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YIELD PREDICTION FOR WINTER WHEAT IN EASTERN POLAND (GRABÓW) USING THE ACCESS-II MODEL

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A b s t r a c t. A trial has been carried out at the experimental site at Grabów, which is situated in the Mazovian Plain in the Central Polish Lowlands, in order to calibrate the soil/crop water balance model ACCESS-II. The main interest of this site is that it furnishes data for 12 consecutive harvests of winter wheat. Firstly, the principles of the model are described. Then the use of the model when the initial water contents are unknown. The first calibration results show that modifications need to be made to allow for the influence of severe winter frosts on crop growth. Following this modification, modelled yields were predicted to within 10 to 15% of measured yields, sufficient to demonstrate the strong link between yield, winter frosts and the amount of snow-cover protection. The discrepancies between measured and predicted values are useful in understanding the reasons for abnormally small yields. At this scale of modelling, the predictions are good enough to classify a region as very good, good or poor for winter wheat production under 'continental' climate conditions.

K e y w o r d s: yield prediction, winter wheat, ACCESS-II model

INTRODUCTION

In 1992 DGXII of the European Commission funded a research program (project EV5V-CT92-0129) involving 6 European laboratories, including the Laboratory of Soil Science of the National Institute of Agronomic Research (INRA-Montpellier, France) and the Institute of Agrophysics (IA PAN, Lublin). The aim of this program was to evaluate the impact of climatic change on agricultural production at the European scale, against the hypothesis of global warming due to the greenhouse effect. To achieve this, a computer model, ACCESS-II, was constructed (with the help of ADAS-Gleadthorpe, GB), which simulates crop growth and water balance under real or modified climatic conditions.

The water balance part of the model is mainly inspired by the MOBIDIC model [8], and the crop part derives from the EPIC model [18]. Many students [1,2,5-7,17] and Leenhardt herself [9] were involved in the software development.

In this paper we describe first the principles of the model, then the results of its calibration and validation at the Grabów site. Finally, the significance of these results is discussed.

PRINCIPLES OF ACCESS-II

Crop growth is controlled by the transformation of solar energy into vegetal material, using crop available water and the minimum thermal requirements as limiting factors. It is impossible to describe here the whole model, which has been done elsewhere [12,13,16], so we deal only with its main parts.

Biomass calculation

The principle of the growth routine is: the plant grows so that it reaches maturity when the sum of degree-days reaches the value set in the crop file. The daily increase in biomass (*ddm*) is proportional to the active solar radiation (*PAR*), to the photosynthesis efficiency coefficient (*WA*), and is reduced by a stress factor (*reg*):

$$ddm = 0.001\ PAR\ WA\ reg \qquad (1)$$

where *ddm* is daily increase in biomass (t/ha), *PAR* is photosynthetically active radiation (MJ/m^2), *WA* is photosynthesis efficiency coefficient (dg/MJ), *reg* is dominant stress between water stress and thermal stress with a value between 1 and 0, zero corresponding to the maximum stress, which stops plant growth. The definitions of the two stresses are given below.

To avoid error accumulation, leaf and root growth are not derived from the biomass calculation, but are calculated directly.

Leaf growth

The value of the *LAI* (Leaf Area Index, i.e., the surface covered by all the leaves divided by the corresponding soil surface area) is essential in estimating plant transpiration. The potential value of *LAI* is calculated from accumulated temperature (degree-days), then reduced by using a factor proportional to the stress factor (*reg*) presented above.

Root length

Root length is used to define the depth of the reservoir from which the roots can extract water. It is given by a curvilinear function of time until the maximum permitted length is reached [3]. Root density (i.e., relative root quantity inside each horizon) is calculated using a function which allows the user to describe roughly the form of the root system.

