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Forecasting of locust mass breeding by using satellite data

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The recent locust outbreaks in Russia raised considerable interest in applying remote sensing methods to locust control and forecast. The life cycle of the locust depends on such environmental conditions as temperature, soil moisture, air humidity, plant biomass, and soil type. Few remote sensing methods are able to retrieve these parameters; in our investigations, we used NOAA (AVHRR) and EOS (MODIS) satellite data. A complex index of locust hazard based on other indexes, such as NDVI, aridity, number of sunspots, was developed for the area of Western Siberia. It was found that the risk to locust hazard in the Southern Siberian region should be considered high when the locust index is higher than, or equal to 0,51. However, no correlation was found between that index and the locust outbreak in the southern part of European Russia, which led to the investigation, based on GRACE satellite effective water layer thickness in the Lower Volga region. It was concluded that the complex index of locust hazard has to be localized regionally.

Keywords: Italian locust, multi-temporal satellite data, locust mass breeding, locust hazard index, Western Siberia, European Russia.

Introduction

Few types of locust are common in Russia: Moroccan locust (*Dociostaurus maroccanus*), Asian migratory locust (*Locusta migratoria migratoria*), and Italian locust (*Calliptamus italicus*), which is considered to be the most harmful [5, 7]. The locust significantly affects two areas in Russia: North Caucasus-Lower Volga River and the Southern part of Western Siberia.

The dangerous locust population outbreak in South Siberia was observed in 1996-2001 with the maximum manifestation between 1999-2001. Locust population density reached up to 150 adults per square meter, while in the ordinary conditions it does not exceed 10 adults per square meter. The main species of the outbreak was Italian locust. In 1999 Italian locust destroyed 220000 ha of cropland in Kazakhstan, with estimated financial losses ~15 million USD. Agricultural protection expenses amounted to 23 million USD in 2000 [12]. During the 3-rd decade of April 2012 in the North Caucasus, the average density was of 47 hoppers/m² [1]. More than 3 million ha were treated during the June 2012 in Kazakhstan and in the Russian Federation [8]. The dramatic rise of Italian locust activity in European Russia requires additional investigations to find out the reasons and factors behind those outbreaks.

A successful application of Landsat data [6, 10, 11] is mapping Asian migratory locust habitats in Central Asia. These positive results are based on the Migratory locust (*Locusta migratoria migratoria*) ecology. Deltas of Central Asian rivers are reed covered forming an ecological niche of migratory locust. It was proved in [6, 10, 11] that the spectral features of reed beds in visible and nearest infrared spectral bands are significantly different from the spectrum of other land-cover types. As a result, Terra (MODIS) and Landsat TM data are quite effective for Migratory locust population habitat mapping for the region of Central Asia. Italian Locust ecology is more complicated than other locust species [5, 7]. There are no specific ecosystems representing the natural habitat of this locust, which is the main difficulty for remote sensing monitoring of spatial distribution of Italian Locust population density. The methodology of quantitative remote mapping of Italian locust habitat was developed and verified on the basis of this investigation [3, 4].

The next step in using remote sensing data for the locust control is prediction of locust population outbreaks. The locust, being an insect, strongly depends on climatic conditions such as temperature and humidity. Climate has changed dramatically during the last decades affecting the distribution of locust population. Looking at temperature variations in the above-mentioned areas of Russia (*Fig. 1*) it is possible to see an important difference between them. The temperature growth in the City of Astrakhan (Lower Volga Region) is typical of the Northern Hemisphere, with +1 - +2 °C increase in the last 40 years. A different situation is in the Southern part of Western Siberia: the annually averaged air temperature was steadily growing during the period of observations at the City of Barnaul (Altai's capital), starting from 0 °C in the first half of 19-th century, which was an unacceptable condition for locust development. Now the annually averaged temperature has exceeded +3°C and it opens possibilities for the locust invasion. Considerations on the global warming were supported by the recent results announced by Berkeley Earth Team (http://berkeleyearth.org/results-summary/).

