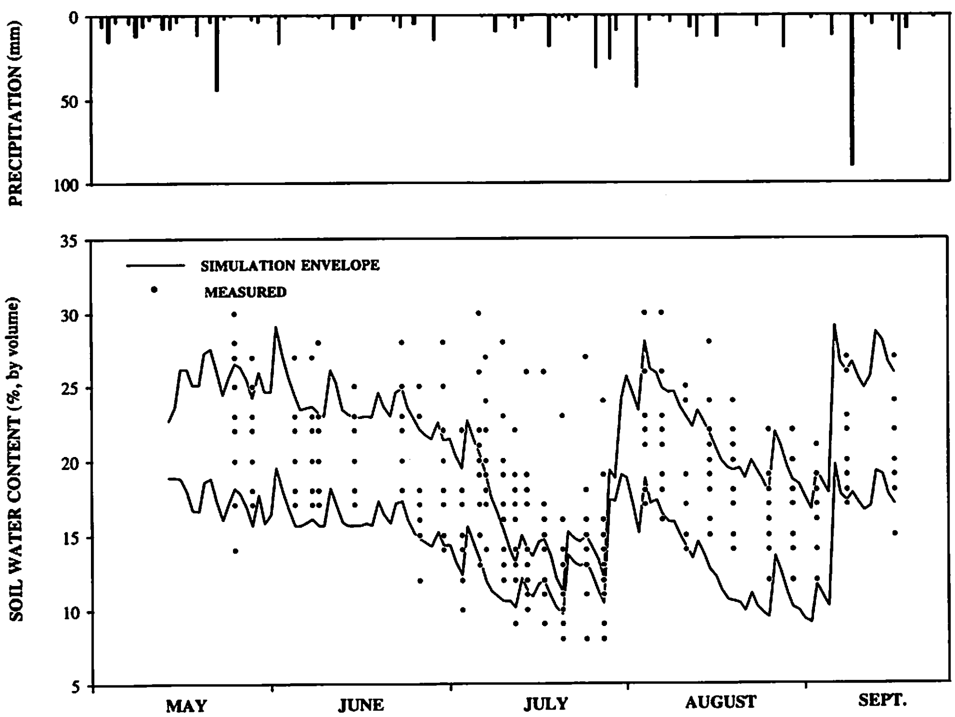

Fig. 2. Measured and simulated soil water content in the root zone for 12 plots in 1993.

julian date of 260 in 1992, and 256 in 1993. The accuracy of SUBSTOR in this respect is attributed to the model's predicting this value as the date when the simulated leaf area index falls to 10% of its maximum value during the growing season. In our simulation, simulated leaf area index did not fall to this value and, consequently, SUBSTOR defined the harvesting date as the maturity date. Results for the fresh yield of tubers were similar to dry yield, with a 9% overestimation in 1992 and a 12% underestimation in 1993. Tuber initiation date was simulated almost exactly in 1993, but was predicted sooner than observed by 10 days in 1992. The maximum leaf area index was always overestimated by SUBSTOR as can be seen in Fig. 3. The dry mass of the above ground biomass was underestimated in 1993 with an average simulated value of 3627 kg/ha and a measured value of 5266 kg/ha. The difference between measured and simulated biomass may be explained by the specific leaf area used in estimating the biomass. SUBSTOR increments the LAI by multiplying the net increment in leaf mass by the specific leaf area (SLA) that has a fixed value of 2.7 x 10^{-3} m^2/g. In reality, SLA varies during the growing season. At the 1993 site, the average measured value of SLA was 2.1 x 10-3 m2/g (ranging from 1.4 x 10^{-3} to 3.3 x 10^{-3} m^2/g) that is below the constant value defined in SUBSTOR and explains the overestimation of LAI. Since LAI was overestimated and tuber yield underestimated, the problem with the growth component of SUBSTOR might lie in the partitioning of biomass.

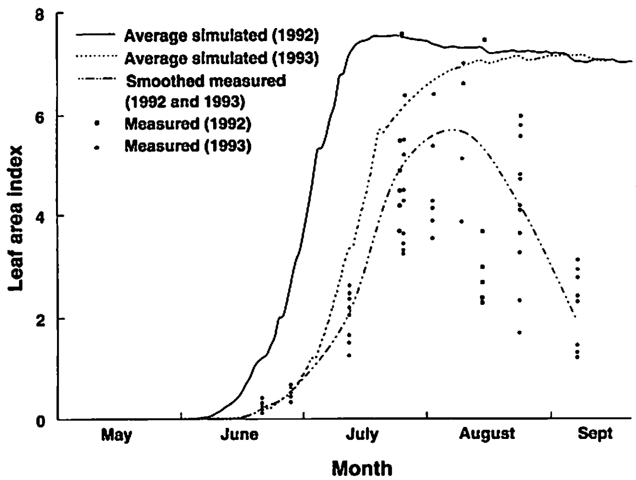

Fig. 3. Measured and simulated leaf area index during the growing seasons 1992 and 1993.

Relative performance of the model

The accuracy obtained with SUBSTOR was comparable with that reported in the literature. Johnson et al. (1988) validated a growth model for Russet Burbank potatoes using data for two years at two dryland sites and one irrigated site on silty loam and sandy soils in the United States. Their model showed an average underestimation of 1% for dry yield. Employing the model of MacKerron and Waister (1985), Kundel and Campbell (1987) obtained an average yield overestimation of 57% for Russet Burbank potatoes using data from many experimental sites in the Columbia Basin of Washington. Ritchie et al. (1996) used the SUBSTOR model for simulating Maris Piper potato yield from four years of data in the United States. Their results show an average underestimation of 34% for dry yield. In view of these results, the overestimation of 4% in 1992 and the underestimation of 15% in 1993, that we obtained, could be considered reasonable. However, for the two years of this study, the climatic conditions were wet and only minor water stress might have occurred. For drier climatic conditions, the performance of SUBSTOR is unknown.

CONCLUSIONS

Potato yield and other biological output parameters simulated by SUBSTOR were sensitive to variations of the genetic parameters, particularly the degree of determinancy, the potential tuber expansion rate, and the date of emergence. Among model outputs, above ground biomass and the maximum leaf area index were most affected by plant and genetic parameters.

SUBSTOR overestimated potato dry yield by 4% during the calibration year (1992), but underestimated it by 15 % in the verification year (1993). The 1993 yield underestimation might be attributable to the underestimation of soil water content that increased simulated soil water stress. The two years of the study, considered wet years, might explain the good performance of the model. For drier years, SUBSTOR might not have performed as well.

The standard deviation of simulated dry yield was always lower than that of measured values, indicating that the model was unable to reproduce completely the spatial variation of soil and physiological processes.

Leaf area index was overestimated in both years simulated by SUBSTOR. Yield prediction was not improved when measured values of leaf area index were used as input in the model. This indicates potential problems in the biomass partitioning component of SUBSTOR.

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