Evaluation of growth conditions and maize yield forecast in Russian regions from satellite data in a simulation model

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Abstract: *The purpose of this study was to develop a method and a technology of the real-time crop yield forecasting for the Russian Federation on the basis of a simulation plant growth model using satellite data. Relationship between the ground and satellite data is analyzed. Remote sensing data are added as entries into the simulation crop growth models used in operational practice of the Russian Federal Service on Hydrometeorology and Environmental Monitoring. A new simulation model of maize production process is devised using satellite data. Based on this model the dynamic-statistical methods for forecasting the maize grain yield have been developed. The efficiency of maize yield forecasting is estimated for some Russian Federation regions. Technology has been developed of operative forecasting of maize productivity using satellite data for Russian Federation subjects.*
Keywords: *crop yield forecast, maize, corn, simulation model, plant production process, remote sensing, satellite data, NDVI, photosynthesis.*

Riassunto: *L'obiettivo di questo studio è stato quello di sviluppare per la Federazione Russa un metodo e una tecnologia di previsione in tempo reale della crescita delle colture, sulla base di un modello di simulazione della crescita delle piante a partire da dati satellitari. È stata studiata la relazione tra i dati rilevati a terra e quelli da satellite. I dati telerilevati sono stati inseriti come dati in ingresso nei modelli di simulazione della crescita delle colture utilizzati nella pratica operativa dal Servizio Federale Russo per il Monitoraggio Idrometeorologico e Ambientale. È stato ideato un nuovo modello di simulazione del processo di produzione del mais utilizzando dati satellitari. Sulla base di questo modello sono stati sviluppati metodi dinamico-statistici per la previsione della resa in granella del mais. È stata stimata l'efficienza della previsione di resa del mais per alcune regioni ed è stata sviluppata una tecnologia per la previsione operativa delle rese di mais utilizzando dati satellitari per la Federazione Russa.*
Parole chiave: *previsione di resa delle colture, mais, modelli di simulazione, processi di produzione vegetale, telerilevamento, dati satellitari, NDVI, fotosintesi.*

1. INTRODUCTION

From year to year maize growing is becoming more and more important in the Russian Federation, because it is the most high-yielding cereal crop in the world and widely cultivated. Furthermore, the new varieties of maize possessing high crop capacity suitable for Russian climate conditions have been introduced. Hence, the average maize productivity in Russia has increased by 10 % over the last 5 years (from 36.6 q/ha in 2004-2008 to 40.2 q/ha in 2009-2013), herewith the total maize yield in Russia has increased by 61% as compared to that in the preceding 5-year period (from 4.2 in 2004-2008 to 6.8 million tons in 2009-2013, on the average).

Since maize high economic value is very useful for food security (Mejía, 2003; CIMMYT, 2011), timely and qualitative agro-meteorological forecasts of maize yield are necessary, considering its importance for agriculture. Forecasts will allow making strategic and tactical decisions with the purpose of increasing the amount of high quality products and developing the grain balance of the country. This work is aimed to improve the efficiency of crop yield forecasts.

Maize productivity prediction requires a thorough evaluation of the weather conditions impact on the corn production (Muchow, 1990, for example), taking into account the whole series of complex biological phenomena involved in this process. Until recently, physical and statistical models (Komotskaya, 1991; Svisyuk, 1991; Strashnaya, 2009) have generally been used in Russia for the real-time forecast of maize yields. These models are known to have a number of limitations and cannot effectively account for the above-mentioned requirements during the whole growth period

Several studies considered satellite data to be of primary importance (Kleshchenko, 1986; Seguin, 1992; Maas, 1993; WMO, 2000, 2003; Tao *et al.*, 2005; Corbari *et al.*, 2010). Quite a few papers have used satellite data in the regression models (Kleshchenko, 1986; Huete, 1999; Evtyushkin,

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Rychkova, 2004; Kleshchenko *et al.*, 2011; Kleschenko, Savitskaya, 2014) to assess the yield by the year-analog method. Based on available approaches to the application of satellite data in yield assessment (Tolpin *et al.*, 2009), to correct the biological productivity in simulation models (Clevers, 1988; Acutis *et al.*, 2006; Bryksin, 2009), namely, to correct the plant density, leaf area index and yield. These studies with simulation models, however, have been conducted in different areas and are not adapted to the field work in the Russian Federation.

