

# Integrated assessment of crop productivity based on the food supply forecasting

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**Abstract:** Climate change scenarios suggest that long periods without rainfall will occur in the future often causing instability of the agricultural products market. The aim of the research was to build a model describing the amount of precipitation and droughts for forecasting crop yields in the future. In this study, the authors analysed a non-standard mixture of gamma and one point distributions as the model of rainfall. On the basis of the rainfall data, one can estimate the parameters of the distribution. The parameter estimators were constructed using the method of the maximum likelihood. The obtained rainfall data allow confirming the hypothesis of the adequacy of the proposed rainfall models. Long series of droughts allow one to determine the probabilities of adverse phenomena in agriculture. Based on the model, the yields of barley in the years 2030 and 2050 were forecasted which can be used for the assessment of other crops productivity. The results obtained with this approach can be used to predict decreases in agricultural production caused by the prospective rainfall shortages. This will enable decision makers to shape effective agricultural policies in order to learn how to balance the food supplies and demands through an appropriate management of the stored raw food materials and the import/export policies.

**Key words:** climate changes, decision-making tools, estimation of parameters, forecasted outputs, gamma distribution, predicting yields

Precipitation is a key component that links the atmosphere and the Earth's surface, thus, the accurate knowledge of the amount of precipitation is a fundamental requirement for improving the predictions of weather systems and of the prospective anticipated climate changes. Weather conditions, especially the rainfall variability, may adversely affect the financial results of companies operating in various industries, whereby agriculture (beside energy and transport) is obviously the most weather exposed business (Taušer and Čajka 2014). Some of the weather forecast models use data assimilation techniques that require accurate precipitation estimates at high spatial and temporal resolutions (Berg et al. 2010; Miętus et al. 2010; Watson and Challinor 2013) essentially influence the crop yields and the agricultural production output (Yoo et al. 2005; Czarnecka and Nidzgorska-Lencewicz 2012).

The aim of the research was to build models describing the amount of rainfall and the periods of drought based on a mixture of gamma distribution and one point distribution. The findings from this model can forecast the future yield of a selected crop.

This allowed us to build an economic model useful for calculating agricultural output to predict the expected decreases in the agricultural production of spring barley, caused by the prospective rainfall shortages. It will enable shaping, in a wider scope, of an effective agricultural policy, and will provide us with a knowledge of how to balance the supply and demand of food through the appropriate management of the stored raw materials and/or the policies of import/export. Also, the dependencies between the precipitation and yield will allow for the earlier used methodology (Bojar and Knopik 2013) to be verified through a comparison of the obtained solutions concerning forecasted yields in the future and through an uncertainty analysis. On the basis of the rainfall data from the Kujawsko-Pomorskie region - the central lowland part of Poland, one can forecast the crop yields in the future (in the years 2030 and 2050) (Mager and Kępińska-Kasprzak 2010; Bojar et al. 2013). The data can be used for the assessment of productivity of the selected crops in the region. The assumptions and parameters of large-scale spatial economic models will be applied to construct the

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relevant solutions. Socio-economic and technical criteria could be useful in the study of the specially forecasted cropping areas, yields, prices and costs, which will be employed to estimate the possible economic effects of the forecasted more frequent periods of drought.

## MATERIAL AND METHODOLOGY

### Research site and the data

For the analysis of the results of the standard, homogeneous measurements of rainfall carried out at the Research Station of the University of Technology and Life Sciences in Bydgoszcz were used. The Research Station is located in the poorly urbanized and industrialized rural area (geographic coordinates 53°13' N, 17°51'E, altitude 98.5 m a.s.l.), approximately 20 km from the city. Meteorological observations have been carried out at that measuring point since 1949, which means that the data are free of the influence of the anthropogenic factors existing in an urban area; therefore, one can assume that these data represent the climatological conditions of the Kujawsko-Pomorskie region. The rainfall totals of ten-day periods in growing seasons (1 April to 30 September) were taken into account in Case A, while the analysis of Case B was based on daily totals of the period from 1st June to 20th August. The data series covered the years 1999–2012. Data regarding the yields of spring barley under the production conditions in the Kujawsko-Pomorskie region were taken from the databases of the Central Statistical Office published on the relevant websites (BDL GUS 2014). These data covered the same period as the meteorological data.

