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Prediction of yellow lupin yield (*Lupinus luteus* L.) for northern Poland using weather-crop model*

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Abstract: *Prediction of yellow lupin yield (Lupinus luteus L.) for northern Poland using weather-crop model.* The paper presents an analysis of the impact of meteorological factors (solar radiation, maximum, minimum and mean temperature, precipitation) on the development and yield of yellow lupin Parys cultivar in the northern Poland in the years 1987–2008. Using multiple regression methods (linear and quadratic function) created regression equations that were estimated using the coefficients of determination (R^2, R^2_{adj} and R^2_{pred} – using the Cross Validation procedure). Selected regression equation used to estimate the yield of yellow lupin, using generated – by means of model WGENK – daily values of global radiation, maximum and minimum temperature, precipitation, and climate change scenario GISS Model E for Central Europe. Examined dependencies weather-yield of lupine seeds (cultivar Parys) allowed the application of the chosen model to forecast yields from the time when the values are independent variables in the model by the end of the growing season. The comparison of distributions of actual and simulated yields shows that real yields are slightly (by 0.06 $t \cdot ha^{-1}$) higher than those generated for 2 × CO_2 conditions.

Key words: weather conditions, lupin yield, climate change

INTRODUCTION

There is currently an increased interest in leguminous plants, the cultivation of which is gaining growing importance (Gawłowska and Święcicki 2007, Święcicki at al. 2007a, b, Jansen 2008, Prusiński 2010). This is caused by their versatile consumer values and the exceptional role they play in ecological and sustainable farming systems. These plants include yellow lupin, which has low and variable yields depending on the course of agricultural and weather factors. Their effects have not been sufficiently recognized, since meteorological conditions for cultivation of this plant were most frequently provided based on studies of an agricultural nature or are fragmentary (Szwejkowski et al. 2001, 2002, Andrejko and Grochowicz 2003, Strobel, Pszczółkowski 2007). Most of the research concerning weather influence on yield currently focuses on issues related to construction of a model (the choice of a model describing the yield-weather phenomenon, estimation of parameters, verification) and its application, e.g. forecasting yields with an appropriate time horizon. The application of various modelling methods makes it possible to assess the status of vegetation, to recognize quantitative regularities in plant production (for the entire country and for individual farms) and to plan production activities in agriculture.

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In the cognitive sphere, models enrich the interpretation of the results obtained in agricultural experiments (Faber 1996). The practical usefulness of a model is determined, first of all, by the consistency of simulation results with reality (Kuchar 1993). With this aim in view, the model is assessed with the use of independent data that were not applied in its construction or calibration, however in this case, the material at disposal is reduced. A certain solution to this problem is the application of the cross-validation method, which consists in subsequently excluding from the model various data (years) for which the error is determined (Michaelson 1987, Kuchar 1994, 2001).

Simulation models are not universally adjusted to any conditions of the natural environment. The evaluation of the model is carried out under conditions for which it was constructed. Forecasting in agriculture is a highly complex issue affected by specific habitat conditions; therefore, many published studies have stopped at the stage of constructing the weather-yield model (Kuchar 1993).

This study is an attempt to determine the dependencies between the spatial and time variability of meteorological factors and growth and the development and yield of yellow lupin in northern Poland in 1987–2008. The selected weather-yield model was applied for forecasting the yield of the plant in conditions of double CO_2 ($2 \times CO_2$), using the generated data (total radiation, maximum temperature, minimum temperature and precipitation) and a typical GISS climate change scenario, Model E.

MATERIALS AND METHODS

The study makes use of source materials concerning the yield, dates of sowing and dates of the occurrence of basic phenological phases of yellow lupin (Parys cultivar) obtained in experimental stations (Wyczechy, Nowa Wieś Ujska, Głodowo and Marianowo), situated in northern Poland. The experiments were carried out according to the methodological instruction applicable in all experimental stations in Poland, which ensures the comparability of the results obtained.

Daily values of meteorological elements accompanying lupin cultivation (i.e. mean, maximum and minimum air temperatures and sums of precipitation) were obtained from the experimental sites. The lack of records for solar radiation in experimental stations lead to estimation of daily values of this factor according to the equation provided by Hunt et al. (1998) in the following form:

$$SR = a_0 \cdot SR_0 \cdot (TMAX - TMIN)^{0.5} + a_1 \cdot \cdot TMAX + a_2 \cdot P + a_3 \cdot P^2 + a_4$$

where:
a_0, a_1, a_2, a_3, a_4 – coefficients,
SR – daily sums of total radiation ($MJ \cdot m^{-2} \cdot d^{-1}$),
SR_0 – daily sums of radiation at the boundary of the atmosphere ($MJ \cdot m^{-2} \cdot d^{-1}$),
$TMAX$, $TMIN$ – daily minimum and maximum temperature (°C),
P – daily sums of precipitation (mm).