The purpose of our research is to develop a method and a technology of the real-time crop yield forecasting for the Russian Federation subjects, integrating plant growth simulation models with satellite data. At the same time, statistical methods and physical models are used for yield forecast correction.

To achieve this, the following problems have been solved: 1) study of the ground and satellite data interrelation; 2) addition of remote sensing data as entries into the simulation crop growth models used in operational practice of the Russian Federal Service on Hydrometeorology and Environmental Monitoring (Roshydromet); 3) assessment of quality of the results obtained; 4) development of methods and technologies of operational crop yield forecasting from remote sensing data; 5) introduction of satellite data into the existing prognostic system of Roshydromet.

2. DATA AND METHODS

2.1 Description of the Study Area

The studies have been carried out in the territory of 16 regions (the region area fluctuated from 30 to 50 thousand square kilometers) in the mid and south of European part of Russia. Regions name are given in Tab. 1 below. The area is characterized by subtropical and moderate climate and falls into the area of risk farming.

2.2 Data collection and Analysis

The statistical, agro-meteorological and remote sensing information and some data from-field experiments were used in this work. The statistical data were the annual maize productivity or the total yield and planted area; the period was 59 year long (1955-2013); the territory – 16 regions. Data are available at the site of Russian statistic service. Agro-meteorological data were the result of every ten days observations on the agro-meteorological

	Forecast-time interval, months:	(2; 4]	(1; 2]	(2; 4]	(1; 2]
Federal District	Russian Federation subjects	Relative errors, %		Absolute errors, q/ha	
South and North Caucasian	Volgograd Region	29,8	2,7	16,1	1,3
	Rostov Region	31,9	8,1	16,2	5,2
	Krasnodar Territory	34,2	13,5	12,7	6,8
	Republic of Kabardino-Balkaria	26,8	19,9	8,5	8,1
	Stavropol Territory	39,4	6,7	12,7	2,1
	Republic of North Ossetia	27,7	14,5	7,4	5,2
	Republic of Dagestan	18,4	11,4	7,6	3,7
Central	Lipetsk Region	14	6,2	7,7	2
	Kursk Region	33,8	14,1	5,3	2,9
	Belgorod Region	40,5	2,2	13,8	0,5
	Voronezh Region	12,6	2,2	1,5	0,5
Privolzhsky	Ulyanovsk Region	6,6	1,7	3,6	0,7
	Samara Region	11	1,7	8,3	0,9
	Saratov Region	7,1	2,6	4,2	1,3
	Orenburg Region	4,2	2,5	2,9	1,4
	Republic of Tatarstan	7,4	2,5	1,9	0,8
Average forecast errors		**21,6**	**7**	**8,1**	**2,7**

Tab. 1 - Average (2010-2013) relative and absolute errors of maize crop yield forecasts with NDVI.
Tab. 1 - Media (2010-2013) e errori assoluti delle previsioni di resa del mais con NDVI.

