International Journal of Plant Production 7 (3), July 2013
ISSN: 1735-6814 (Print), 1735-8043 (Online)
www.ijpp.info

GUASNR

Application of the MoDrY model for the estimation of potato yielding

A. Żyromski[a], W. Szulczewski[b], M. Biniak-Pieróg[a,*], R. Żmuda[a]

[a] *Wroclaw University of Environmental and Life Sciences, Institute of Environmental Protection and Development.*
[b] *Wroclaw University of Environmental and Life Sciences, Department of Mathematics.*
*Corresponding author. E-mail: malgorzata.biniak-pierog@up.wroc.pl

Received 3 August 2012; Accepted after revision 10 January 2013; Published online 1 April 2013

Abstract

The study was conducted with the application of the model MoDrY (Model-Dry periods-Yield) for the estimation of the level of potato yields on the basis of dry periods occurring during the particular periods between the phenological phases of the crop plant. A characteristic feature of this model, unlike most existing weather-yield models, is that the principle of its operation is based only on information on the occurrence of precipitation. In the study the authors used research material from the years 1971-1983 and 1985-1996 (25 years) and diurnal sums of atmospheric precipitation from the same periods. Five interphase periods were adopted for the analyses: planting-emergence, emergence-lateral shoots, lateral shoots-start of blooming, start of blooming-haulm drying, haulm drying-harvest. The authors also used a model of changes in the resources of water available for plants during dry periods. Six measures were adopted to characterise the error of approximation: coefficient of correlation, coefficient of determination, mean relative error, RRMSE, EF and CRM. The coefficient of correlation obtained was at the level of 0.92 and the mean relative error at the level of 9.27%. Validation was performed by means of the Cross Validation test (CV), version LOO.

Keywords: Potato; Dry periods; Phenological phases; Weather-yield model; MoDrY.

Introduction

The objective of agricultural activity is the obtainment of the highest possible yields of crop plants. Since the levels of yields vary from year to year, many attempts have been made in the world to describe that process through the construction of mathematical models permitting the prediction of yields of various crop plants. Accurate estimation of yields is a difficult task and requires taking into account a number of determining factors-stimulating or inhibiting. Most frequently such models require many variables as input data, among which we should mention soil and climatic conditions and in certain cases also soil and plant cultivation treatments. Irrespective of the crop plant species, the main factor that significantly affects their growth and development and consequently the level of their yields, is atmospheric precipitation which is the primary source of supply of soil water (e.g. Jafari et al., 2009; Jørgensen et al., 2011; Nielsen et al., 2010; Sun et al., 2010). For use as input data, atmospheric precipitations can be presented in the form of diurnal sums or as numbers of days with no precipitation (dry periods). That latter form, applied in studies by Szulczewski et al. (2010) and Szulczewski et al. (2012) for modelling of yields of spring barley and spring wheat, gave highly satisfactory results.

For many years, in Poland and in the world, studies have been conducted on the modelling of potato yielding, which results from the high popularity of that crop plant. Among the known models of potato yielding we should mention e.g. SUBSTOR, POMOD, POTATOS, WOFOST (IBSNAT, 1993; Kadaja and Tooming, 2004; Koning et al., 1995; Spitters, 1990; Štastná and Dufková, 2008; Wolf, 2002). Under the conditions of Poland, favourable for the growing of potato, its growth, development and yielding are determined primarily by the amount and distribution of rainfalls during its vegetation (Biniak et al., 2007; Rojek, 2006; Rolbiecki et al., 2009). For this reason, the objective of this study was an attempt at the application of the model MoDrY (Szulczewski et al., 2010; Szulczewski et al., 2012) for the estimation of yields of that popular crop plant. The feature that sets this model apart from other existing models of the weather-yield type is that this model uses only information on the occurrence of days with no precipitation (dry periods).

Materiale and Methods

The study reported herein was focused on the effect of dry periods on the yielding of potato. Data on the occurrence of dry periods were used for the development of a weather-yield model based on a model proposed by the authors in earlier studies (Szulczewski et al., 2010; Szulczewski et al., 2012).