Equation coefficients were estimated on the basis of available data, including total radiation, for each month and each station separately, in the period between March and September. Daily values of total radiation originated from the period of 1998–2000, from meteorological stations conducting actinometric measurements. For the experimental stations in Wyczechy and Nowa Wieś Ujska, the data from Piła were used as radiation values, for Głodowo – data from Toruń were used, and for Marianowo – from Mikołajki. Equations were assessed with the application of known measures of adjustment: determination coefficient (R^2) and root mean squared error (RMSE).

In further analyses, total radiation, air temperature and precipitation were considered to be basic variables, determined in the following way:

*SR*1	*TSR*1	*TMAX*1	*TMIN*1	*P*1
*SR*2	*TSR*2	*TMAX*2	*TMIN*2	*P*2
*SR*3	*TSR*3	*TMAX*3	*TMIN*3	*P*3
*SR*4	*TSR*4	*TMAX*4	*TMIN*4	*P*4

where:
SR – sum of radiation ($MJ \cdot m^{-2}$),
TSR – mean air temperature (°C),
TMAX – maximum temperature (°C),
TMIN – minimum temperature (°C),
P – sum of precipitation (mm),
while the figure at the variable means the period:
1 – sowing-germination,
2 – germination-beginning of blossoming,
3 – beginning of blossoming-end of blossoming,
4 – end of blossoming-technical maturity.

The statistical analysis of the relations between the weather and the lupin seed yield applied the method of multiple regression, with the use of a linear function and a square, step-wise progressive function. Regression equations included only those variables for which regression coefficients (tested by the t-Student statistics) were significant at the level of at least $\alpha = 0.1$. Equations were created for subsequent phenological phases, for the examined cultivar in the analysed stations. Model adjustment was evaluated using the coefficient of determination R^2, adjusted coefficient of determination R^2_{adj} and determination coefficient R^2_{pred}, established with the use of the Cross Validation (CV) test (Kuchar 1994, 2001) and evaluated using F-Snedecor's test.

The essence of the CV test is the multiple division of original data into subsets, of which one is used for estimating model parameters and the other for its verification. In particular, this division can be made in such a way that the subset used for estimation should be composed, each time, of $n - 1$ elements, while the remaining element should be used for verification purposes. According to this principle, each observation will be subsequently used for verification. In the proposed procedure, the verification of the method is independent of estimation in the model, since the set of observations used for estimation does not include observations used for verification. The CV test is used to avoid over-parameterization of the model, i.e. wrong description of the phenomenon, particularly in case of a small number of empirical data in relation to the number of estimated parameters.

The selected equation was used to determine the yield of narrow-leaf lupin, Parys cultivar, in the experimental station of Nowa Wieś Ujska, for $2 \times CO_2$ conditions. With this aim in view, 100-year annual total radiation (*SR*), minimum temperature (*TMIN*), maximum temperature (*TMAX*) and precipitation (*P*) data were generated for a typical scenario of climate changes for Central Europe, i.e. GISS Model E, using the WGENK model (Richardson 1985, Macdonald and Sertorio 1990, Hayhoe 1998, Soltani et al. 2000, Kuchar 2004, 2005, 2009). On the basis of these data, annual dates of sowing and the dates of occurrence of main phenological phases, i.e. germination, beginning and end of blossoming and technical maturity were determined, using the historical data from Nowa Wieś Ujska. For each year, values of independent variables used in the regression equation created for the Parys cultivar were then determined and the value of the future yield was estimated. The distributions were determined for observed and estimated yields, using the Weibull distribution. Afterwards, distribution quantiles were determined, together with critical values, tolerance limits and probabilities of tolerance.

RESULTS AND DISCUSSION

Weather-yield of lupin seeds multiple regression models

In the examined multi-year period, for subsequent years, no statistically significant increase in lupin seed yield was observed. The amount of experimental yield of the cultivar and their statistical parameters are presented in Table 1.

In the examined period, the mean level of yield of the Parys cultivar ranged from 1.4 (Wyczechy) to 2.2 t·ha^{-1} in Głodowo; while in other stations it amounted to 2.0 t·ha^{-1}. In individual years, the yield span of the cultivar was relatively large (4.1–0.3 t·ha^{-1}), with low yield falling on years with disadvantageous amounts and distributions of meteorological elements during its vegetation period.