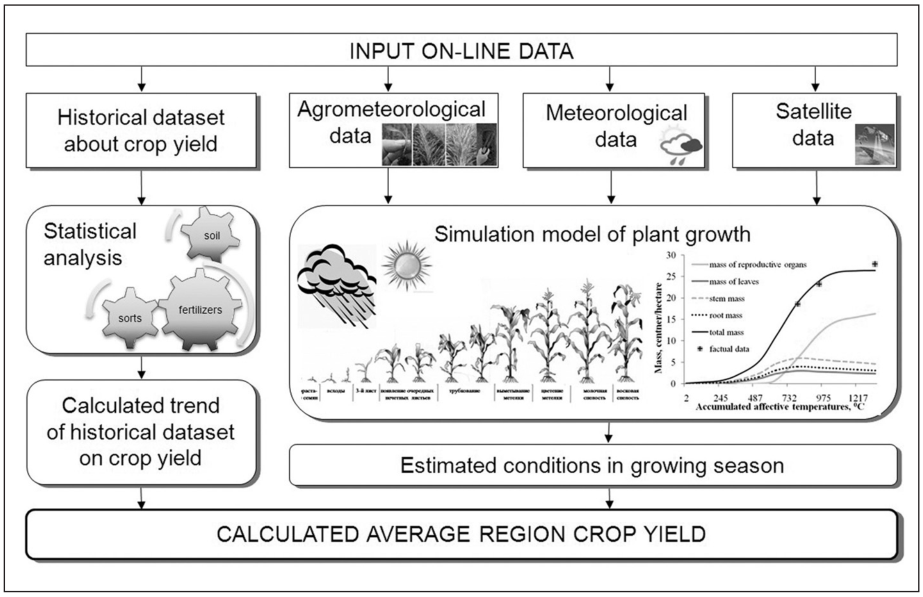

Fig. 1 - Block diagram for crop yield calculation.
Fig. 1 - Diagramma a blocchi per il calcolo della resa delle colture.

network. There are 6-15 agro-meteorological stations in every region; the period was 14 year long (2000-2013). Agro-meteorological data include the density of planting (the number of plants per square meter), the dates of maize seedling emergence and ripeness, mean daily air temperature (°C), rainfall sum (mm), sunshine hours and plant organ biomass. Data are available in the archive at the World Meteorological Center (in the town of Obninsk). Field experiments conducted by Kuban State University during the vegetation periods of 2003-2007. They did the ground measurements on the maize leaf area index (square meter of leaf area per square meter of planting area).
The remote sensing data in the form of ten days normalized difference vegetation index (NDVI) prepared by Russian Space Research Institute on the base MODIS data) has been chosen as satellite data. The reasons are the following: 1) rather high spatial resolution of MODIS (250 m); 2) data are obtained and processed by unified methodology (http://www.iki.rssi.ru/); 3) availability of a continuous 14-year series of the average ten-day regional NDVI values; 4) on-line NDVI values used in prognostic models. The NDVIs are available for each regions for winter and spring crops, tillage and forests.
During the period of 2003-2008 there were available only NDVI values for tilled fields and winter crops, therefore NDVI values for spring crops were calculated from (Naidina, 2010):

$$NDVI_{sp} = \frac{NDVI_{pf} - NDVI_{w} \cdot S}{1 - S}, \qquad (1)$$

where $NDVI_{sp}$ is value for spring crops, $NDVI_{pf}$ is for tilled fields, $NDVI_w$ is for winter crops, S is the proportion of area under winter crops in the tillable acreage for a given year (ha ha^{-1}).
Since 2009, the NDVI values for spring crops have been provided by the VEGA-PRO service – professional information service for monitoring the renewable biological resources based on satellite data analysis (http://pro-vega.ru/). The service performs automated satellite data processing that makes possible daily information updating

2.3 Forecast methods

2.3.1 The base model short description

The dynamic-statistical forecast methods developed at the National Research Institute on Agricultural Meteorology are used for operational forecasting of major crop yields in Russia. The "weather - crop" model is the basis of these methods. Fig. 1 presents its scheme. The dynamical-statistical methods are based on the combination of two forecasts. The first forecast is the forecast of a trend in the historical dataset on crop yields. The second forecast is the forecast of deviations from this trend. To predict the yield the following formula is used (Polevoy, 1988):

$$Y = Y_{t+1} \cdot E \qquad (2)$$

where Y_{t+1} is the crop yield trend in a forecasted year, E is the estimate of discrepancy between observed (at the date of forecast) agro-meteorological conditions of plant growth and multiyear conditions against which the yield trend is formed.