Field experimentation

The study was conducted at the Agro and Hydrometeorology Observatory of the University of Life and Environmental Sciences in

Wrocław, Poland. Data concerning the yields of potato covered the period of 1971-1996, with the exception of the year 1984 (questionable yield data resulting from extreme meteorological conditions in this year) (25 years). In parallel, measurements of diurnal sums of precipitation were conducted and provided the basis for the determination of the beginning and duration of dry periods during the vegetation period of the crop plant under study.

The Observatory is situated in the South-Western part of Poland, within the Silesian Lowlands, on the outskirts of the city of Wrocław (lat. 51° 07', long. 17° 07', el. 120 m a.s.l.). The soils in the area of the Observatory are brown soils developed from boulder loams and their surface horizon has the grain size composition of weakly loamy sands, generally with little differentiation (Mazij et al., 1965). The particle size composition of soils in the area of Agro-and Hydrometeorology Observatory is presented in Table 1. The field water capacity in the 0-100 cm horizon is 217 mm and the soils are characterised by a high capillary rise capacity. With ground water table at the depth of 100 cm, the surface horizons contain 18% of water relative to the volume. The wilting point for plants is ca. 5%. The mean depth of the ground water table during the period from April till August varies within the range from 120.0 to 140.0 cm.

Description of the model

The developed weather-yield type model MoDrY (Model-Dry periods-Yield) is designed to estimate the fluctuations in potato yielding on the basis of dry periods occurring in the particular periods between the phenological phases of the crop plant. Each time when the term "interphase period" appears in the text, it means a period between observed phenological phases of the crop plant. A list of the phenological phases and the mean and extreme dates of their occurrence during the period covered by the study are given in Table 2.

For the presented material, covering the period of 1971-1996, no detail analyses were made concerning the particular cultivars used in the experiments or the cultivar-related causes of variation in yielding. Also, no analysis was performed concerning the meteorological conditions prevailing in the particular years when the experiments were conducted. The only element taken into account was the earliness of harvest of the potatoes: middle late varieties of potato (ripening from late September to early October) only.

Table 1. Mechanical composition of soil in % in the area of Agro and Hydrometeorology Observatory Wrocław, Poland.

Depth (cm)	Particie Φ [mm]								
	>1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.006	0.006-0.002	<0.002
10	1.9	11.0	21.7	34.5	15.8	6.0	3.0	3.0	5.0
30	1.4	11.3	21.2	35.0	14.5	6.0	4.0	2.0	6.0
50	1.7	12.0	18.9	32.2	21.5	9.0	2.0	1.0	3.0
70	2.4	13.0	23.5	30.5	21.0	5.0	2.0	2.0	3.0
90	1.3	13.2	23.3	31.0	22.5	1.0	1.0	1.0	1.0
110	3.8	12.6	29.0	32.6	6.0	1.0	1.0	1.0	8.0

Table 2. Middle late potatoe's agrophenological phases, average and extreme dates of their appearance in the years 1971-1996 (without year 1984).

Agrophenological phases	Mean dates	Sequent day of the year	Min dates	Sequent day of the year	Max dates	Sequent day of the year
Planting	27.04	117	12.04	102	10.05	130
Emergence	29.05	149	23.05	143	08.06	160
Lateral shoots	14.06	166	06.06	157	25.06	176
Start of blooming	29.06	181	21.06	172	11.07	192
Haulm drying	23.08	235	31.07	213	17.09	261
Harvest	25.09	268	05.09	248	09.10	282

During the period under analysis medium-late potatoes were cultivated and their yields varied from 12 610 kg·ha^{-1} in 1992 to 36 520 kg·ha^{-1} in 1985 and 1989. Analysis of yield variability for the whole period of the study revealed eight instances of yields within the range of up to 20 000 kg·ha^{-1}, nine in the range of 20 000-30 000 kg·ha^{-1}, eight with yields in the range of 30 000-40 000 kg·ha^{-1}. In view of the fact that the results covered a period of 25 years, statistically such a set should be classified as a small one.