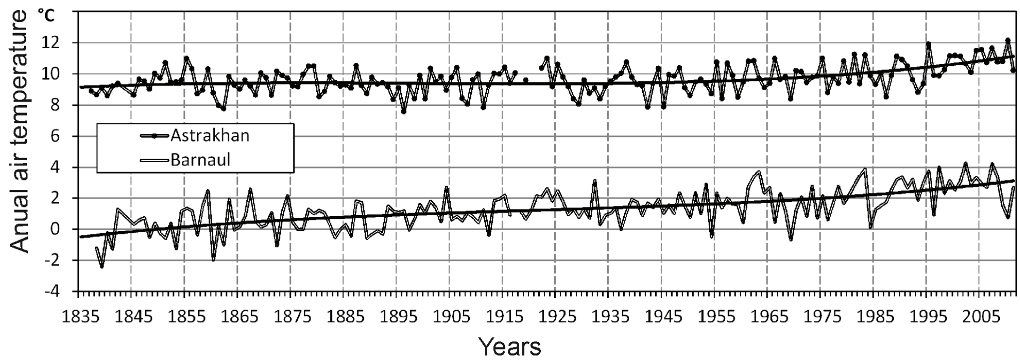

Fig. 1. Longtime average annual temperature variations in the City of Astrakhan (North Caucasus – Lower Volga region) and the City of Barnaul (South Siberia). Solid lines show polynomial temperature trend

Modern satellites make it possible to obtain information on above-mentioned environmental characteristics. This paper describes practical verification of the methodology we used to predict locust outbreaks in the West Siberian region, as well as our attempt to apply this methodology on the territory of the Southern part of European Russia for medium-term prediction of Italian locust outbreaks.

1. Data and methods

1.1. Sites

The following two regions affected by locust were selected for investigations:

- “Siberian Region” in the southern part of Western Siberia (53-55N and 76-79E, area ~ 50 000 km^2) is located in the Steppe Biome and characterized by continental climate. Most of the natural zonal ecosystems there have been destroyed by anthropogenic activity, and native plant communities almost never occur now [9]. From the beginning of the XXI century cultivation agriculture has been reoriented to livestock breeding, which resulted in the increasing areas of unplowed lands, hay-fields, and pastures displaying a succession of steppe communities. A number of vegetation communities are common in this area: steppe and meadow on saline soils; halophytes on salt marshes; coastal lakes and rivers; riparian vegetation of steams; fragments of forests (birch forests and artificial planting belts).

– “European Region” is the southern part of European Russia (North Caucasus – Lower Volga River) with coordinates: 43-50N, 38-50E, the area ~ 450000 km^2. The climate of this land varies from moderate-continental to arid. The region is represented by three biomes - Temperate steppe, Semi-desert and Mountain forests. The greater part of the region is plain, intensively plowed fertile steppe. “European Region” includes a semi-desert area near the Caspian Sea, which, in some places, transforms into a real sand desert. The salted steppe areas are located in small depressions of surface relief in some parts of the territory. The southern part of the region is a mountainous area covered with broad leaves forests. The Valley of the Lower Volga with its rich soils is used for vegetable growing. The Volga River delta is characterized by rich vegetation including reed beds.

1.2. Data

The locust outbreaks data were used in the form of binary time series (*Table 1*).

Table 1. Binary time series of locust outbreaks (“1” - outbreak. “0” - outbreak absence)

Year	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Siber. Region	1	1	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1
Europ. Region	1	1	1	0	1	1	1	0	0	0	0	1	1	1	0	0	0	0	0	1	1	1	0	0	0	0	0	1	1	1	0	0

This study has used the data collected by TERRA (MODIS) and NOAA (AVHRR) satellites. AVHRR NDVI data were acquired from 1981 to 1998, and TERRA (MODIS) monthly NDVI data from 1999 up to the present time have been used for assessing vegetation condition and changes during the study period.