### Rainfall distribution model

We consider that the continuous random variable  $T$  describes the value (size) of rainfall per day. We assume that  $T$  has a cumulative distribution function of  $F(t, \alpha, \beta)$  with  $F(0, \alpha, \beta) = 0$ . In this paper, we assume that  $F$  is a two-parameter gamma distribution with parameters  $(\alpha, \beta)$ . The density function is the following:

$$f(t : \alpha, \beta) = \frac{1}{\beta^\alpha \Gamma(\alpha)} t^{\alpha-1} e^{-t/\beta} \quad (1)$$

where  $t > 0$ ,  $\alpha > 0$ ,  $\beta > 0$ .

$\Gamma(\alpha)$  describe the gamma function given by

$$\Gamma(\alpha) = \int_0^\infty x^{\alpha-1} e^{-x} dx$$

We assume that the days without rainfall are recorded as '0' so that the modified distribution has the density function given by:

$$g(t : p, \alpha, \beta) = \begin{cases} 1-p & \text{for } t=0 \\ pf(t : \alpha, \beta) & \text{for } t>0 \end{cases} \quad (2)$$

The mean value of the random variable  $T$  is  $ET = p\alpha\beta$ .

The purpose of this paper is to consider the probability density function given by (2), when  $F$  is a two-parameter gamma distribution. The problem of statistical inference about  $(p, \alpha, \beta)$  has received a considerable attention (Kale 1999; Kale and Muralidharan 2000; Muralidharan and Kale 2002). The paper by Muralidharan and Kale (2002) considers the case where  $F$  is a two-parameter gamma distribution with the shape parameter  $\beta$  and scale parameter  $\alpha$ , where they obtain a confidence interval for  $\alpha$  and  $\beta$ . In the article, this distribution is considered and the maximum likelihood estimation of parameters  $(p, \alpha, \beta)$  is obtained. The approximate  $1 - \gamma$  confidence interval for the mean value of  $T$  is the following:

$$(p\alpha\beta - u_\gamma \frac{\sqrt{K}}{\sqrt{n}}, p\alpha\beta + u_\gamma \frac{\sqrt{K}}{\sqrt{n}}) \quad (3)$$

where

$$K = p\alpha\beta^2[1 + (1-p)\alpha]$$

and  $u_\gamma$  is the value of the standard Gauss random variable  $U$  such that

$$P\{|U| < u_\gamma\} = 1 - \gamma$$

To characterise the outputs of spring barley within the Kujawsko-Pomorskie region, some calculations based on the CAPRI model and its output databases and also the agro climatic model and the findings from the UTP, were made. The data from the CAPRI model (CAPRI 2012) was used, based on the assumptions of the S1 AgMIP (The Agricultural Model Intercomparison and Improvement Program: [www.agmip.org](http://www.agmip.org)) scenario created with the SSP2 (Shared Socioeconomic Pathway) and the RCP (Representative Concentration Pathways) – the present climate and a specific bioenergy model, and they concerned the farmland areas, yields and input prices from 2010, 2030 and 2050 for the modelling crop.

The CAPRI large spatial model was used in the paper to set up the regional characteristics necessary to set the outputs (CAPRI-MODEL). The core of the CAPRI model consists of a comparative-static