Plant transpiration and soil evaporation

The *LAI* determines potential evaporation (*PE*) from potential evapotranspiration (*PET*) as measured at a climate station or estimated from the relevant parameters:

$$PE = PET\ e\ \beta\ LAI \qquad (2)$$

where β is a coefficient depending on the crop spatial structure, then, we calculate:

$$PT = PET - PE. \qquad (3)$$

The real evaporation (*RE*) is then derived from the water content of the top soil layer, *PE* being the maximum permitted value. Real transpiration (*RT*) is a function of the availability of water in the soil (water potential) and of the capacity of the plant to pump it (leaf potential and global resistance of the plant system).

Stresses

The water stress is taken as the ratio *RT/PT*. The thermal stress *TS* is:

$$TS = \sin\left[\frac{\pi}{2}\left(\frac{T - T_g}{T_{Op} - T_g}\right)\right] \qquad (4)$$

where T is the mean daily temperature (°C) at the soil surface; T_g is the basal temperature (°C) under which growth stops; T_{Op} is the optimum temperature (°C) for growth.

This expression is used only for values of $(T-T_g)/(T_{Op}-T_g)$ between 0 and 2. Below 0 (mean daily temperature below the minimum value for growth) and above 2 (mean daily temperature more than twice the optimum) the value of *TS* is set to zero. The stress value used for growth limitation (*reg*: Eq. (1)) is most severe at a point between the thermal stress and the water stress (note that the influence of the stress is maximal when its value is minimal).

Computer organisation of ACCESS-II

The source code is written in FORTRAN 5 and runs under MS-DOS. The main program (ACCESS3D.FOR) calls another program (GLOBAL3D.FOR) that contains the common, i.e., universal, declarations of the variables. The runs need several files, *viz*:

- the soil file contains the description of the soil, and all the corresponding parameters;

- the crop file contains all the parameters relevant to the crop. During model calibration, most of the changes are made in this file;

- the climate file contains the climatic data (temperature, rainfall, *PET*, solar radiation). If the user is dealing not only with a site, but with several sites corresponding to a whole region, then several soil files and several climate files are requested by the system;

- the spatial file gives, for each land unit, the references to the relevant climate files and soil files. If the user needs to work not only on a crop but on a crop rotation involving several crops and years, several crop files are requested;

- the calendar file drives the run for the appropriate time.

With these 5 main files plus some subsidiary files, ACCESS-II can work both in time and space. As the model was especially designed for evaluating the consequences of a climatic change, some functions allow the user to modify the climatic data at the input level. The results, principally accumulated biomass, amount of soil water reserve, and crop yield, can be obtained on a daily, monthly, or annual basis, or for a crop season. When the user is dealing with many sites, crops and years, output at a daily timestep can easily saturate the computer memory and should be avoided.

CALIBRATION AT THE GRABÓW SITE

The experimental at Grabów (central Poland) is representative of large areas of soils (sands, loamy sands and 'light' loams) derived from coarser-textured glacial sediments in Central and Eastern Europe, and farmed under a 'continental' climate (dry warm summers, cold winters with severe frosts, but frequently without prolonged or deep total snow cover). This site furnished a long succession of cultivation cycles of winter wheat (12 harvests within the 13 years from 1982 to 1993), and a corresponding climate series with no missing data. These data allowed us to start a simulation over several successive years, to see if there was any systematic bias in the water storage calculation (cumulative errors over several years being easier to see).

The approach was as follows: calibration of harvests using the 6 central years (85 to 90) and validation of the model for the years 1982-1984 and 1991-1993. Thus, we could ignore a hypothetical climatic trend. The principle of the calibration was to adjust the input parameters of the model (53 crop parameters, 4 parameters for the computation of soil temperature, 1 soil parameter) by comparing the results of the simulations with the real observations.

Pet calculation

For Grabów, the available climate files do not contain the value of daily *PET*. One of us (JPL) wrote a FORTRAN program (PENMONT) that calculates *PET* according to the method of Penman-Monteith, following exactly the method used by the French 'Office National de la Météorologie'. PENMONT uses the global solar radiation as one of the main input data. The corresponding values were calculated by the previously developed PHEBUS computer program [4] as modified by Legros *et al.* [11]. The final step in this sequence was put the files into the proper format, as ACCESS is unforgiving in this respect.