The trend is assumed to reflect the impact of cultivation technology, changes in the varieties and fertilizer quantity on plant productivity. The trend is found by statistical methods using extrapolation from the crop yield time series. Trend deviations are estimated from the plant growth simulation model as the ratio of reproductive organ biomass calculated for a given year to this biomass calculated using the averaged long-term data (Fig. 1). The crop yield is calculated as the product of this trend and assessed conditions in a vegetation period. Satellite data have been added to the current method of forecasting.

Fig. 2 shows the block diagram of a simulation model for crop yield forecasting. The model includes a ten-days data-input unit. This unit was supplemented by satellite data, NDVI. The model also contains the units of input initial data, photosynthesis, respiration and biomass buildup.

The crop yield is governed mainly by the intensity of plant photosynthesis and respiration costs, in other words, the intensity of plant gas exchange. The plant biomass buildup () is calculated as the difference between photosynthesis and respiration (Sirotenko, 1981; Polevoy, 1988):

$$\frac{\Delta M^j}{\Delta t} = P^j - R^j, \quad (3)$$

where P^j is the total photosynthesis of crop, is R^j the respiration, j is the number of the estimated period.

Biomasses of the whole plant and of the single organs are calculated for the specific time intervals. The biomass of isolated separate plant organs is calculated from the following differential-difference equations (Sirotenko, 1981; Polevoy, 1988):

$$\left.\begin{aligned} m_i^{j+1} &= m_i^j + \left(\beta_i^j \frac{\Delta M^j}{\Delta t} - \upsilon_i^j m_i^j\right) n \\ m_p^{j+1} &= m_p^j + \left(\beta_p^j \frac{\Delta M^j}{\Delta t} + \sum_i^{l,s,r} \upsilon_i^j m_i^j\right) n \end{aligned}\right\}, \; i \in l,s,r, \quad (4)$$

where m_l is the total dry biomass of separate organs, m_s is the total dry biomass of stems, m_r is the total dry biomass of roots, m_p is the total dry biomass of reproductive organs; β_i is the function of distribution of "fresh", newly created assimilates; υ_i is the function of redistribution between the organs of "old" earlier stocked assimilates; n is the number of days.

2.3.2 *Maize yield forecasting*

As known, seasonal variability of the crop leaf area index is one of the most important indicators for analyzing and modeling the plant production process (Sirotenko, 1981; Boschetti, 2006). It was found that the annual period of maximum plant leaf area coincides with the period of the maximum NDVI. The maximum NDVI value of winter crops coincides with the winter crop flowering, the