The study examined the complex effect of selected meteorological factors on the yield of yellow lupin seeds of the Parys cultivar (Table 2). The table presents only those equations which passed the CV test, which is considered

TABLE 1. Basic statistic parameters of yellow lupin yield

Station	Years of experiment	Average (t·ha^{-1})	Min (t·ha^{-1})	Max (t·ha^{-1})	SD (t·ha^{-1})	CV (%)
Wyczechy (ϕ 53°41', λ 17°02')	1992–1997, 1999–2006	1.4	0.3	2.4	0.6	42.9
Nowa Wieś Ujska (ϕ 53°02', λ 16°45')	1987–1989, 1991, 1993–1998, 2002–2008	2.0	0.5	3.0	0.7	36.4
Głodowo (ϕ 52°50', λ 19°14')	1987–1998, 2000–2008	2.2	0.6	4.1	0.8	36.4
Marianowo (ϕ 53°13', λ 22°06')	1997, 1999–2008	2.0	1.0	3.2	0.7	35.0

Explanations:
SD – standard deviation, Max – maximum, CV – coefficient of variation, Min – minimum.

TABLE 2. Coefficient of determination (R^2, R^2_{adj}, R^2_{pred}) and regression equations the significance of between yield and weather variables

Period	Variables (in regression equation)	*N*	R^2	R^2_{adj}	R^2_{pred}	S_{yx}	Equation regression
				Wyczechy			
1	*SR*1		0.10	0.02	0	0.6	No selection
1–2	∑*KTSR*2		0.26*	0.20	0.02	0.5	–
	∑*KTSR*2 *P*2		0.43**	0.32	0.18	0.5	–
	∑*KTSR*2 *P*2 *KTMAX*2	14	0.58**	0.46*	0.17	0.4	–
1–3	∑*KTSR*2 *P*2 *KTMAX*2 *KTMIN*3		0.73**	0.61*	0.37	0.4	–
1–4	lack of better						
				Nowa Wieś Ujska			
1	*TSR*1		0.54****	0.51***	0.46***	0.5	*y* = 3.919**** – 0.222**** *TSR*1
1–2	*TSR*1 *KP*2		0.64****	0.58***	0.47**	0.5	*y* = 3.784**** – 0.237**** *TSR*1 + 0.0002* *KP*2
1–3	*TSR*1 *TMAX*3	17	0.66****	0.61***	0.58***	0.4	*y* = 6.733**** – 0.235**** *TSR*1 – 0.117* *TMAX*3
	*TSR*1 *TMAX*3 *KP*2		0.81****	0.77****	0.55**	0.3	*y* = 7.258**** – 0.258**** *TSR*1 – 0.146*** *TMAX*3 + + 0.0003*** *KP*2
1–4	lack of better						lack of better
				Głodowo			
1	*TMAX*1		0.12	0.07	0	0.8	No selection
1–2	*TMAX*1 *KTMIN*2		0.20	0.11	0	0.8	–
1–3	*TMAX*3	21	0.20**	0.15*	0.01	0.8	–
1–4	lack of better						–
				Marianowo			
1	*KSR*1		0.17	0.08	0	0.7	–
1–2	*P*2		0.69***	0.65***	0.57***	0.4	*y* = 3.6****– 0.017****P*2
	*P*2 *SR*2	11	0.78***	0.72***	0.59**	0.4	*y* = 5.4****– 0.017*****P*2 – 0.002**SR*2
1–3	*P*2 *SR*2 *KTMIN*3		0.89****	0.84***	0.77**	0.3	*y* = 7.9**** – 0.017*****P*2 – 0.003****SR*2 – – 0.009***KTMIN*3
1–4	lack of better						

Eksplanations: *, **, ***, **** – means significance level at α = 0.1, 0.05, 0.01, 0.001.
K – squared variable, *N* – number of observations, S_{yx} – standard error of estimation, *SR* – sums of global radiation, *TSR* – average temperature of air, *TMAX* – maximal temperature, *TMIN* – minimal temperature, *P* – precipitation (mm).

to be a very strict and still rarely used criterion for assessing the adjustment of regression equations. As results from its analysis, regression equations which the CV test verified positively were created only in stations of Nowa Wieś Ujska and Marianowo. A hierarchical system of equations constructed for each agrophase (from the poorest to the best R^2 and R^2_{pred}) was applied in the description of the results. It was noted that the precision of the description increases with advancement of the vegetation stages, since more information was obtained about the quantities comprising the yield. In the Nowa Wieś Ujska station (in the first phase of plant development) the R^2 coefficient was 0.54, and during the blossoming, it increased to 0.81, while improved coefficients of determination ranged from 0.51 to 0.77, and R^2_{pred} ranged from 0.46 to 0.58 after application of the CV test. No better results were found for the last interphase. The following variables proved statistically significant: *TSR*1 (mean temperature of the sowing-germination period), which was used in all equations and *TMAX*3 – maximum temperature of the blossoming period. The high yield of the cultivar was favoured by values of those factors which were lower than average and by *KP*2 (precipitation between the germination and the beginning of blossoming).