The choice of parameter values

The calibration method is that of Legros and Bonnet [13]. The first stage was to calibrate the parameters linked to time and temperature by trial and error, upon which the following values were obtained:

- 15 for T_{Op} (optimum growth temperature);
- 0 for T_g (minimum growth temperature);
- 100 for *IHU* (number of degree-days between sowing and emergence);
- 2300 for *MHU* (number of degree-days between emergence and maturity).

Note that for the 6 years used for the calibration, the harvests gave a range of values for *MHU*. Thus, 2300 is a mean for those 6 years. Simulations were also carried out with *MHU* = 2700, the results showing that biomass and yield hardly changed.

Measured values of *LAI*, root growth, soil water content and biomass were unavailable, so the calibration was only carried out with yield data, which limitation complicated matters considerably. At first sight, using a site where the measured values are so scarce seems to be a poor choice, but as we wanted to work not only on reference sites but also for a whole region, we needed to find as good a solution as possible to deal with the problem of scarce, but otherwise good, information.

Definition of the initial water stock

The water content of the soil horizons had, in principle, been determined at the start of the 12 years, but there was doubt about the precise date of this measurement. Therefore, we studied the influence of this lack of data on the results of the simulations. A solution for this problem was found by using two different values of the initial water stock (Figs 1 and 2). After one year, the simulation furnishes exactly the same results concerning the amount of stored water if one starts from a low (near wilting point) or a high (near field capacity) initial water stock.

The reason for this is that the amount of rainfall is higher than the crop and atmosphere water requirements. The excess rain is lost by drainage. After one or two years the soil reservoir is always filled in autumn, whatever the initial conditions. This implies that the results of simulations are credible only after the two first years are taken into account. But, if we suppose that the soil-crop system is in a kind of equilibrium, the loss of information corresponding to the first two years of simulation can be avoided by running the model three times or more in a row with the same yearly climatic data (and with an arbitrary value of initial water stock). Then the final value of the water stock is taken as the initial value for the simulations (Fig. 3), starting from a given day.

For the simulations that follow we took a day in late summer as day 1 of the simulation, with a low value of the water stock. We saw *a posteriori* that this approach had no significant influence on the results.

Results of calibration between 1985 and 1990

It was not possible to get 5 simulated yield values, for all the years between 1985 and 1990, which fitted the 5 measured values for the same years perfectly, if we used a similar set of parameter values for all these years (Fig. 4). It is clear that the main errors are for

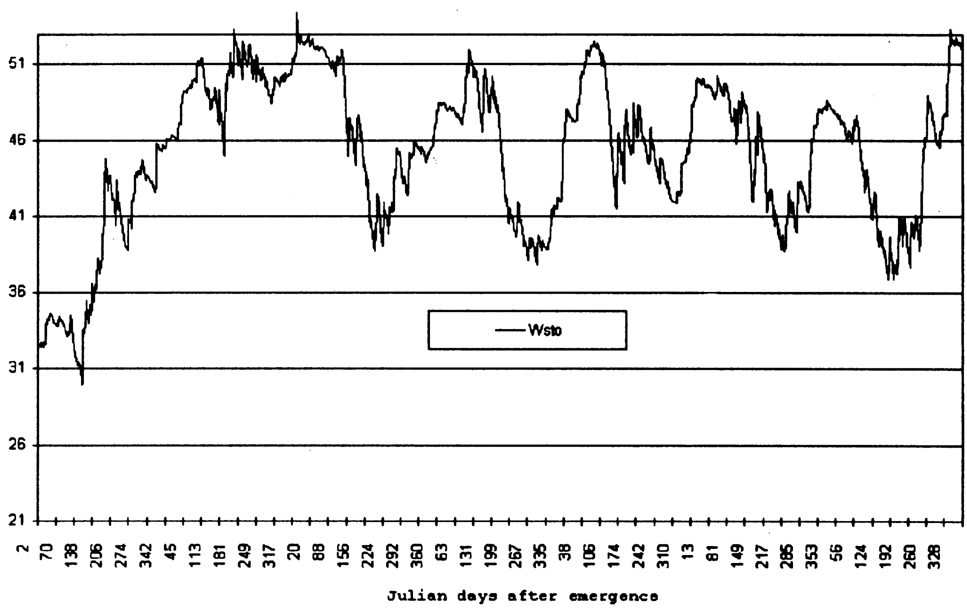

Fig. 1. Water stock (Wsto, cm) from 1985 to 1990; initial stock (Winit) = 29 cm.