partial equilibrium economic model which is based on the linkage of a European-focused supply module and a global market module (Britz and Witzke 2012; Köchy and Zimmermann 2013; Stocco et al. 2013). The supply module includes independent aggregate non-linear programming models which cover the EU27, Norway, Western Balkans and Turkey, while the programming models are a kind of hybrid approach combining the Leontief-technology for a low and high yield variant of variable costs for the different production activities with the non-linear cost function. This way, the effects of labour and capital on the farmers' decisions are captured. Within the CAPRI Common Agricultural Policy (CAP), the current findings are also depicted in detail for the EU. Prices are provided by the market module. The sub-module for the marketable agricultural outputs delivers the output prices and enables a market analysis at a global, EU-wide and national scale, including a welfare analysis at the Member State level, or globally, at a country or country block level. It is a spatial, non-stochastic global multi-commodity model for about 50 agricultural products, covering about 80 countries or country blocks in 40 trading blocks. The supply and market modules are integrated based on the sequential calibration (Britz 2008). The CAP premiums are re-calculated to ensure compliance with the national ceilings. The post-model analysis includes the calculation of different income indicators for both individual production activities and different regions. This approach confirms the comparability of results across products, activities and regions and allows for the low cost system maintenance. This enables its integration with other models.

For the survey data regional resolution, the NUTS2<sup>1</sup> was considered. The Kujawsko-Pomorskie region belongs to the PL6<sup>2</sup> Northern Region (NUTS 1), PL61<sup>3</sup> voivodeship (NUTS 2).

For the agricultural projection needs, we selected the SSP2 scenario, while the socio-economic adaptation and mitigation challenges (fossil and recourse intensity) were at a medium level and the present climate within the AgMIP S1 was assumed.

Within the SSP2 scenario, the variability forecasted in the yields, the farm land acreage, prices and in productivity is smaller than in the SSP5 or other

scenarios and that is why the SSP2 was applied to reach the goal of this approach.

The SSP2 is referred to as the "Continuation" and includes a slowly decreasing fossil fuel dependency, reductions of resources and energy intensity, an uneven development of low-income countries, several weak global institutions, a slow continuation of globalisation with some barriers in place, a well-regulated information flow, a medium economic growth, a slow convergence, high intra-regional disparities, a medium population growth related to medium educational investments and a delay in the achievement of the MDGs (Millennium Development Goals) (Köchy and Zimmermann 2013). The land-use change regulation, the land productivity growth and the environmental impact of food consumption are at a medium level while the international trade is regionalised. The GCM (Global Climate Models) and the crop model is at zero.

The total volume of output of the selected crop of the region expressed in physical units is calculated according to Formula 4:

$$TRO = L \times Y \quad (4)$$

where: *TRO* – the total regional output of a given crop (number in thousand tonnes); *L* – land area of a given crop (number of hectares); *Y* – yield of a given crop (number of tonnes per 1 hectare) (from the CAPRI model and output database or from the agro climatic model and findings)

The values of production of the particular crops within the region were calculated to compare the findings based on the CAPRI model and the findings based at the linked CAPRI and the agro climatic models according Formula 5:

$$TOV = L \times Y \times P \quad (5)$$

where: *TOV* – the total regional value of output of a given crop (thousand euro), *L* – land area of a given crop (number of hectares), *Y* – yield of a given crop (number of tonnes per 1 hectare) (from the CAPRI model and output database or from the agro climatic model and findings), *P* – producer prices (EUR/t)

All parameters in these formulas were set up using methods described within the CAPRI database.

<sup>1</sup>NUTS (Nomenclature of Territorial Units for Statistics) codes of Poland (PL), the three levels are: NUTS1 – Regions, NUTS2 – Voivodeships, and NUTS3 – Subregions

<sup>2</sup>PL6 North Region Kujawsko-Pomorskie, Warmińsko-Mazurskie, Pomorskie

<sup>3</sup>PL61 Kujawsko-Pomorskie voivodeship

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## RESULTS AND DISCUSSION

### Influence of rainfall on crop yield and agricultural production

It has been assumed that the projected effects of the climate change on agricultural production will differ in the respective parts of the world (Olesen et al. 2007). In future, the main limiting factor of the amount of yield in Poland will be the availability of water. The most recent research proved that for the last 25 years such phenomena as droughts have occurred in Poland more frequently than in the previous period. What is more, at present the droughts are more long-lasting and affect a much larger area of the country (Łabędzki 2006). Furthermore, some models (e.g. HadRM3-P relating to the A2 scenario) forecasting the future climatic conditions indicate that a 5-day dry period will extend to 10 days (daily rainfall  $\leq 0.5$  mm) (Kundzewicz et al. 2006).