In Marianowo, in significant equations, the R^2 coefficient grew between 0.69 and 0.89 in the blossoming period, adjusted determination coefficients ranged from 0.65 to 0.84, and R^2_{pred} after applying the CV test ranged between 0.57 and 0.77. A set of interpretation variables was composed mainly of: sum of precipitation (*P*2) and radiation (*SR*2) calculated for the germination-beginning of blossoming period, which had a negative effect on the yield of the cultivar. According to Ceglarek (2000), the best conditions for lupin development include sufficiently high humidity, accompanied by a slightly higher temperature.

In the assumed set of meteorological elements, the *SR* variable (total radiation) estimated for the needs of those analyses, played a lesser role in yield development, although it significantly affected the yield of other lupin cultivars, e.g. Emir (Grabowska et al. 2010), and some leguminous plants, e.g. grass pea (Grabowska 2004). However, it must be emphasized that those studies did not include extreme temperatures in the set of interpretation variables.

No regression equations were constructed for the stations in Głodowo or Wyczechy and the determination coefficients (which in the majority of previous studies formed a basic criterion proving the usefulness of equations) failed the CV test despite often reaching values of more than 0.70 (Wyczechy).

The application of the weather-yield equations to estimate yield for conditions of 2 × CO_2 – Selection of climate change scenario

To determine a potential effect of climate changes on agricultural production, various scenarios (GISS, GFDL, Hadley Center and others) are commonly applied. Currently, one of the most frequently used scenarios for Central Europe and for Poland is GISS Model E scenario (Kittel et al. 1998, Macdonald and Sertorio 1991, Smith and Pitts 1997, IPCC 2001, 2007, Kuchar 2009, http://www.giss.nasa.gov).

Characteristics of the scenario are presented in Table 3.

TABLE 3. Characteristics of climate changes according to a scenario for Central Europe by GISS Model E (2 × CO_2)

Circulation model	Temperature		Precipitation	
	parameter and period	change	parameter and period	change
GISS (Model E)	average – annual – winter – summer standard deviation – annual	 +2.8°C +3.2°C +2.0°C +12%	average – annual – winter – summer standard deviation – annual	 +10% +15% 0% +15%

Generating daily meteorological data sequences to the climate changes scenario for 2 × CO_2 conditions

The WGENK model (Kuchar 2004, 2005, 2009) applied for data generation is made of two blocks: water and thermal energy. The state of the current day (wet/ /dry) – defined with the use of first order Markov chains – the water block affects the values of total radiation and temperatures in the thermal energy block, described according to a generalized linear model. It also determines the value of precipitation generated with the use of two-parameter gamma distribution, $\Gamma(\alpha, \beta)$. Generation of *SR*, *TMAX*, *TMIN* and *P* values starts as of 1st January.

In the first step, two values from the [0.1] range are generated, according to the uniform distribution. Those numbers determine the status of the day. In case of specifying the day with precipitation, its amount is generated according to $\Gamma(\alpha, \beta)$ distribution, taking into account parameters determined for the *i*-th day of the year, and afterwards, daily values of total radiation, maximum and minimum temperatures are created on the basis of a linear model. After creating a sequence of observations for 1st January, a number from the [0.1] range is generated again, the probability of a wet/dry day under the condition of the previous day is determined, and the previously described procedure is repeated. The process ends on the last day of the year, when the predeclared number of observation years has been generated (Richardson 1985, Macdonald and Sertorio 1990, Hayhoe 1998, Soltani et al. 2000, Kuchar 2004).

Table 4 shows modified – according to the described procedure – climatic characteristics of the station, necessary to generate a 100-year sequence of observations, specified according to the GISS Model E scenario for 2 × CO_2 conditions.

The values of parameters ($\bar{x}$ and SD) of data observed and generated depend primarily on the type of variables. According to the research assumptions, the values of total radiation and the number of days with *Rn* precipitation do not change in future, but they are the same as currently. However, the changes concern mean values and standard deviations of maximum, minimum temperatures and sums of precipitation.