Maps of the land surface temperature (LST) were retrieved from NOAA (AVHRR) for 1981-2002 period and TERRA (MODIS) for 2003-2011 period. The choice of the satellite data on precipitation or soil moisture was based on the following considerations: we did not use TRMM (Tropical Rainfall Measuring Mission) precipitation data due to the relatively high latitude of our regions. Precipitation data are reliable in the strip within the latitudes 50 degrees South up to 50 degrees North. Soil moisture provided by AQUA (AMSR) is inadequate in our Regions, as we discovered a significant difference between precipitation data observed at meteorological stations and by satellite observations. Most probably, this difference is caused by a considerable number of unknown parameters and by the problem of vegetation/roughness separation.[1] For this reason the soil moisture retrieved from AQUA (AMSR) data is more accurate for desert region without rich vegetation and with a big percentage of bare soil, whereas the Lower Volga and the North Caucasus regions are almost totally covered with natural (forest) and agricultural vegetation with small areas of semi-desert landscape. On the other hand, the satellite gravimetric survey data are based on Newton's law of universal gravitation and only well-known astronomical corrections are needed. That is why the estimation of soil moisture required the equivalent thickness of water layer (ETWL) provided by the satellite gravimetric survey (GRACE constellation [13]). The GRACE satellite mission was launched in March 2002[2]. It is a tandem of two small satellites, moving at sub polar orbits at an altitude of 220 km. The mission can measure the gravity field with square root error ~ 1 mGal, which corresponds to ~1 cm of ETWL. The spatial resolution of data is about 100x100 km. ETWL combines underground water, water in soil, water of snow cover, and water in atmosphere. The GRACE monthly averaged 1° x 1° fragments of ETWL were used for the total investigated territory from June 2002 to April 2009. Our aim was to calculate the accumulated ETWL in the moving 5 months window, taking into account that survivability of locust eggs depends on the soil moisture during the total time of eggs being in the soil (autumn, winter, and spring). ETWL time series were analyzed for the territory of three administrative areas (*Fig. 2*), representing different agricultural and climatic conditions.

Meteorological data from 16 weather stations in “European Region” and from 7 weather stations in “Siberian Region” were processed and monthly average LST, NDVI (satellite data) and precipitations (meteorological station data) in the period of 1981-2011 were compiled. Some

[1] NSIDC. AMSR-E/Aqua L2B Surface Soil Moisture, Ancillary Parms, & QC EASE-Grids: http://nsidc.org/data/docs/daac/ae_land_l2b_soil_moisture.gd.html#njoku05.
[2] NASA/German Aerospace Center (DLR) Gravity Recovery and Climate Experiment (GRACE) mission: http://www.csr.utexas.edu/grace/.

additional information (number of sunspots from astronomical observations, the air temperature from weather stations) was involved in data processing. The air temperature was used in processing for satellite data validation. The number of sunspots was taken as an indicator of periodic climate processes probably affecting the locust outbreaks [14].