Despite enormous technological advances, the contemporary agriculture still heavily depends on the weather conditions. The short-term weather variability as well as the predicted climatic changes in the future are the cause of a considerable risk in agricultural production. Though it is hard to assess their impact on the prospects in the coming decades and to predict the average temperature on a global and local scale – especially in relation to the projected total amounts of precipitation and their distribution in time and space (IPCC Fifth Assessment Report 2013), one thing is certain: the variability of weather will increase. The increasing temperature and the precipitation variability increases the risks to yield. Monteith (1981) stated, on the basis of his calculations, that the two largest climatic causes of instability in the crop yield are the temperature and rainfall. In case of winter cereals cultivated in England on heavy soils, he proved that 12% of yield variation was caused by the variation in temperature, radiation and rainfall, while on light soil, it increased to 17% of the yield variation. Porter and Semenov (2005) discussed the impacts of the climate variability, especially rainfall, on crop production in a number of crops, based on numerous studies. The rainfed production is very unstable, which is confirmed by the positive results of field experiments with irrigated crops carried out all over the world in different climatic zones (arid, Mediterranean, temperate). These results show how the shortages of rainfall and dry periods have a significant effect on yielding of different kinds of crops

(Erdem et al. 2006; Holden and Brereton 2006; Źarski 2009; Dmowski et al. 2010; Dowgert 2010; Van der Velde et al. 2010; Daccache et al. 2011; Podleśny and Podleśna 2011; Źarski et al. 2011, 2013a, b, c; Shirazi et al. 2014). Olesen and Bindi (2002, 2005) discussed the relationship between agricultural production and the characteristics of climate in Europe. They confirmed that agriculture of any kind is strongly influenced by the availability of water. If the predicted climate change modifies rainfall, it will influence evaporation, runoff, and soil moisture storage. The demand for water in agriculture is already the largest among consumers and the use for irrigation is projected to increase due to more severe heat waves. For instance, a severe heat wave over large parts of Europe in June 2003 (over 20 days) resulted in the low rainfall during this period. The water shortage failed to compensate for the accumulated evapotranspiration of almost 400 mm in the Mediterranean area, creating an accumulative water balance deficit of up to 380 mm in South Europe and of 200 mm over the most of France, Germany, the Western Czech Republic, Hungary and Southern Romania. Such extreme weather conditions caused a decrease in the quantity and quality of crop yields, especially in the Central and Southern European agricultural areas; threatening a large proportion of harvests, and increasing production costs.

### Application of the model

Case A. We analyse the data set which contains the value of daily rainfall in ten-day periods. The ten-day periods observed were from April 1st to September 30th during the years 1999 to 2012. The statistical analysis was performed for  $n = 252$  10-day periods. The probability distribution of rainfall shows a good coordination with the distribution (2). The estimated parameters have the values  $p = 0.071$ ,  $\alpha = 1.2$  and  $\beta = 17.27$ .

A concordance of the empirical distribution and the theoretical distribution test was carried out using the classical  $\lambda$  – Kolmogorov test and the  $\chi^2$  – Pearson test. The value of the test statistics  $\lambda = 0.17$ . For the good of the fit test, the  $\chi^2$  – Pearson statistic calculated  $\chi^2 = 7.92$ ,  $p$ -value = 0.44. This confirms the concordance of the model with the empirical data. Figure 1 shows the distribution of the empirical and theoretical distribution functions. The average value calculated from the data is  $ETe = 20.27$  and the standard deviation  $s = 18.21$ . The average value calculated from the model is  $ET = 20.73$ , while the

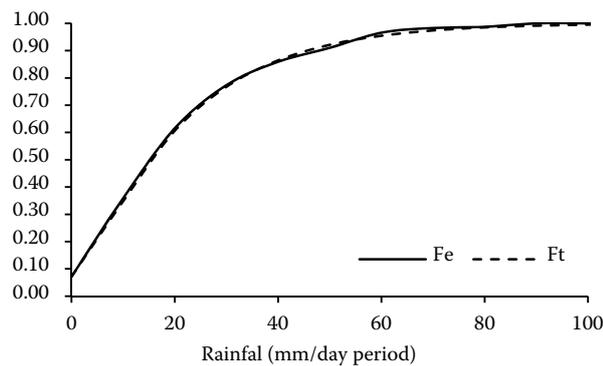


Figure 1. Empirical (Fe) and theoretical (Ft) distribution functions for ten-day period rainfall

standard deviation  $DT = 18.92$ . The confidence interval for the mean value, with a confidence level of  $1 - \gamma = 0.95$ , was determined from the formula (3) and is as follows: (19.36, 21.17).