TABLE 4. Characteristics of climate specific months (March–September) for the 2060 year by the GISS Model E scenario demanded for the generation data

Month	Global radiation dry/wet day					Maximum temperature dry/wet day					Minimum tempera-ture		Precipitation		
	$\bar{X}$	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{X}$	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	Sum	*Rn*	SD
3	9.0	10.6	3.5	7.0	3.2	7.0	7.0	5.3	7.0	4.1	-0.6	4.3	40.3	14.1	46.5
4	13.9	15.8	4.3	10.8	4.8	13.5	14.4	5.2	12.0	4.1	3.2	3.7	36.1	11.2	43.3
5	20.2	22.9	3.4	16.1	4.3	18.8	19.9	4.1	17.3	4.8	7.5	3.5	52.8	12.6	61.0
6	18.6	20.7	4.2	16.0	4.7	21.5	22.4	3.8	20.3	4.2	10.5	3.0	64.4	13.3	79.5
7	18.1	20.6	4.1	14.7	4.9	24.1	25.4	4.2	22.3	3.9	12.9	2.8	73.4	13.4	91.4
8	15.8	17.1	2.5	13.9	3.3	23.5	24.6	3.8	21.9	4.4	12.6	2.9	68.2	12.9	83.5
9	10.6	12.2	3.8	8.6	3.5	18.2	19.1	4.1	17.1	3.5	9.1	3.1	49.1	12.8	56.3

Explanation: $\bar{x}$ – average; SD – standard deviation; Sum – sum of precipitation; *Rn* – number of rainy days.

Determination of variables to the model and prediction of yield

Hundred-year sequences of meteorological data (*SR*, *TMAX*, *TMIN*, *P*) were generated and used as a basis to determine annual dates of the occurrence of phenological phases. The values of independent variables: *TSR*1 and *TMAX*3, selected in regression equations created for the third agrophase for the Parys cultivar in experimental station in Nowa Wieś Ujska were calculated for each year (Table 2). Afterwards, based on the determined values of those variables, values of yields were estimated (according to the selected equation) for 2 × CO_2 conditions (Table 5).

The data concerning yields (generated and observed) were compared in relation to mean and extreme values, standard deviations and coefficients of variation. The distributions of yields for observed and generated data were then estimated.

As follows from Table 5, the mean real yield was significantly (0.06 t) higher than the generated value, and the variance of real yield was also higher, which can be seen in the figure Figure 1. On the other hand, the maximum and minimum yield was higher for the simulated yield. This is because the variability of

TABLE 5. Descriptive statistics of observed (*Y*) and simulated (*YGEN*) yields

Parameter	Observed yield *Y*	Simulated yield *YGEN*
N – sample size	17	100
y – average	1.95	1.89
s^2 – variance	0.50	0.25
SD – standard deviation	0.707	0.495
y_{min} – minimum	0.45	0.49
y_{max} – maximum	2.95	3.03
$y_{max} - y_{min}$ – range	2.50	2.54
CV – coefficient of variation	36.4	26.2

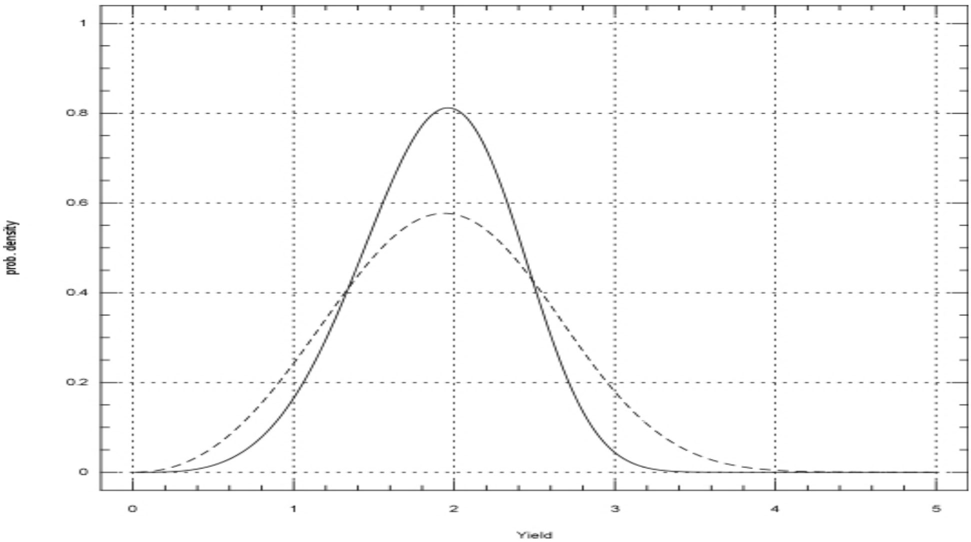

FIGURE 1. Probability distribution of observered and simulated yield

meteorological factors was also subject to change (Table 6), namely: *TSR*1 – mean generated value is closer to the real value, but its variance is lower, *TMAX*3 – mean generated is higher, but its variance is also lower.