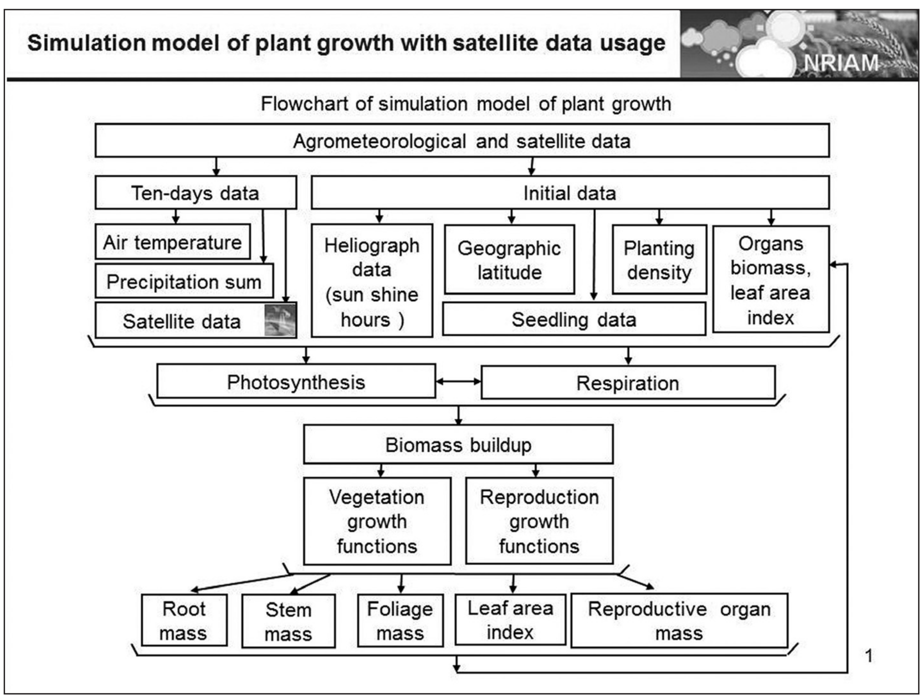

Fig. 2 - Simulation model of plant growth with satellite data.
Fig. 2 - Modello di simulazione della crescita delle colture con dati da satellite.

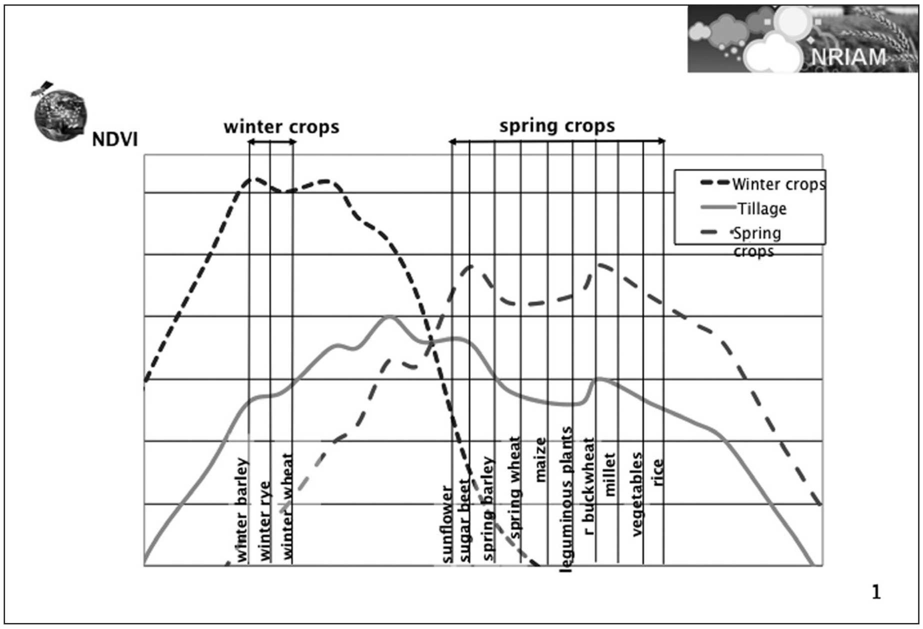

Fig. 3 - Interconnection of satellite and ground data.
Fig. 3 - Interconnessione tra dati rilevati da satellite e dati rilevati da terra.

maximum NDVI value of spring crops includes the date of the highest leaf area index of spring crops. And, ultimately, the period of maximum NDVI of arable land includes the dates of the highest leaf area index of winter and spring crops (Fig. 3). Thus, the graphs allow concluding that NDVI values reflect the dynamics of crop photosynthesis during the growth period (Kleshchenko *et al.*, 2011; Naidina, 2010).

The basic model considers changes in the physiological plant age as a function called the "ontogenetic curve of photosynthesis". This has been implemented in the simulation models of major crops have been introduced in the operational divisions of the Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet).

The "ontogenetic curve" for maize without satellite data is (Kleshchenko, Naidina, 2012):

$$\alpha^j = \alpha_0^{\left(\frac{\Sigma T}{\Sigma T_m}-1\right)^2} \qquad (5)$$

where Σ^T is the sum of effective temperatures, cumulatively; Σ^T_{m} is the sum of effective temperatures at the maximum leaf photosynthetic rate; α_0 is the initial photosynthetic rate relative to the maximum possible one early in the growing season at $\Sigma^T = 0$.