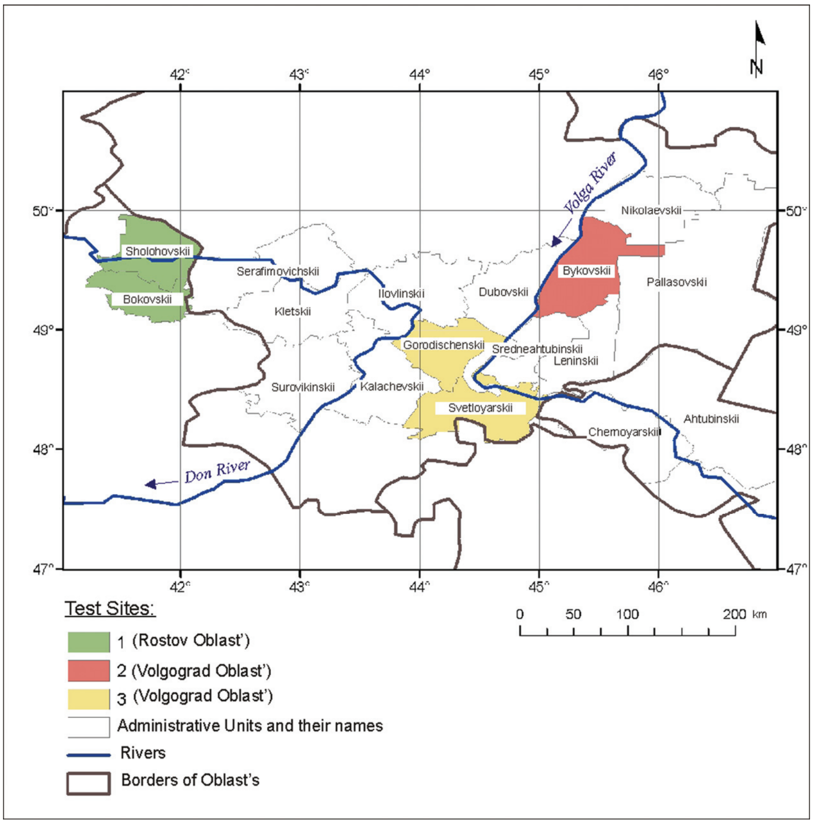

Fig. 2. The map of sites in the Lower Volga Region (European Russia), chosen for the investigation of local variations of environmental conditions important for locust ecology

ETWL (GRACE data) and day time LST (TERRA (MODIS) data) were averaged over the territory of three administrative units with different mesoclimatic conditions. Variations of ETWL (GRACE data) and daytime LST were plotted for each of these test sites for the period of three-year cycles (2006-2009 – two years before 2009, when the locust mass breeding occurred, and one year before, as the background). For simplicity, ETWL was normalized, based on the maximum value for the investigated period.

1.3. Methods

After the visual analysis of time series shown in *Figs. 3* and *4* we came to the preliminary conclusion that there is a correlation between some environmental factors (which we will call indicators of risk) and the locust population density. These factors were averaged for the whole area of West Siberia region. We obtained three quantitative time series of NDVI, a number of sunspots, and aridity index (*Figs. 3*, *4*). The annual increment of sunspot numbers was chosen as an indicator of risk, as suggested by Uvarov [14]. The aridity index describes the ecological conditions of the area: $I_A=P/t$, where: P is the total precipitation in August, mm (meteorological data), t is averaged LST for the same period, °C. From the practical point of view, it is better to use the complex index of locust hazard. It was introduced [3, 4] as a linear combination of NDVI, number of sunspots, and an aridity indexes:

$$I_{LH}=1-(I_A+I_{NDVI}+I_o) \tag{1}$$

where: I_A is the normalized aridity index, I_{NDVI} is normalized NDVI (satellite data), I_o is the normalized index of the annual increment of sunspot numbers (indexes are normalized according to the maximum value during the investigated period). The one year shift into a future was done for time series of indexes, taking into account the main aim of index application, which, in our case, is forecasting locust outbreaks for the next year using the current year index values.

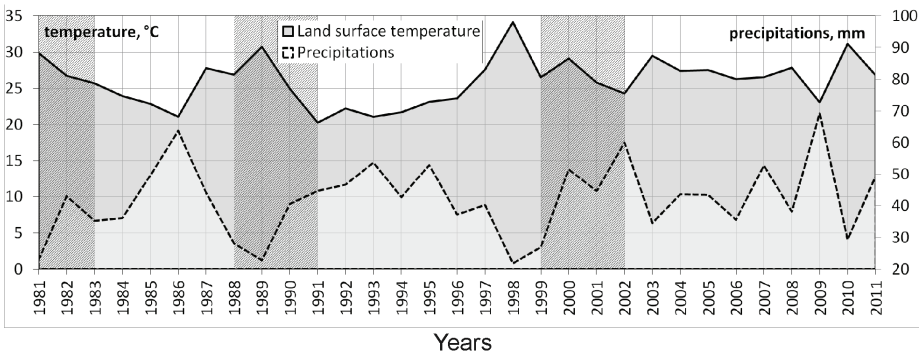

Fig. 3. Land surface temperature and precipitations in "Siberian Region". Grey columns indicate the periods of locust mass breeding