Therefore, a lower variance of *TSR*1 and *TMAX*3 probably affected the reduction of the yield variance.

The best regression equation (the highest R^2_{pred}) for yellow lupin of the Parys cultivar in Nowa Wieś Ujska was as follows:

$$Y = -0.235\ TSR1 - 0.117\ TMAX3 + 6.733$$

where:
Y – yield,
*TSR*1 – mean temperature in the sowing--germination period,

TABLE 6. Characteristics of observed and generated model variables

Variables parameter	Observed		Generated	
	*TSR*1	*TMAX*3	*TSR*1	*TMAX*3
N – sample size	17	17	100	100
y – average	8.86	23.05	8.76	23.76
s^2 – variance	5.47	4.38	3.85	3.18
SD – standard deviation	2.338	2.094	1.963	1.783
y_{min} – minimum	5.64	19.32	5.50	20.0
y_{max} – maximum	15.6	27.32	15.2	28.6
$y_{max} - y_{min}$ – range	9.96	8.0	9.70	8.6
CV – coefficient of variation	26.4	9.1	22.4	7.5

*TMAX*3 – maximum temperature of the beginning of the blossoming-end of blossoming period.

An increase in temperatures: the mean temperature of the sowing-germination period (*TSR*1) and the maximum temperature for the blossoming period (*TMAX*3), resulted in a small decrease in yield.

Determination of probability distribution for current yield and for 2 × CO_2 conditions

The Weibull probability distribution, according to suggestions from the literature (Barczyk et al. 1999, Kuchar 1999), was applied to determine yield probability distribution. For current yield and yield estimated for 2 × CO_2 conditions, α and β parameters of the distribution were calculated (Table 7). Charts for both distributions were prepared (Fig. 1), and quantiles of distributions, critical values and $\overline{Y} \pm k \cdot \delta$ (k = 1, 2, 3) ranges were calculated.

The analysis of the table shows that quantiles of distributions, critical values and probabilities of current and estimated yield are similar, which means that any changes that will occur in future (according to the GISS scenario) will affect the yield only to a minor extent.

TABLE 7. Additional information about yields level probability

Estimated parameters	Actual yields	Yield in 2060 (acc. to a scenario by GISS Model E)
Weibull distribution parameters		
α	3.225	4.462
ß	2.173	2.076
Distribution quantiles		
$P(Y < 0.5\ t \cdot ha^{-1})$	0.008	0.002
$P(Y < 1.0\ t \cdot ha^{-1})$	0.079	0.038
$P(Y < 1.5\ t \cdot ha^{-1})$	0.261	0.209
$P(Y > 2.5\ t \cdot ha^{-1})$	0.208	0.101
$P(Y > 3.0\ t \cdot ha^{-1})$	0.059	0.005
$P(Y > 3.5\ t \cdot ha^{-1})$	0.001	~ 0.000
Critical values		
$P(Y < Y_0) = 0.01$	0.52	0.74
$P(Y < Y_0) = 0.05$	0.87	1.06
$P(Y > Y_0) = 0.05$	3.05	2.65
$P(Y > Y_0) = 0.01$	3.50	2.92
Tolerance limits and probability		
$P(\ddot{Y} - \delta < Y < \ddot{Y} + \delta)$	0.690	0.690
$P(\ddot{Y} - 2\delta < Y < \ddot{Y} + 2\delta)$	0.970	0.965
$P(\ddot{Y} - 3\delta < Y < \ddot{Y} + 3\delta)$	0.999	0.999

CONCLUSIONS

1. During the years of research (1987––2008), for individual experimental stations located in the area of northern Poland, on the basis the weather-yield model constructed and verified with the application of a CV test, it can be claimed that the effect of meteorological factors (total radiation, maximum, mean and minimum air temperature and precipitation) on the yield of lupin of the Parys cultivar was differentiated depending on the location of the station and the vegetation stage.
2. The obtained statistical models of yield (as for most statistical models) have a limited application as to the point and time for which they were established. The verification procedure that was carried out (the cross-validation test), showed that the only regression equations that can provide good yield estimation were constructed for the Nowa Wieś Ujska and Marianowo stations.
   In the Nowa Wieś Ujska station, the factors having a significant effect on the yield of the cultivar included the mean temperature of the sowing-germination period, the maximum temperature of the blossoming period and precipitation during the time from germination to the beginning of blossoming.
   In Marianowo, the yield was significantly affected mainly by sums of precipitation and total radiation in the germination-beginning of blossoming period.
   For the experimental stations in Wyczechy and Głodowo, the regression models created (despite high determination factors R^2 and R^2_{adj} commonly applied in this type of studies) failed the verification procedure with the use of a CV test.
3. The examined dependencies between the weather and the yield of lupin seeds (Parys cultivar) made it possible to apply a selected model of yield forecast from the moment of obtaining the values of independent variables used in the model to the end of vegetation.
   As results from comparison of real and simulated yield distributions (on the basis of synthetic meteorological data and the GISS Model E climate change scenario), the real yield is insignificantly higher (by 0.06 $t \cdot ha^{-1}$) than the yield generated for $2 \times CO_2$ conditions.

