Spatial and Temporal Analysis of Changes in Crop Yield Series in the Regions of Mid - Latitude Agriculture

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Introduction

Achieving high and stable crop yields is a very important problem for the sustainable agriculture development. At the present time, under the conditions of ever increasing climatic changes this problem becomes more and more actual. It is obvious that climate change would unavoidably affect agrotechnologies and crop distribution in the future. Therefore, the spatial and temporal analysis is made for variations in the crop yield long-term series. A few methods are suggested for predicting changes in economically guaranteed (economically provided) crop yields and yield variability in the future. Main emphasis has been given to wheat crops occupying vast areas in the grain-producing regions of the FSU, the USA, Canada and European countries.

Revealing the technological trends in crop yield series

Due to crop yield series transitivity caused by cultivation improvement the methods have been used for revealing technological trends in the crop yield dynamics. Basing on the regional patterns of yield per hectare dynamics, including those due to the features of local cultivars, the dynamics was described by linear, parabolic, exponential, linear-fractional, and logistic functions. For example, figure 1 illustrates the yield dynamics described by means of the logistic function.

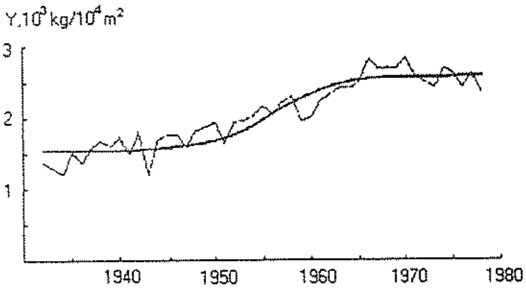


Figure 1. The wheat yield dynamics in the New York State between 1932 and 1980 approximated by logistic curve.

At the same time for some US regions and European countries with the intensive agriculture the realization was made of an approach consisting in revealing technological trends in crop yield series by taking account of dynamics of specific agrotechnological indicators. They are as follows: NPK consumption per hectare of arable lands (subsequently called the "fertilizer index"), the number of power-equivalent tractors per 1000 ha of arable lands, the number of power-equivalent grain combines per 1000 ha of harvested areas, and others are taken into account. In this connection in the case of describing yield dynamics with "saturation" Nikolaev[1985], Menzhulin and Nikolaev[1887] suggested to consider as a model of technological yield trend the functional of the following shape:

$$Y_{tr}(t) = a' + \frac{1}{a'' + \Sigma^{k}_{j=1} a_j / x_j(t)} \qquad (1),$$

where:

Y_{tr} is the trend yield;

x_j is the selected specific technological index;

a_j, a', a" are the design estimates;

a', a" (a_0/x_0) are the constants meaning the cultivar advantages of the natural agronomical background;

t is time factor.

However, multicollinearity among changes in technological indices impedes building the models of multifactor technological trends. For this reason, among specific indices we choose one that could provide the smallest variance of actual yield departures from the trend basing on the least-square criterion. The "fertilizer index" appeared to be this indicator. It is quite logical if one takes into account that the intensive use of fertilizers is a powerful mean to increase the yield levels.

When choosing the shape of approximating functions to describe the yield dynamics in certain regions, the relationships were analyzed between the growth of actual yields and annual NPK consumption. Let us mention that due to different response of cultivars to fertilizers and moisture conditions the shape of these relationships varies from close to linear (e. g., for high yielders) to those with "saturation" (e. g., for drought-resistant cultivars).

Then comparison was made among the statistical characteristics (r^2, η^2, $\sigma\Delta y$) obtained with approximation actual data on technological trends both with considering the "fertilizer index" dynamics and without. The results of calculations for spring wheat in the Wheat Belt and the wheat in European CMEA-member countries conducted by Nikolaev [1989a, 1991c] showed that the accounting of fertilizer consumption dynamics allows obtaining more accurate approximations that is confirmed by increased determination and lowered residual variance. The advantage of this method is shown in Figure 2 where one can see different technological trends revealed in wheat yield dynamics in Bulgaria. As seen, by means of the "fertilizer" trend the dynamics of actual yields is described more accurately. For instance, at time intervals of 1953-1967, 1972-1975, 1978-1980 the yield growth is closely agreed with fertilizer consumption growth. Similarly, in the dynamics of wheat yield in Hungary (see Appendix 1) the years of 1952, 1954 and especially 1975 are observed more distinctly as unfavourable.