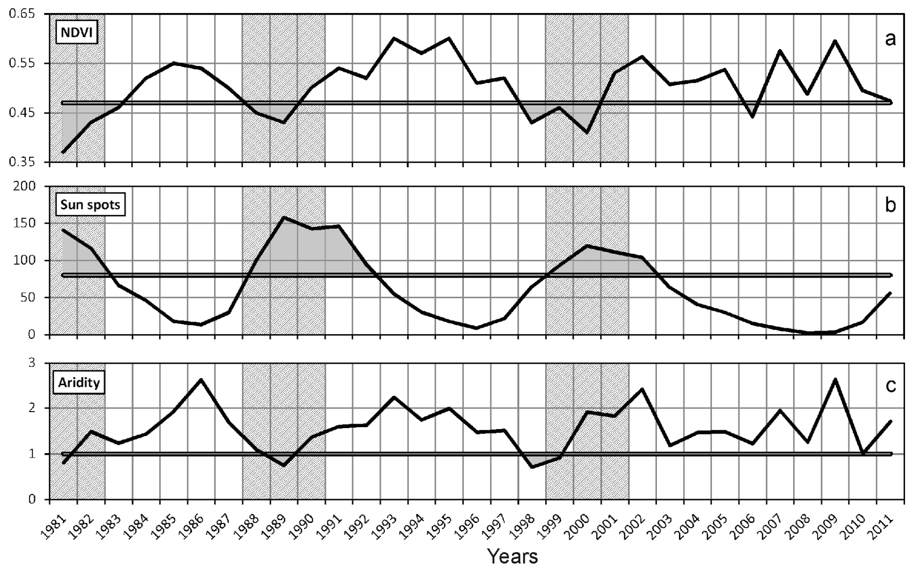

Fig. 4. Indexes for "Siberian Region". Grey columns indicate the periods of locust mass breeding

The statistic dependence of chosen time series indexes on binary time series of locust outbreaks was investigated. The Kendall tau rank correlation coefficient was applied, as most correct in this case (*Table 2*. Only the smallest (optimal) sums of probabilities of false alarm and outbreak miss are shown in *Table 2*).

As one can see, p-values of the Kendall correlation are very small for all indexes. Thus, there is the strong statistic dependance between the chosen indexes and binary locust outbreak time series. The Locust Hazard index is characterized by the biggest Kendall correlation coefficient and by smallest probabilities of false alarm and outbreak miss. That is why the Locust Hazard index was chosen as the best.

Table 2. Parameters of rank correlations between different indexes and binary time series of locust outbreaks (the Siberian Region)

Statistical parameter	I_{NDVI}	I_o	I_A	I_{NDVI} **and** I_o	I_{LH}
Coefficient of Kendall correlation	-0,54	-0,55	-0,40	-0,74	0,75
Kendall correlation p-value	0,0004	0,0003	0,009	$1,5*10^{-6}$	$1,0*10^{-6}$
Probability of false alarm	0,13	0,09	0,43	0,09	0,04
Probability of outbreak miss	0,13	0,13	0,13	0,0	0,0

2. Results

2.1. Siberian Region

The analysis of LST and precipitation variations indicates a clear relationship between the drought and the locust outbreak (*Fig. 3*). Two drought periods of 1986-1991 and 1996-2000 were followed by locust outbreaks in 1988-1991 and 1991-2001. From 2001 to 2011 Italian locust outbreaks were not detected in this region. LST value was not too high during these years, and there was enough precipitation. 2010 looked like the beginning of a drought, whereas 2011 appeared to be wet enough.