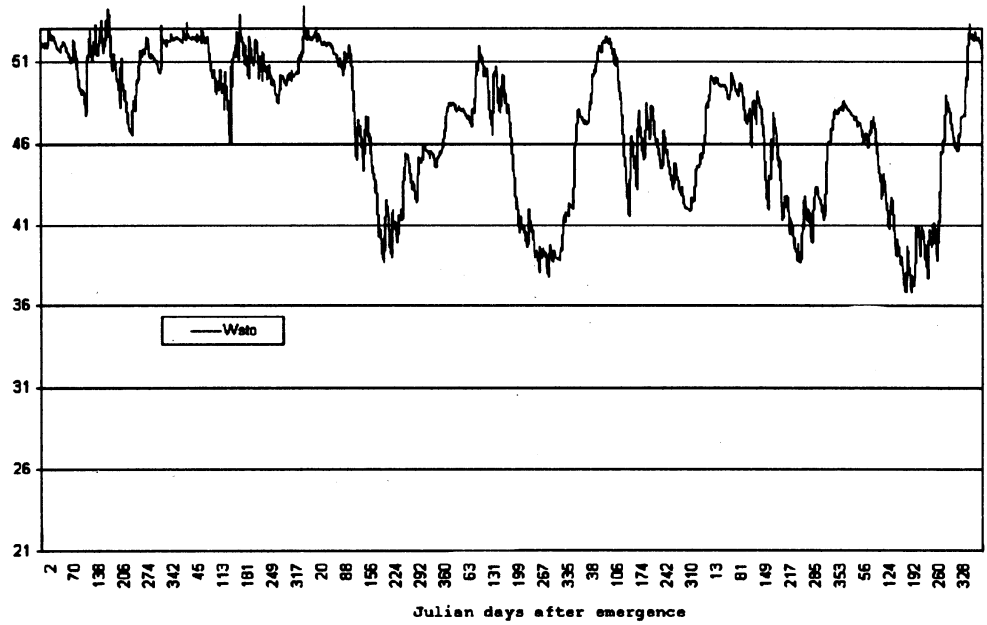

Fig. 2. Water stock (Wsto, cm) from 1985 to 1990; initial stock (Winit) = 49 cm.