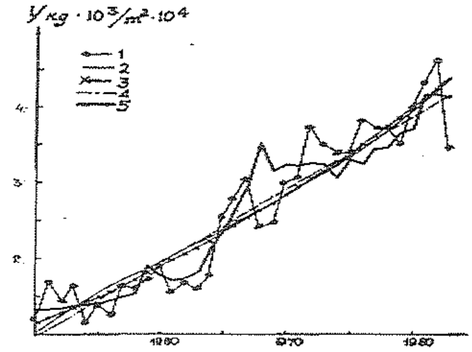


Figure 2. Actual crop yields and technological trends for wheat in Bulgaria: 1 - actual crop yields; 2 - linear trend; 3 - parabolic trend; 4 - linear-fractional trend; 5 - "fertilizer" trend.

Let us mention that the indicated approach can be realized to predict the levels of economically guaranteed yields, e. g., by Fertilizer Consumption Scenarios.

Spatial and temporal analysis of interannual crop yield variability

At the same time specifying economic trends in crop production is very important in terms of revealing more reliably the nature of yield variations near the trend. Thus, by means of "fertilizer index" dynamics one can reveal more distinctly unfavourable, as a rule, dry and excessively wet years (periods), when the efficiency of NPK component is noticeably reduced. For instance, in Figure 2 this fact is reflected by the value of yield departures from the "fertiliser" trend during 1968-1971 and 1983.

Subsequently the yield departure dynamics was compared to the hydrometeorological network data, primarily to find the causes of yield drops and their recurrence due to the occurrence of extreme events (droughts, heavy rainfalls, etc.).

As known, in continental regions the recurrence of crop failures is mostly caused by droughts and accompanying phenomena. For instance, comparison of a centennial wheat failure dynamics with the drought catalogues by Drozdov [1980], Karl et al. [1982] shows that along with the occurrence of a single failure (or two successive failures) they are concentrated at time intervals corresponding to those when droughts become more frequent. Especially extreme failures were observed during the 1930s, when mean global air temperatures noticeably increased.

The frequency of wheat failures, shown by Nikolaev [1991a], is 1.5-2 times lower in the forest zone than in the forest-steppe. It is twice as frequent in the dry steppe zone than in the forest-steppe. The recurrence of extreme wheat failures because of severe droughts is somewhat different. During a hundred years in the forest zone it is about 2%, in the steppe and dry steppe zones above 25%.

Excessive moisture causing wheat beating down is the most essential in the humid zone (about 47% failures). In forest-steppe regions the failures because of crop beating down amount to not more then 20% on average, in steppe - 7%, in semiarid regions less then 2%.

Winter wheat yield losses are also observed because of frost-killing, especially in the regions with severe and non-snowy winters (e. g., in Russia). The causes of crop failures can be rotting and pushing out due to alternative soil freezing and thawing (e. g., in the Baltic regions), early fall and late spring frosts (e. g., in the Mediterranean and Balkan countries) and others. During recent decades the cases of crop flooding have become more frequent due to catastrophic floods caused by heavy rainfalls.

To reveal the regional features of yield variations, the analysis by Nikolaev [1991a, 1993a, 1993b] of spatial correlation of yield departures has been made. Thus, the regions were isolated with synchronous (for smoothed time series - in phase) yield variations. They include: for winter wheat 7 regions in the FSU, southern Great Plains, US North East, US South East, Palouse, Middle Danube Plain; for spring wheat 9 regions in the FSU, Wheat Belt, Canadian Prairie provinces and Maritimes. In the European and Asian parts of the FSU there are regions with asynchronous (not in phase) yield variations.

In order to clear up the statistical features of long-term yield variations the spectral analysis is used by Nikolaev [1992a]. It is shown that spectra of some realizations contain little features consisting in increasing power in lower frequencies with periods of decades, mainly in the interval of 10 to 25 years. The analysis of spectral functions shows that in most cases interannual crop yield variability is caused by white noise. For some realizations (sampling) the stochastic process in the shape of "white noise plus Markov stationary stochastic process" can be taken as approximated models.