REFERENCES

ANDREJKO D., GROCHOWICZ J., 2003. Changes of lupine seed moisture content caused by infrared radiation (in Polish). *Acta Agrophysica*, 2(4), 683–690.

BARCZYK R., DUBICKA M., KUCHAR L., 1999. Winter wheat yield in Wroclaw area during the period 2010-2050, simulations using CERES-Wheat model and GISS scenario (in Polish). *Zesz. Nauk. AR we Wrocławiu, Roln.* LXXIV, 367, 303–315.

CEGLAREK F., BURACZYŃSKA D., BRODOWSKI H., 2000. Yielding and chemical composition of the chosen legume-cereal mixtures (in Polish). *Roczniki AR w Poznaniu* CCCXXV. *Roln.* 58, 7–21.

FABER A., 1996. Deterministic models. Practice analysis of yield forecasting methods for Poland (in Polish). *IUNG Puławy*, R(339), 43–94.

GAWŁOWSKA M., ŚWIĘCICKI W., 2007. Cultivation, market and usage of grain legumes in the EU (in Polish). *Zesz. Probl. Post. Nauk Roln.*, 522, 505–513.

GRABOWSKA K., 2004. *Mathematical modeling of pea (Pisum sativum) yield on the basis of meteorological factors.* Monograph (in Polish), 99, 1–86.

GRABOWSKA K., BANASZKIEWICZ B., DYMERSKA A., 2010. Weather conditions vs. agrophenology and yielding of *Lupinus angustifolius* in north-eastern Poland. *Acta Agrophysica, Meteorology and Climatology Research, Monograph*, 185 (6), 111–122.

HAYHOE H.N., 1998. Relationship between weather variables in observed and WXGEN generated time series. *Agric. For. Meteorol.*, 90, 203–214.

HUNT L.A., KUCHAR L., SWANTON C.J., 1998. Estimation of solar radiation for use in crop modeling. *Agric. For. Meteorol.*, 91, 293–300.

IPCC, 2001. *Climate Change*: *Working Group II: Impacts, Adaptation and Vulnerability, 13.1.5. Climate Scenarios for the Future.*

IPCC, 2007. *Summary for Policymakers.* In: *Climate Change*: *The Physical Science Basis. Contribution of Working Group I to the 4th Assessment Report of the Intergovernmental Panel on Climate Change*. Eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

JANSEN G., 2008. *Effects of temperature on yield and protein content of Lupinus angustifolius culitvars.* In: *Lupins for Health and Wealth*. Eds. J.A. Palta, J.B. Berger. Proceedings of the 12th International Lupin Conference,14-18 Sept. 2008, Fremantle, Western Australia. International Lupin Association, Canterbury, New Zealand, 342–345.

KITTEL T.G.F., ROSENBLOOM N.A., PAINTER T.H., SCHIMEL D.S., FISHER H.H., GRIMSDELL A., VEMAP Participants, DALY C., Hunt E.R. Jr., 1998. *The VEMAP Phase I Database: An Integrated Input Dataset for Ecosystem and Vegetation Modeling for the Conterminous United States*. Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A. (VEMAP 1: U.S. Climate Change Scenarios Based on Models with Increased CO_2).

KUCHAR L., 1993. Forecasting of total precipitation and mean temperature for yield prediction of vegetable plants (in Polish). *Monograph. Zesz. Nauk AR Wrocław*, 118.

KUCHAR L., 1994. Validation test for weather forecasting method using plant phenology and data sets from Poland (in Polish). *Zesz. Probl. Post. Nauk Roln.*, 405, 115–119.

KUCHAR L., 1999. Generation of daily meteorological data for a given climate change scenario (in Polish). *Fol. Univ. Agric. Stetin.* 202 *Agricultura* 79, 133–138.

KUCHAR L., 2001. Evaluation of Mathematical Models Using Cross Validation Test (in Polish). *Przegl. Nauk. Wydz. Inż. Kszt. Środ. SGGW*, 21, 165–170.