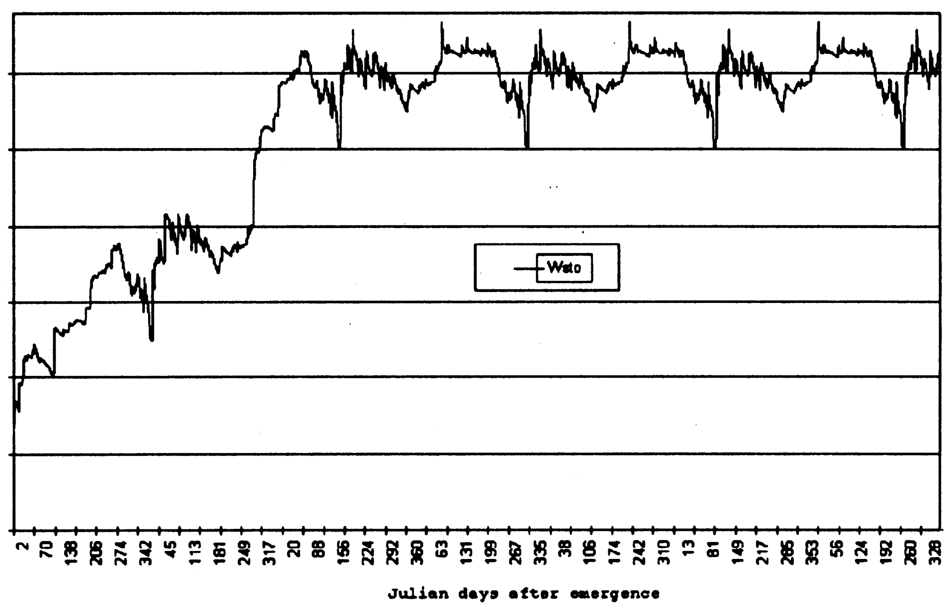

Fig. 3. Water stock (Wsto, cm)of the soil; year 1985 repeated 5 times.

1985 and 1990, the reasons for which are explained below. For the other years, the simulations are good.

Analysis of the discrepancies

For the 1984-1985 crop season we found the following climatic data (Fig. 5).

We can see that there were 2 periods of severe frosts during the winter 1984-1985, a situation which is common in Poland. However, in this case snow cover was absent and a great proportion of the young plants was destroyed. The ACCESS-II software was unable to take this into account because it works as follows:

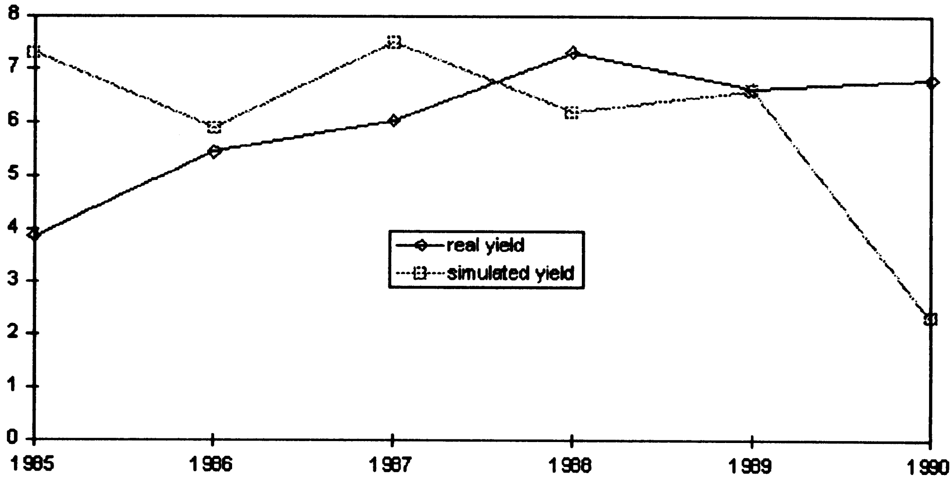

Fig. 4. Comparison of real yield with simulated yield (t/ha).