The dynamics of crop yield variations in latitudinal zones and large regions of the Northern Hemisphere was also compared to variations in the characteristics of global temperature regime including the meridional temperature gradient by seasons and months. For example, there is the statistically significant correlation (at the level $\alpha = 0.01$) between the secular course of the mean monthly temperature in June in the latitudinal zone 0 - 90°N and cereal crop variations. For 9 summer running mean anomalies the value of correlation

coefficient reaches $r = -0.60$. The analysis by Nikolaev [1994b] shows that supposedly temperature fluctuations affecting moisture conditions make a pronounced effect in subhumid zone sensitive to drastic changes in agroclimatic regime.
The spatial distribution of yield variability is characterised by "V-index" as

$$V = (\sigma\Delta y) / \bar{y}, \qquad (2)$$

where $\sigma\Delta y$ is the value of yield departure standard from technological trend,

$\bar{y}$ is the average yield.

As shown by Nikolaev [1989b, 1991b, 1991d, 1992a, 1993a, 1994a], the spatial features of cereal crop yield variability (i. e. wheat, corn for grain, barley, rye and oats) reflect, as a whole, the zonal character of agroclimatic indicator effects. For instance, the isolines of certain values of "V index" for spring wheat in FSU (see Figure 3) agree with the boundaries of landscape zones. The isoline V = 0.30 approximately conforms northern boundary of the forest-steppe zone, whereas V = 0.35 - to steppe, V= 0.40 - dry steppe, and V = 0.55 - semidesert. The "V-index" isoline course for winter wheat in the FSU also reflects the effect of a more azonal factor - the wintering conditions.

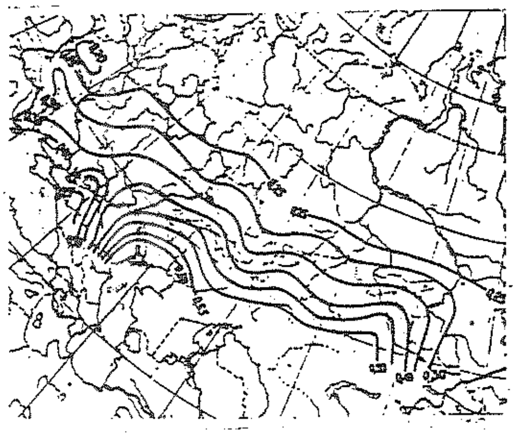
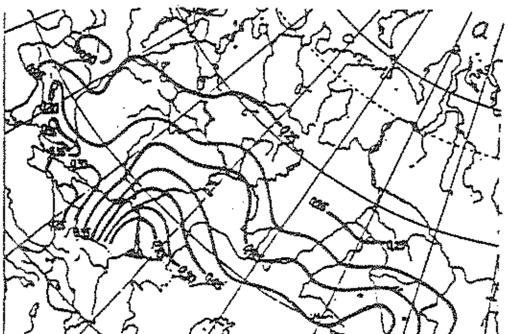


Figure 3. Present-day "V-index" spatial distribution of spring wheat in the FSU.

To estimate the effects of external factors on the "V-index" change in space, the analysis is made for more than 40 different correlation dependencies relating "V-index" changes in space with changing long-term averages and probabilistic characteristics of agroclimatic conditions and a number of regression models built including those for predicting future yield variability.