Without satellite data this "ontogenetic curve" is calculated from the effective temperature in the given period and the heat amount optimal for plant growth (Fig. 4).

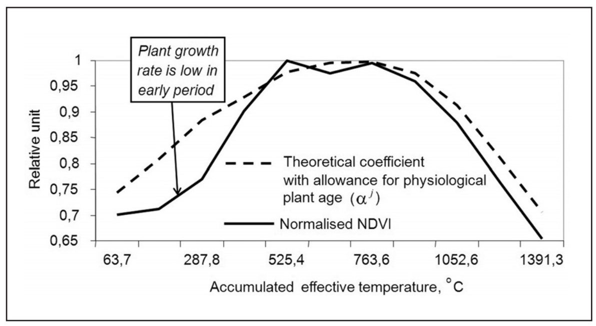

Fig. 4 - NDVI and "ontogenetic curve" of photosynthesis.
Fig. 4 - NDVI and "curva ontogenetica" della fotosintesi.

When using satellite data, this function is replaced by NDVI. Fig. 4 presents the "ontogenetic curve" (dotted line) with no satellite data for Krasnodar Territory. The normalized NDVI value is shown by firm line. Similar graphs are plotted for 2001-2010. The NDVI benefits are: 1) NDVI values are adequate for the plant growth dynamics, i.e. the biomass growth rate is low in early period; 2) NDVI values are observed rather than calculated data; 3) NDVI values are considered to be a comprehensive indicator of plant conditions (Kleshchenko, Naidina, 2011, 2012, 2013).

3. RESULTS AND DISCUSSION

Fig. 5 shows the actual crop productivity and maize yield forecasts for Krasnodar Region for the 2007-2013 periods. The forecast values are provided with different methods: the dynamic-statistical methods with and without NDVI, the inertial method, where

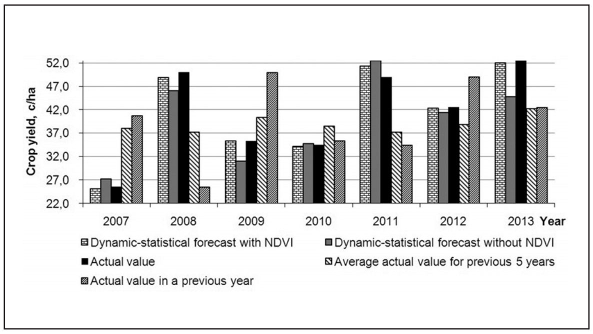

Fig. 5 - Results of maize grain yield forecast.
Fig. 5 - Risultati della previsione di resa in granella del mais.

the forecast is the observed yield of the previous year and the 5 year statistics method (average of observed crop yield for the previous 5 years).
The dynamic-statistical method with NDVI gives the best forecasts, especially in years with extreme maize yield. The rare high maize yield for this territory (53.5 q/ha) was observed in 2013 and the year 2007 was characterized by extremely low productivity (25.5 q /ha). The forecasts with NDVI are the best for these extreme years (Fig. 5). The average (2007-2013) relative and absolute errors of forecasts by these methods are the following: 1.8% (0.8 q /ha), 7.7% (3.4 q /ha) and 22.1% (8.7 c/ha), 31.2% (12.5 q /ha) for dynamic-statistical with NDVI, dynamic-statistical without NDVI, inertial methods and 5 year statistics respectively.