Case B. In this case, the precipitation is analysed due to the day. There are also data from 1999–2012 and the months spanning June 1<sup>st</sup> to August 20<sup>th</sup>. Together, there was an analysis of  $n = 368$  data on rainfall. The values of the estimated parameters are  $p = 0.61$ ,  $\alpha = 0.79$  and  $\beta = 8.18$ .

A concordance of the empirical distribution and the theoretical distribution test was carried out using the classical  $\lambda$  – Kolmogorov test. The value of the test statistics is  $\lambda = 0.26$ . For the good of the fit test, the  $\chi^2$  – Pearson statistic is  $\chi^2 = 7.92$ , and  $p$ -value = 0.44. This confirms the concordance of the model with the empirical data. Figure 2 shows the distribution functions as empirical and theoretical. The average value calculated from the data are  $ETe = 7.16$  and the standard deviation is  $s = 9.34$ . The mean value is calculated from the model  $ET = 6.45$ , while the standard deviation  $DT = 7.26$ . The confidence interval for the mean value with a confidence level  $1 - \gamma = 0.95$  is determined from the formula (3) as follows: (6.33, 7.98).

The socio-economic scenarios projected on the basis of the relevant forecasted trends and the tendencies allow the formation of important models for exploring the long-term consequences of the anthropogenic climate change and the available options of response. A number of authors face the challenge of producing regional and sub-national scenarios over long periods of time (Gaffin et al. 2004; Theobald 2005; Britz 2008; Van Vuuren et al. 2010; Hallegatte et al. 2011). In order to do it effectively, a key role should be played by the local scenarios in which the global environmental change could be represented (Bojar et al. 2014).

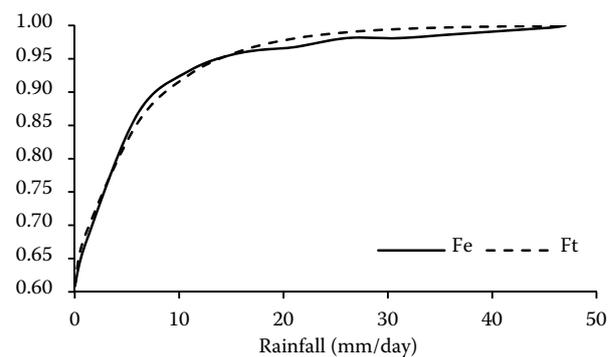


Figure 2. Empirical (Fe) and theoretical (Ft) distribution functions for daily rainfall

The models, the data and tools verified positively that projecting the impact of the climate change on yields and agricultural production in the future can be upscaled for wider areas with the consideration of similarities between different spatial scopes of the local and regional approach.

A previous study confirms that the prices in 2050 projected without the climate change scenarios acc. to different models (AIM, ENVISAGE, FARM, GTM, MAGNET, GCAM, GLOBIOM, IMPACT, MAGPIE) would vary significantly (Antle 2014), so we tend to draw very cautious conclusions derived from the application of the integrated economic models and the impact of the climate change on agricultural production in the perspective of 2020 and 2050. It is better, therefore, to show several different options forecasted as likely scenarios of the future events, which also applies to the forecasted results for the years 2050 and 2030 for spring barley, obtained in this article.