In model MoDrY (Szulczewski et al., 2010; Szulczewski et al., 2012) simple transformations were used to eliminate the effect of variability of planting dates and duration of the periods between the phenological phases. To be independent from the variation in the times of sowing and the duration of the interphase periods and, consequently, to permit comparison of the effect of each of the periods on the yield, the data on the interphase periods and on the dry periods were subjected to linear transformation:

$$\overline{T_i^j} = \frac{T_i^j - T_{pi}^{j-1}}{T_{pi}^j - T_{pi}^{j-1}} \tag{1}$$

Where $\{T_i^j\}$ is the string of the rainless periods, the first of which occurs in jth interphase period (j=I,…,V) in ith year (i=1971, …, 1996); T_{pi}^{j-1}, T_{pi}^j is the number of days in the year on which there occurred (j-1) and jth phenological phase, respectively; and $\left\{\overline{T_i^j}\right\}$ is the string of processed (rescaled) data on rainless days (duration of dry period), in ith year (i=1971,..,1996), jth interphase period (j=I,..,V).

This permitted comparison of the effect of each of those periods on the yields. Additionally, the value of yield for each year was divided by a maximum yield, also adopted *a priori*, at the level of 40000 kg ha^{-1} to obtain numbers from 0 to 1. In accordance with the adopted methodology, the estimation of the effect of dry periods on potato yields was made with the use of the model of changes in the resources of water available for plants during dry periods proposed by Machowczyk and Szulczewski (2007). The procedure of applying this model in MoDrY application was described in details by Szulczewski et al. (2012).

The application of model MoDrY for various crop plants requires adaptation of the three functions shown below, as was the case in studies concerned with barley and spring wheat (Szulczewski et al., 2010; Szulczewski et al., 2012). The integral part of the model defined in equation 5 are the functions 2, 3 and 4 described below. In the MoDrY model these functions vary depending on the plant considered and they are defined to obtain the best fitting of the model. Based on analyses performed, the following were adopted for potato:

$$R\left(x_6, x_9, t, y\right) = 10x_6(1 + te^{-x_9 t}) \quad (2)$$

$$Q(x_7, x_9, t, y) = x_7(1 + 0.17ye^{-x9t}) \quad (3)$$

$$E\left(x_8, x_9, t, y\right) = -x_8(1 + 0.17ye^{-x_9 t}) \quad (4)$$

Where: x_6, x_7, x_8, x_9 - parameters approximated;

t- rescaled number of rainless days in accordance with equation 1,

y- rescaled number of the day on which the rainless period began, where $y = (j-1) + z$ (z-rescaled day, in accordance with equation 1, when the rainless period began, j^{th} number of particular phonological phase (j=I,…V)).

The notations applied permit the definition of a function, dependent on nine unknown parameters, that is the sought value of the rescaled yield of potato in year *i*:

$$F^i(x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9) = 1 - 0.01\sum_{j=1}^{5}\sum_{m=1}^{M_j} S^i(R, E, Q, B(T_i^j))x_j T_i^j \quad (5)$$

Where: T_i^j - data on rainless days (duration of dry period), in i^{th} year, j^{th} interphase period,

S^i - percentage decrease of water uptake in relation to initial value, where B is the number of rainless days, M_j - number of dry periods in j^{th} interphase period.

Parameters from x_1 to x_5 characterise the effect of rainless periods in particular interphase periods for which they are responsible on the yield level and occur in equation 5. Parameters from x_6 to x_9 occur in equations 2, 3 and 4.

The developed model was validated with the Cross Validation test (CV), version LOO (Piccard and Cook, 1984), due to the available 25 values from the successive years of the field experiment and as many as 9 model parameters.

Results and Discussion

Approximation of the model

Approximation of the model parameters $x_1,...,x_9$ was performed searching for the global minimum of a function defined as follows:

$$U = \sum_{i=1971 \wedge i \neq 1984}^{1996} (F^i(x_1,x_2,x_3,x_4,x_5,x_6,x_7,x_8,x_9) - \overline{F}^i)^2 \quad (6)$$

Where $\overline{F}^i$ is the value of yield obtained in year *i*. This task was solved using the algorithm of genetic search for the global minimum of multi-variable functions developed by Price and Storn (2005). In this way the model defined in equation 5 was determined and comparison of results obtained with the model with measured values is shown in Figure 1. The values of model parameters obtained through the performance of that procedure are presented in Table 3.