KUCHAR L., 2004. Using WGENK to generate synthetic daily weather data for model ling of agricultural processes. *Math. Comp. Simul.*, 65, 69–75.

KUCHAR L., 2005. The WGENK modified generator of daily weather for the needs of agrometeorological modelling. *Woda – Środowisko – Obszary Wiejskie*, t. 5, 14, 185–195.

KUCHAR L., 2009. *Validation test of WGENK weather generator for Polish Lowland.* In: *Environmental aspects of climate changes*. Ed. Z. Szwejkowski. UWM Olsztyn, 9–20.

MacDONALD G., SERTORIO L. (Eds.), 1991. *The global climate and ecosystem change.* New York, Plenum Press, 268.

MICHAELSON J., 1987. Cross-Validation in Statistical Climate Forecast Models. *J. of Climate and Appl. Meteorol.*, 26, 1589–1600.

NASA Goddard Institute for Space Studies (GISS), at Columbia University in New York City http://www.giss.nasa.gov.
PRUSIŃSKI J., 2010. The legumes i European Union (in Polish). *Zesz. Probl. Post. Nauk Roln.*, 550, 11–19.
RICHARDSON C.W., 1985. Weather simulation for crop management models. *Trans. ASAE*, 28, 1602–1606.
SMITH J.B., PITTS G.J., 1997. Regional climate change scenarios for vulnerability and adaptation assessments. *Climatic Change*, 36, 1–2, 3–21.
SOLTANI A., LATIFI N., NASIRI M., 2000. Evaluation of WGEN for generating long term weather data for crop simulations. *Agric. For. Meteorol.*, 102, 1–12.
STROBEL W., PSZCZÓŁKOWSKI P., 2007. Effect of pod moisture content and weather conditions on pod dehiscing and seed shedding in narrow-leafed lupin (in Polish). *Zesz. Probl. Post. Nauk Roln.*, 522, 317–323.
ŚWIĘCICKI W., CHUDY M., ŻUK--GOŁASZEWSKA., 2007a. Grain legumes in the EU framework programmes (in Polish). *Zesz. Probl. Post. Nauk Roln.*, 522, 55–65.
ŚWIĘCICKI W., SZUKAŁA J., MIKULSKI W., JERZAK M., 2007b. Possibilities to replace the soybean cake with domestic raw materials (in Polish). *Zesz. Probl. Post. Nauk Roln.*, 522, 515–521.
SZWEJKOWSKI Z., BIENIASZEWSKI T., WIATR K., FORDOŃSKI G., 2001. Determination of yielding and developing of yellow lupine by meteorological condition. *Natural Science* 3, 115–132.
SZWEJKOWSKI Z., BIENIASZEWSKI T., FORDOŃSKI G., 2002. The correlations between surface temperature and monthly sums of precipitation on the growth and yield of yellow lupine. *Agro & Forest Meteorology XXV. American Meteorological Society*, 33–45.

Streszczenie: *Prognozowanie plonu łubinu żółtego (Lupinus luteus L.) w północnej Polsce przy użyciu modelu pogoda-plon.* W pracy przedstawiono analizę wpływu czynników meteorologicznych (promieniowania słonecznego, temperatury maksymalnej, średniej i minimalnej oraz opadów atmosferycznych) na rozwój i plonowanie łubinu żółtego odmiany Parys w północnej Polsce w latach 1987–2008. Przy użyciu metody regresji wielokrotnej (funkcje liniowa i kwadratowa) utworzono równania regresji, które oszacowano za pomocą współczynników determinacji (R^2, R^2_{adj} i R^2_{pred} – wyznaczonego przy użyciu procedury Cross Validation). Wybrane równanie regresji zastosowano do określenia plonowania łubinu żółtego, wykorzystując wygenerowane – za pomocą modelu WGENK – dobowe wartości promieniowania całkowitego, temperatury maksymalnej, temperatury minimalnej i opadów oraz scenariusz zmian klimatu GISS Model E dla Europy Centralnej. Zbadane zależności pogoda plon nasion łubinu (odmiana Parys) umożliwiły zastosowanie wybranego modelu do prognozy plonów od momentu uzyskania wartości zmiennych niezależnych będących w modelu do końca wegetacji. Z porównania rozkładów plonów rzeczywistych i symulowanych wynika, że plony rzeczywiste są nieznacznie (o 0,06 $t \cdot ha^{-1}$) wyższe niż wygenerowane na warunki $2 \times CO_2$.

Słowa kluczowe: warunki pogodowe, plon łubinu, zmiany klimatu

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