### Prognosis based on long-series of ten-day periods without precipitation

On the basis of the probability distribution model presented above, we predicted a long series of 10-day periods where there were days without rain. The application of the Monte Carlo method generated 18 of the elements series of 10-day periods (six months). On this basis, the likelihood determined 10-day periods without rain as a series of a given length  $k$  ( $k = 7, 8, 9$ ). If  $p_k$  is the probability of the occurrence of at least one  $k$  – element series without rain, then  $(1 - p_k)^m$  is the probability of the absence of the series  $k$  – element with no rain in the next  $m$  years. Let  $p_{km}$  be denoted by the probability of at least one series of  $k$  – element in the following  $m$  – years without rain. For the assessment of the occurrence of a long series of 10-day periods without rain, we are assuming until

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Table 1. Probability of the occurrence of a series of 10-day periods without precipitation until 2030 and 2050

Year	Series length	Probability
2030	7	0.199
	8	0.085
	9	0.035
	10	0.010
2050	7	0.393
	8	0.180
	10	0.021

2030  $m = 17$ , and 2050  $m = 27$ . Table 1 below shows the values of the probability  $p_{km}$  for the years 2030 and 2050 and the series length  $k = 7, 8, 9, 10$ .

The calculation results contained in Table 1 show that for the length of the series 10-day periods without rain equal to  $k = 7, 8$ , the calculated probability is relatively high. This means that the probability of the occurrence of extreme weather events in the considered span of time is high.

The analysis of the statistical data on yields shows that low cereal yields are associated with long periods without precipitation. This fact will be the basis for building a simple regression model enabling one to predict the occurrence of adverse events in the cultivation of the selected plants. Below, the occurrence of a significant dependence of the yield of barley on the length of successive 10-day periods without precipitation is shown. On the basis of data on the yields of barley and the length of the series of 10-day periods without rain, a regression line describing the dependence of the yield of barley on the number of 10-day periods without rain was determined. A regression line takes the form of yield = length of series

Table 2. Yield of spring barley for different length of series

Length of series	Yield (t/ha)
7	2.409
8	2.255
9	2.100
10	1.946

$\times (-1.544) + 34.8995$ . The correlation coefficient is  $R = 0.595$ ; the square of the correlation coefficient is referred to as the 'coefficient of determination' and defines the percentage of variation explained by the equation  $R^2 = 0.354$ . Testing the significance of the regression equation was performed using the F test; the calculated value of the  $F$ -statistics = 6.58 and the significance level corresponding to this value  $p$ -value = 0.0247. On this basis, it is concluded that the proposed regression equation is statistically significant.

The findings described above can be applied to forecasting the yields of spring barley in the Kujawsko-Pomorskie region.

For 2030 and for 8 series of 10-day periods without rain at a probability of 8.5%, one can forecast a spring barley yield at the levels equal to 2.255 t/ha while for 2050 and for 8 series of 10-day periods without rain at a probability of 18.00%, one can expect the same level of a spring barley yield equal to 2.255 t/ha (see Table 1 and Table 2).

### Economic approach to forecasting the regional output of agricultural production based on spring barley cropping

The obtained findings (see Table 1) show that the extreme lengths of time without precipitation occur

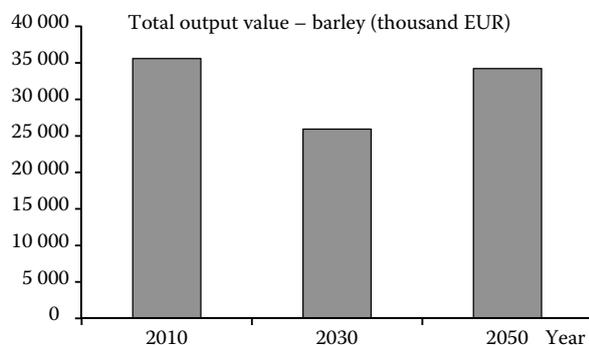


Figure 3. Comparison between the CAPRI K&amp;P and CAPRI-UTP model value output (for the average yield)