An assessment of changes in crop yield variability and economically guaranteed yield levels according to the alternative climate change scenarios

An expected yield variability has been estimated on the basis of Climate Change Scenarios. As agroclimatic predictors the use has been made of precipitation, winter temperature and soil moisture under wheat crops. Previously estimations have been made by Nikolaev [1994c] for expected winter wheat yield variability basing on taking account of joint changes in the two non-correlated predictors: January temperatures and annual precipitation according to the Palaeoanalogous Scenarios of the global warming. According to these estimates an increasing winter wheat yield stability in the continental zone of FSU can be expected, especially in the regions where crops are subjected to frost-killing. By 2005 the "V-index" is expected to decrease by 6-7%, by 2020 by 11-13%, by 2050 by to 15%. In the continental zone of North America in the early 21st century, the "V-index" is expected to increase, especially, in the Great Lakes regions and in the Midwest due to a forecasted regional decrease in precipitation. However, by the mid-21st century the "V-index" is expected to decrease due to predicted more optimum moisture conditions.
To assess an expected variability of spring wheat yield in the FSU, the use is made of the model of soil hydrological regime built by Lemeshko [1993]. This model represents a modification of the Budyko's method, elaborated by Budyko [1971] and allows calculating the mean long-term value of soil moisture during warm months both for the current and future climatic conditions. Estimations of model soil moisture (Wmod.) were compared to those calculated by the data of network observations (Wobs.). A close correlation ($r = 0.95$) between both characteristics of soil moisture point to the reliability of this model.
Spatial "V-index" distributions for spring wheat for future conditions are illustrated on maps in Figure 4.



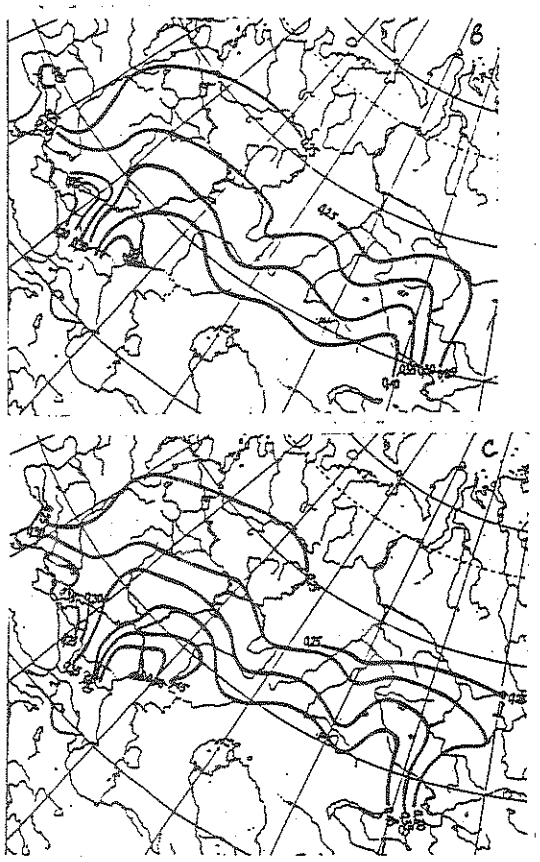


Figure 4. Spatial "V-index" distributions for spring wheat for future conditions: a - by 2005; b - by2020; c -by 2050.

These estimations are obtained on the basis of correlation relationship between the "V-index" and Wobs. changes well described by the parabolic regression curve as well as on the basis of the calculations of Wmod. for summer months for the conditions of palaeoclimatic analogues: the Mid-Holocene Optimum, the Riss-Würm Interglacial and the Pliocene Optimum corresponding to 2005, 2020 and 2050. The comparison of maps shows that the most expressed (statistically significant) "V-index" changes are typical of the dry agriculture zone (steppe, dry steppe). In these regions yield stability is expected to grow as a result of predicted soil moisture increase, especially noticeable in the case of the Riss-Würm Interglacial.

The expected "V-index" changes are also estimated by the scenarios of changing soil moisture during the summer months obtained by GCM simulations: GFDL, UKMO, MPI. In spite of the available difference in the estimates of "V-index" values by these models the MPI model yields the best agreement by the sign of estimates with the palaeoreconstructions of soil moisture field. Nevertheless, all the alternative scenarios predict an insignificant increase in "V-index" in more northern and humid regions, where the tendency is predicted to soil "desiccation" and a simultaneous decrease in "V-index" in semiarid regions where soil moisture conditions would be favourable.

At the same time by means of the soil hydrology model one can also estimate the expected changes in the level of economically-guaranteed spring wheat yields as a result of changing the effectiveness of fertilizer consumption. The calculation is based on the dependence of recommended consumption of NKP components on the value of long-term soil moisture storage means during the autumn-spring months: $W_{IX-XI,\ IV-VI}$. Let us mention that in the FSU regions the autumn and spring soil ploughing are approximately equally effective.