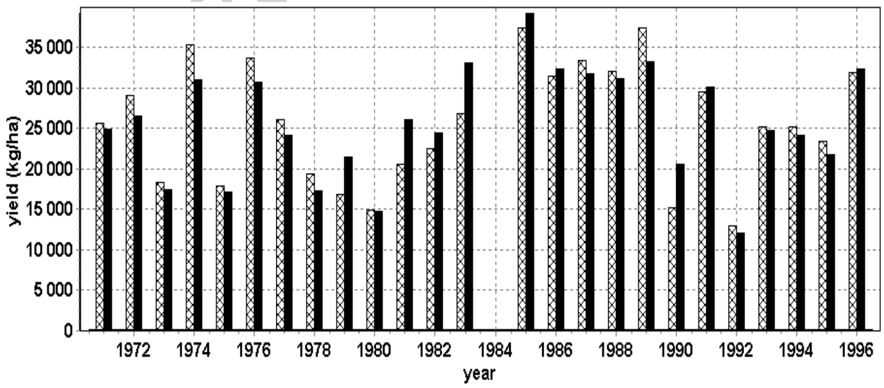

Figure 1. Comparison of yields obtained from the model and observed; explanations: observed yield (right), model yield (left).

Table 3. Parameter values of the model.

x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
0.735	1.712	-0.296	-0.267	0.690	118.6	2.815	3.815	7.665

Model evaluation criteria

Evaluation of the model was performed based on the relative root mean square error (RRMSE), model efficiency (EF) and coefficient of residual mass (CRM) (Walpore et al., 2002; Willmott et al., 1985). RRMSE was calculated from the formula:

$$PRMSE = \frac{[\sum_{i=1}^{n}(P_i - O_i)^2 / n]^{0.5}}{\overline{O}} \quad (7)$$

Where O_i- values observed, P_i- values from the model and $\overline{O}$- mean from the observed data. The model shows the best fit when the value of RRMSE is close to 0. Model efficiency (EF) is a measure of deviation of values obtained from the model from measured values, with relation to the scatter of measured data, calculated from the formula:

$$EF = 1 - \frac{[\sum_{i=1}^{n}(P_i - O_i)^2]}{[\sum_{i=1}^{n}(O_i - \overline{O})^2]} \quad (8)$$

EF value equal 1 indicates ideal agreement between values obtained from the model and values from direct measurements. EF value of 0 or below indicates that the mean value is a better predictor than the model.

Coefficient of residual mass (CRM) is a measure of the relation between predicted and measured values. CRM value equal 0 indicates perfect fit, a positive or a negative value indicate overestimation and underestimation, respectively.

$$CRM = 1 - \frac{\sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} O_i} \quad (9)$$

The hypothesis of equality of mean observed and predicted values was tested with the use of Student's t-test. There were no grounds to reject the zero hypothesis at the level of significance $\alpha=0.05$.

Additionally, three measures characterising the error of approximation were adopted: coefficient of correlation R, coefficient of determination R^2 and mean relative error of deviations B_w. The results obtained are presented in Table 4. Coefficient of correlation value at the level of 0.92 and mean relative error at the level of 9.27% indicate good linear relationship between values obtained with the model and values from direct measurements. The results obtained are presented in Figure 2.

Table 4. Statistical criteria used for the model evaluation.

	R	R^2	B_w	CRM	RMSE	EF
Approximation	0.92	0.85	9.27%	0.00	0.11	0.85
Validation	0.85	0.64	12.40%	-0.008	0.15	0.64

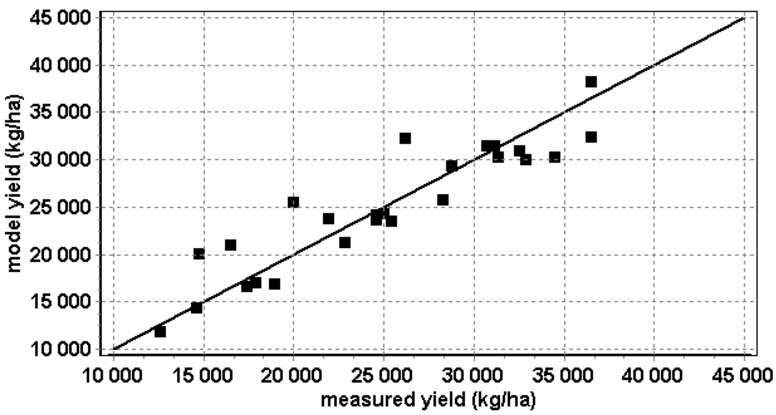

Figure 2. Relation between yield obtained from the model and measured (correlation coefficient r=0.92, relative error B_w=9.27%.