The dynamic-statistical methods for other regions have been developed too. The average (2010-2013) relative and absolute errors of maize productivity forecasts are presented in Tab. 1 for some Russian Federation areas, where maize is mainly grown.
In Russia the real-time forecasts of maize productivity are calculated twice, with the forecast-time interval from 2 to 4 months and from 1 to 2 months. As seen from Tab. 1, the errors in case of the forecast-time interval from 1 to 2 months are small. These results could provide the basis for the operative application of this method.
Hence, the dynamic-statistical method with the satellite data applied and the technology of maize yield forecasting have been developed. The program interface is shown in Fig. 6. The technology permits the calculation of maize productivity and assessment of the efficiency of forecasting methods.
Such an approach of appending satellite data to the simulation model has been used to forecast the spring wheat productivity for Krasnodar Region. At present, the simulation model of spring wheat yield forecast based on the same approach is used in operational work. The results are positive: the difference between the actual values and those forecasted with NDVI for each of considered 13 years (2001-2013) does not exceed 13%; the average relative errors in forecasting are 9.9% for the model without NDVI (base model) and 6.5% for the improved version.

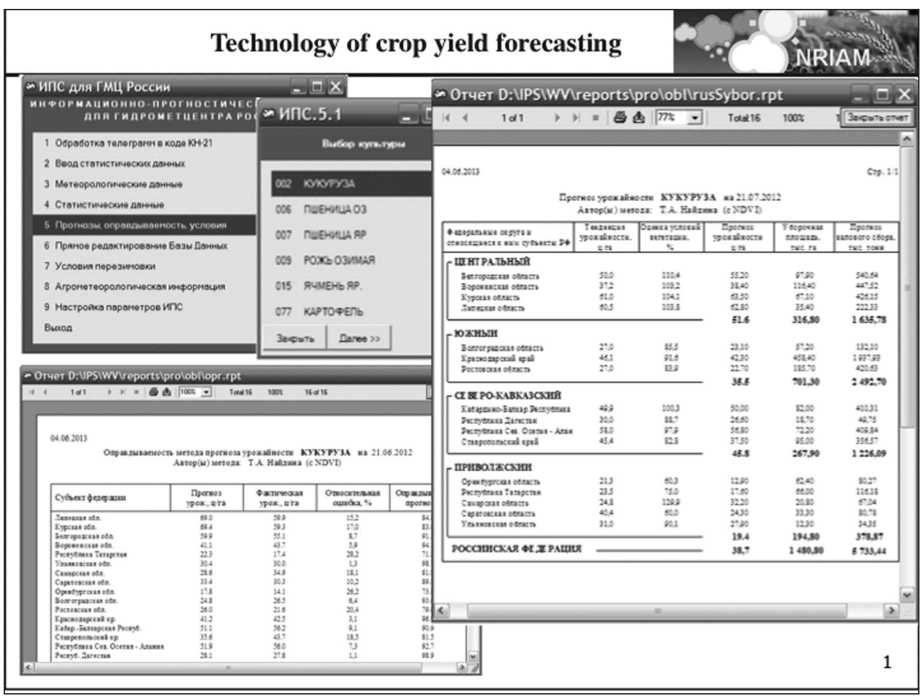

Fig. 6. User interface.
Fig. 6 - Interfaccia utente.

Similar results are obtained for the spring barley yield forecast: the difference between the actual values of barley yield and those predicted with NDVI for the 9 year period 2005-2013 does not exceed 15%; the average relative errors in forecasting are 9.0% for base model and 6.2% for the NDVI model.
The increased forecast efficiency achieved by supplying the operational forecasting models of wheat and barley with satellite data encourages the use of the same technique for maize yield forecast.

4. CONCLUSION

These studies brought about the following important results and conclusions:
– Relationship of ground and satellite data was investigated.
– NDVI application to calculate photosynthesis in the crop yield forecasting models was justified.
– Good results on satellite data application in the simulation models of wheat, barley and maize growth have been obtained.
– Application of satellite information is shown to improve the forecast efficiency, mainly, in years with the extremely high or low maize yield.
– Technology has been developed of operative forecasting of maize productivity using satellite data for Russian Federation subjects.
These findings can be used in developing new methods of yield forecasting using satellite data.

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