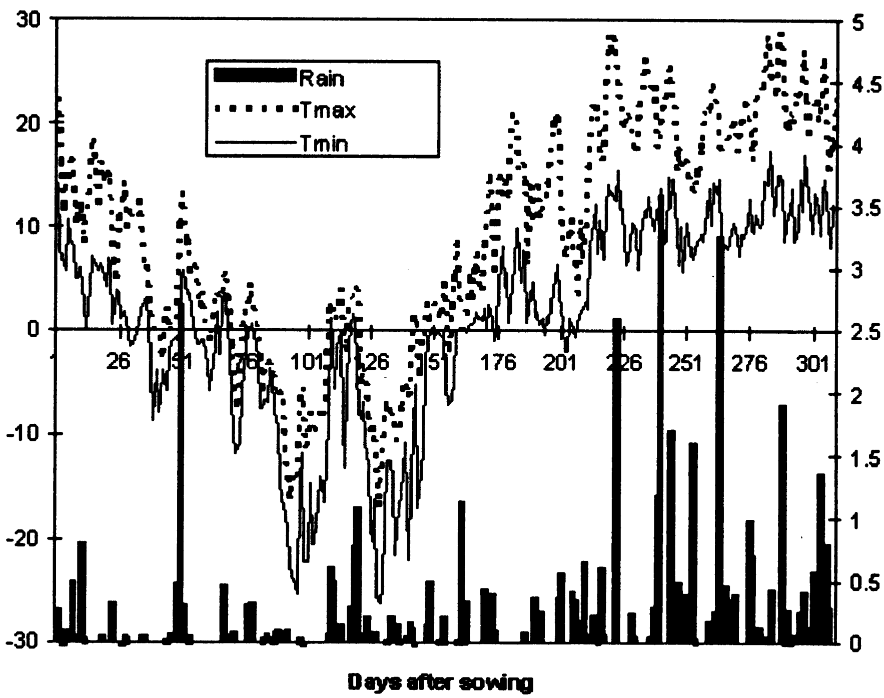

Fig. 5. Climate data during the cycle 1984-1985 (°C and cm, respectively).

when the temperature falls below -1°C there is a loss in biomass depending on the minimum value reached, but of course biomass cannot be negative. So the influence of a moderate or of a very severe frost are roughly the same: growth stops until the weather conditions ameliorate in spring. In other words, growth may be delayed, but in the model severe frosts do not reduce it. Therefore, we needed a means to simulate the death of plants under very cold conditions, and proceeded thus: we considered that the action of the frost (with a threshold at -15°C) causes a fall in the value of the photosynthesis efficiency coefficient in proportion to the amplitude and duration of the frost event. In other words, we suppose that the death of a certain proportion of plants reduces the ability of the whole crop to intercept solar energy and to transform it into biomass. This method avoids the need to consider the crop at the level of the individual plant.

The simulated yield for 1990 was extremely low whereas in reality it was normal. A detailed study of the daily results of the simulation showed that the discrepancy was caused by the appearance in the simulation of a strong (and completely artificial) water stress in summer. We spent much time in trying to understand the reason for this irrelevant water stress. It appeared that the experimental curves of ψ=f(θ), that allow one to pass from the simulated water content to the soil potential, were at fault, the water content measured at wilting point being too high. Because of this water became unusable too quickly, so that in a relatively dry year it became difficult to simulate plant function when water was scarce. If we modified the water content at the wilting point arbitrarily so as to give it a value compatible with the soil texture, the results of the calibration were slightly improved (real yield values and simulated values fit better). This showed two things: first the need to be very careful about the quality of input data corresponding to soil/water relationships, because their weight is crucial to the quality of the simulation. Secondly during the calibration step, it is possible that a data set seems to be perfect in one particular case (see 1989) and poor in another (see 1990). Under such circumstances it is wise to test several years and, if possible, several experiments.

FINAL RESULTS, DISCUSSION AND CONCLUSIONS

Finally, we ran ACCESS3D for 12 cycles (81-82 to 92-93). The results are given in Fig. 6, Table 1 gives the corresponding values, with the relative errors (Fig. 7) calculated from:

$$\textit{Relative error} = \frac{|\textit{Real yield} - \textit{Simulated yield}|}{\textit{Real yield}}$$

During the calibration step it was impossible to fit the yield closer than 22.5%, but the prediction is rather good (relative error of 8% for years before and after the 85-90 period). In others words, the calibration is very acceptable for the values given to the different parameters, even if the years 1985 and 1990 are specific cases of relatively poor fit and diminish the average fitting.

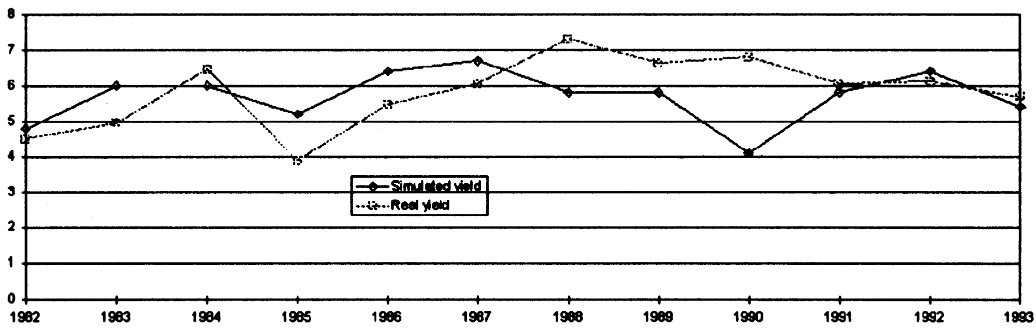

Fig. 6. Real and simulated yields (t/ha) at the end of the validation period.