Validation

The developed model was validated with the Cross Validation test (CV), version LOO. The results obtained are presented in Figure 3. For approximation and validation, the values of CRM and RMSE indicate good fit of the model (Table 4). The EF value obtained for model calibration also confirms good fit of the model. A somewhat worse EF result was obtained at the stage of model validation.

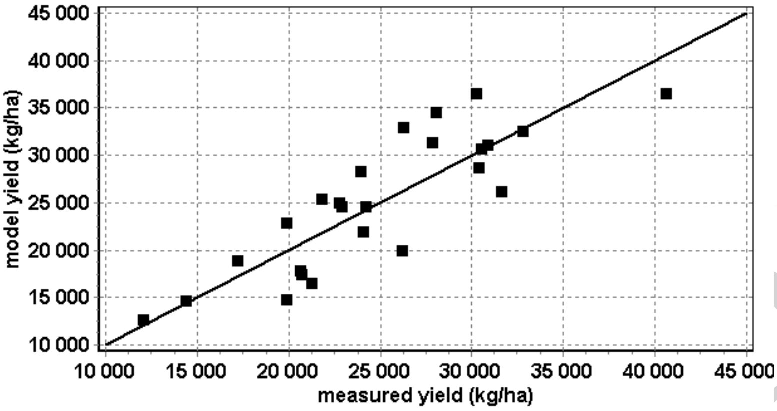

Figure 3. Results of model verification using the Cross Validation method (correlation coefficient r=0.85, relative error B_w=12.40%).

The year 1984 was consciously left out from the analyses, due to the extremely untypical weather conditions of that year. Due to its very dry spring potato planting delayed by three weeks, hard to explain duration of the interphase periods of potato was observed as well as an apparently unnaturally shortened period of its vegetation.

The analyses performed revealed that the strongest effect on the decrease of potato yields is that of dry periods occurring in the interphase periods of emergence-lateral shoots (II). An effect weaker by half is that of the occurrence of dry periods in interphases I and V: planting-emergence and haulm drying-harvest. In interphases III and IV (lateral shoots-start of blooming, start of blooming-haulm drying) dry periods stimulate an increase in potato yields. These conclusions follow directly from the analysis of parameters from x_1 to x_5 presented in Table 3.

In the methods already developed and presented in the literature the problem often consists in the dependence of the result, i.e. the predicted yield level, on many input data, frequently impossible to acquire. In this paper the authors place special emphasis on the development of method which, with as small as possible number of source data (relatively easily available) permits the estimation of potato yields.

In spite of the fact that model MoDrY bases only on information on the number of rainless days in the interphase periods, it provides satisfactory results within a broad spectrum of variation in potato yielding. Considerable divergences appear only in the case of years with extreme weather conditions over the whole vegetation period. The achieved satisfactory results of estimation of potato yields with the use of the model MoDrY, originally developed for spring cereals, indicate a certain flexibility of its application.

The model MoDrY, presented in this paper, according to its simplicity, permits the analysis of the effect of climate changes on potato yields at the adopted scenarios of that changes. Results obtained, apart from the cognitive significance, will also permit the development of simple models, which will be the excellent tool for the estimation of the effect of climate changes on weather conditions on the food economy, regional as well as global.

It is possible, on the basis of the information permitted, to develop software application for the model MoDrY, that will be popularized among the farmers to use for the predictions of different crops yield level.

References

Biniak, M., Kostrzewa, S., Żyromski, A., 2007. Thermal and precipitation conditions of irrigation needs in the region of Wrocław on the example of mid-late potato. Adv. Agric. Sci. Prob. Iss. 519, 31-45. (In Polish)

IBSNAT, 1993. Research Report Series 02. A Simulation Model for Potato Growth and Development: SUBSTOR-Potato version 2.0. Dept. of Agronomy and Soil Science, College of Tropical Agriculture and Human Resources, Univ. of Hawaii, Honolulu, HI.