Estimates of changes in autumn/spring soil moisture storage, optimum fertilizer consumption and thus changes in yield growth (additional yield) by 2005 and 2020 in various agricultural regions of FSU are given in Appendix 2. As seen, the largest yield growth is to be expected in drouhtly (semiarid) regions on steppe chernozems and chestnut soils as on these the effectiveness of fertilizers sharply increases with an additional natural and artificial irrigation.

Conclusions and recommendations

The estimates obtained show that the predicted climate change can exert different effects on yield indicators in different regions of Mid-Latitude Agriculture. The increasing global warming trend would provide the possibilities of enlarging winter crop areas due to the formation of favourable wintering conditions. Along with this the expected regional changes in moisture availability in the coming decades can have an adverse effect on grain production in some regions. However, with further changes in heat and moisture resources the situation can arise that promotes the movement of more productive cultivars to the currently semiarid regions, where the expected soil moisture and agrotechnology regimes would be similar to those in more humid regions. The further development of modelling and simulation scenarios would help to obtain more detailed estimates of future yield changes.

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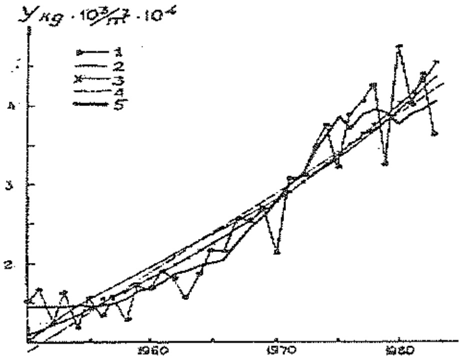
Appendix 1

Actual crop yields and technological trends for wheat in Hungary (disignation as in Figure 2).



Appendix 2

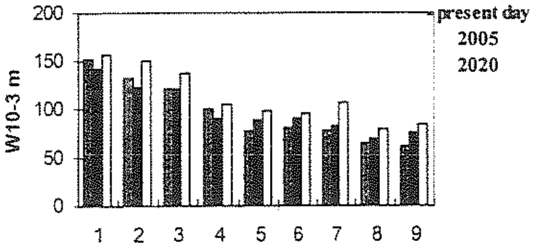
Changes in spring wheat yield levels due to changing fertilizer consuption effectiveness with scenarious of changes in soil moisture conditions (rainfed crops)

Regions and types of soils :
1.Upper Volga , podzolic ;
2.Volga Vyatka , sward podzolic ;
3.Ural , leched chernozem ;
4.Centr.Chernozem , common chernozem ;
5.West Siberia , southern chernozem ;
6.North Kazakhstan , southern chernozem ;
7.North Caucasus , dark chestuut ;
8.Lower Volga , chestnut ;
9.West.-Centr . Kazakhstan ,light chestnut .

▨ - present-day conditions

■ - 2005

☐ - 2020


W10-3 m
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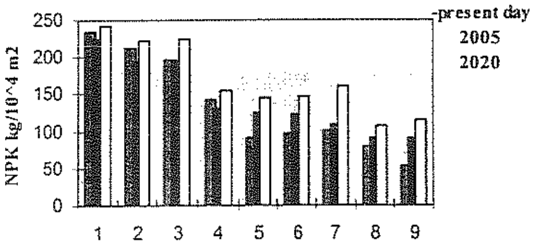
present day
2005
2020


NPK kg/10^4 m2
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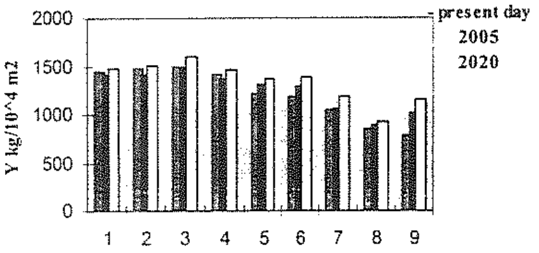
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