Table 1. Comparison of simulated and real yields

	Year	Simulated yield	Real yield	Relative error
Predicted	1982	4.8	4.50	0.067
Predicted	1983	6.0	4.96	0.210
Predicted	1984	6.0	6.46	0.071
Calibration	1985	5.2	3.88	0.340
Calibration	1986	6.4	5.46	0.172
Calibration	1987	6.7	6.04	0.109
Calibration	1988	5.8	7.32	0.208
Calibration	1989	5.8	6.63	0.125
Calibration	1990	4.1	6.80	0.397
Predicted	1991	5.8	6.05	0.041
Predicted	1992	6.4	6.11	0.047
Predicted	1993	5.4	5.69	0.051
Mean (calibration years)				0.225
Mean (predicted years)				0.081
General mean				0.153

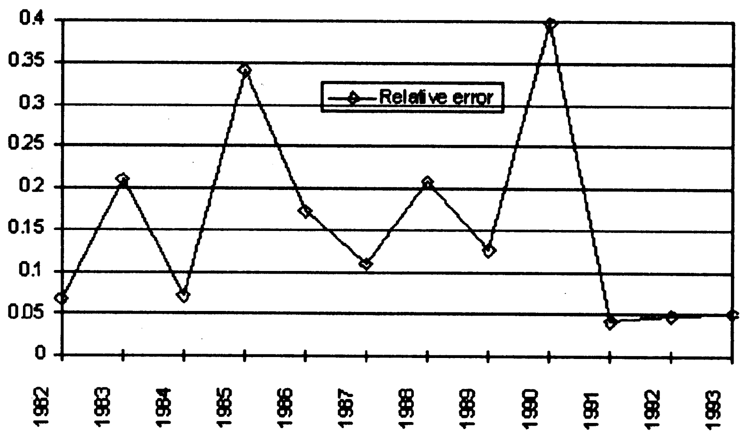

Fig. 7. Relative errors at the end of the validation period.

The use of ACCESS-II on a Polish site was a challenge for two reasons. Firstly, even if the model takes both the water and thermal stresses into account, it attaches the greater importance to the water requirements because it considers the plant mainly as a water pump. However, in Poland, thermal stress predominates. Thus, we were able to discover the drawbacks of the system in relation to the action of very low temperatures and to propose a small improvement. The corresponding modifications of ACCESS-II are not sufficient to give it the ability to simulate crop growth perfectly in situations in which frost is the dominant limiting factor, although they are probably sufficient to avoid large errors relating to destruction of plants by frost. To improve the software further, it would be necessary to have more quantitative data concerning crop growth parameters, viz. *LAI*, root length and biomass at different development stages.

The second point is that the yields in Grabów are not very different from one year to another, so the model must be particularly powerful to simulate accurately the small differences between the different years. The results at this level are very acceptable, in that the model detects the increases and decreases in yields between successive years (ignoring for the moment 1989-1990).

In summary, in the most frequent situations in the central part of Poland it is probably possible to link winter wheat yields with temperature and snow cover without regard to other factors, given an adequate level of farm management, i.e., it has to be assumed that poor management can be excluded as a major determinant of yield.

In the future, we plan to improve the software by using several sites located in different parts of Europe, as did Legros and Bonnet [13], as a measure of the ability of the model to function adequately in a range of climatic situations.

We are also testing the model over a whole region using spatialized soil and climate data, in order to evaluate more precisely the error inherent in spatial predictions at what is a very high level of complexity in modelling terms [10].

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