Jafari, A., Paknejad, F., Jami AL Ahmadi, M., 2009. Evaluation of selection indices for drought tolerance of corn (*Zea mays L.*) hybrids. Int. J. Plant Prod. 3 (4), 33-38.

Jørgensen, S.T., Ntundu, W.H., Ouédraogo, M., Liu, Ch.F., 2011. Effect of a short and severe intermittent drought on transpiration, seed yield, yield components and harvest index in four landraces of bambara groundnut. Int. J. Plant Prod. 5 (1), 25-36.

Kadaja, J., Tooming, H., 2004. Potato production model based on principle of maximum plant productivity. Agr. and Forest Meteorol. 127, 1-16.

Koning, G.H.J., Diepen, C.A., Reinds, G.J., 1995. Crop growth model WOFOST applied to potatoes. In: P. Kabat, B. Marshall, B.J. Van den Broek, J. Vos & H. Van Keulen (eds.), Modelling and parameterization of the soil-plant-atmosphere system; a comparison of potato growth models. Wageningen, Wageningen, pp. 275-297.

Machowczyk, A., Szulczewski, W., 2007. The soil moisture resources in drought season determined by mathematical model application. Adv. Agric. Sci. Prob. Iss. 519, 199-209. (In Polish)

Mazij, S., Kowalski, J., Woźny, F., Szpakowski, A., Krężel, J., 1965. Expertise on hydrogeological and soil conditions in Wrocław-Swojec. Departament of Agro-and Hydrometeorology, Wrocław Agricultural University. (Typescript In Polish)

Nielsen, D.C., Halvorson, A.D., Vigil, M.F., 2010. Critical precipitation period for dryland maize production. Field Crop Res. 118, 259-263.

Picard, R., Cook, D., 1984. Cross-validation of regression models. J. Am. Stat. Assoc. 79 (387), 575-583.

Price, K.V., Storn, R.M., Lampinen, J.A., 2005. Differential Evolution-A Practical Approach to Global Optimization. Springer-Verlag, Berlin, Heidelberg.
Rojek, M., 2006. Need for irrigation in Poland. In: Karczmarczyk, S., Nowak L., (Eds), Plant irrigation. PWRIL, Poznań, pp. 91-108. (In Polish)
Rolbiecki, S., Rzekanowski, C., Rolbiecki, R., 2009. Estimation of needs and results of irrigation of medium-early potato in the vicinity of Bydgoszcz in the years 2005-2007. Acta Agrophys. 13 (2), 463-472. (In Polish)
Spitters, C.J.T., 1990. Crop growth models: their usefulness and limitations. Acta Horticult. 267, 349-368.
Sun, H., Shen, Y., Yu, Q., Flerchinger, G.N., Zhang, Y., Liu, Ch., Zhang, X., 2010. Effect of precipitation change on water balance of WUE of the winter wheat-summer maize rotation in the north China Plain. Agr. Water Manage. 97, 1139-1145.
Szulczewski, W., Żyromski, A., Biniak-Pieróg, M., Machowczyk, A., 2010. Modelling the effect of dry periods on yielding of spring barley. Agr. Water Manage. 97, 587-595.
Szulczewski, W., Żyromski, A., Biniak-Pieróg, M., 2012. New approach in modeling spring wheat yielding based on dry period. Agr. Water Manage. 103, 105-113.
Šťastná, M., Dufková J., 2008. Potato simulation model and its evaluation in selected Central European Country. Agric. Conspec. Sci. 73 (4), 227-234.
Walpore, R.E., Myers, R.H., Myers, S.L., Ye, K., 2002. Probability and Statistics for Engineers and Scientists, 7th ed. Prentice-Hall.
Willmott, C.J., Ackleson, S.G., Davis, R.E., Feddera, J.J., Klink, K.M., Legates, D.R., o'Donnell, J., Rowe, C.M., 1985. Statistics for the evaluation and comparison of models. J. Geophys. Res. 90 (5), 8995-9005.
Wolf, J., 2002. Comparison of two potato simulation models under climate change. II. Application of climate change scenarios. Clim. Res. 21, 187-198.