Source: own study based on the CAPRI and the Agro Climatic UTP data and models

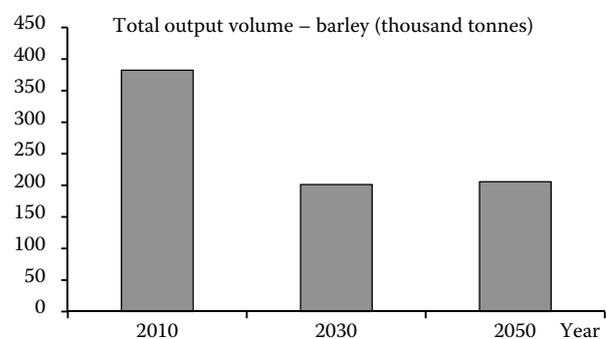


Figure 4. Comparison between the CAPRI K&amp;P and CAPRI-UTP model volume output (for average yield)

Source: own study based on the CAPRI and the Agro Climatic UTP data and models

Table 3. The regional data setup on a wide area model and the UTP findings

CROP	Producer price (EUR/t)			Land (1000 ha)			Average yield (t/ha)		
	2010	2030	2050	2010	2030	2050	2010 (CAPRI)	2030 (UTP)	2050 (UTP)
Spring barley	93.07	128.89	166.21	111.45	89.24	91.30	3.43	2.255	2.255

for the series 8 ten-day periods with a high probability in 2030 and 2050, which determines a high risk of the occurrence of such extreme natural events.

The total volume of output of the selected crop of the region expressed in physical units is calculated according to the Formula (4).

Next, the values of the production of the particular crops within the region were calculated to compare the findings based on the CAPRI model and the findings based at linked CAPRI and the agro-climatic models of the University of Technology and Life Sciences according to the Formula (5).

Explanation: All data concerning prices and land for the Kujawsko-Pomorskie region is based on the CAPRI database, while the yields of spring barley for 2010 are based on the CAPRI database, with 2030 and 2050 based on the UTP findings.

The facts expressed in Figures 3 and 4 allow one to see that the forecasted extreme weather conditions strongly affect the agricultural output of the selected crops in the Kujawsko-Pomorskie region, which are essentially different from the agricultural outputs based on the modelling assumptions (for average yields, see Table 3).

Hence, the specific detailed analysis shows that the undesirable drops in the frequency of precipitation can essentially influence agricultural outputs calculated on the assumed average yields in the region in the future, which increases the probability of this occurrence in the region and at the same time, it can cause an imbalance in the food supply and demand.

## CONCLUSIONS

The calculation of the future agricultural output volume and value in the Kujawsko-Pomorskie region affected by the changes in the yields of spring barley allows for an estimate associated with it and a risk of an imbalance in the food supply and demand. The found solution is based on the expected changes to barley's yield due to the precipitation and its distribution, the extreme changes in 2030 and 2050 and the large-scale spatial model assumptions described briefly in Chapter 4. This allows one to create some

forecasts with a defined probability of the occurrence of extreme output changes compared to the average ones. Projections of producer prices from the selected model baseline scenarios (GAMP) were also possible after the comparison of models based on the regional empirical data. This allows one to forecast the levels of outputs of the selected crops in agriculture in the surveyed region in 2030 and 2050, calculated according to differentiated simulated assumptions. It can help with conducting a more appropriate agricultural and trade food policy to ensure food safety in different spatial scales of Europe and the balance the food supply and demand in the perspective of the next 40–50 years.

The method of forecasting long series without precipitation, as presented in this elaboration, was positively verified through a comparison of the findings from the application made with other methods when the forecasted yield of spring barley was comparable to the yield calculated in Table 2 at the comparable level of the rate of probability of occurrence (Bojar and Knopik 2013).

The obtained results of modelling the biophysical and economic projections should be treated very cautiously due to many assumed variables whose change could also influence the findings. Further research is necessary to produce other projections of yields and agricultural production with different methods and this way provide more relevant parameters for the decision makers responsible for agricultural policy and the development of rural areas. A further development of the undertaken research can also positively contribute the critical scientific view on the issues analysed in this paper. The method presented in the paper may be useful to predict the crop productivity, and hence the prediction of food supply in the area of the temperate climate of Central Europe, where the variability of precipitation is very high and the probability of a more frequent occurrence of droughts in the future is similar.

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