Figure 5 shows the index of locust hazard in the course of the last 30 years. The distribution of false alarm and outbreak miss probabilities for the given threshold is shown in *Fig. 6*.

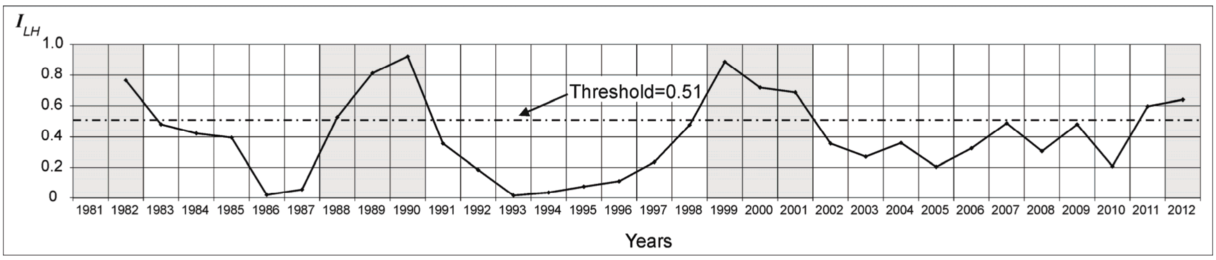

Fig. 5. The index of the locust hazard (I_{LH}) for "Siberian Region". Grey columns indicate the periods of locust mass breeding

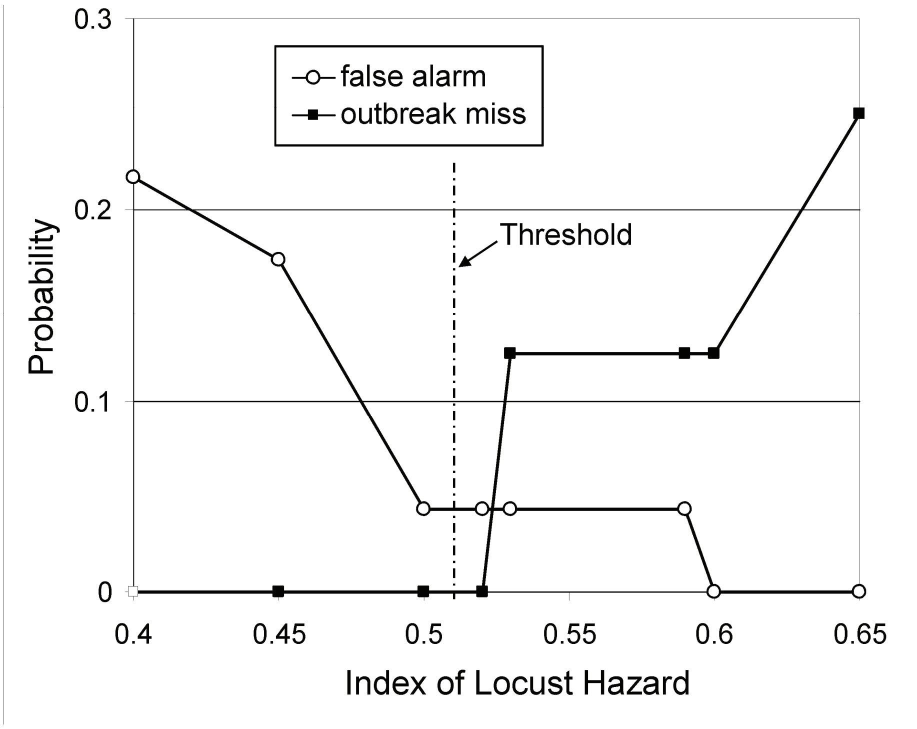

Fig. 6. Probabilities of forecast and the threshold of the locust hazard index. "Siberian Region"

2.2. European Region

The behavior of indexes does not show any strong connection with locust outbreaks (*Fig. 7*), with the exception of aridity index, which has some association with locust mass breeding. Outbreak miss and false alarm probabilities (*Fig. 8*) are too high for practical application.

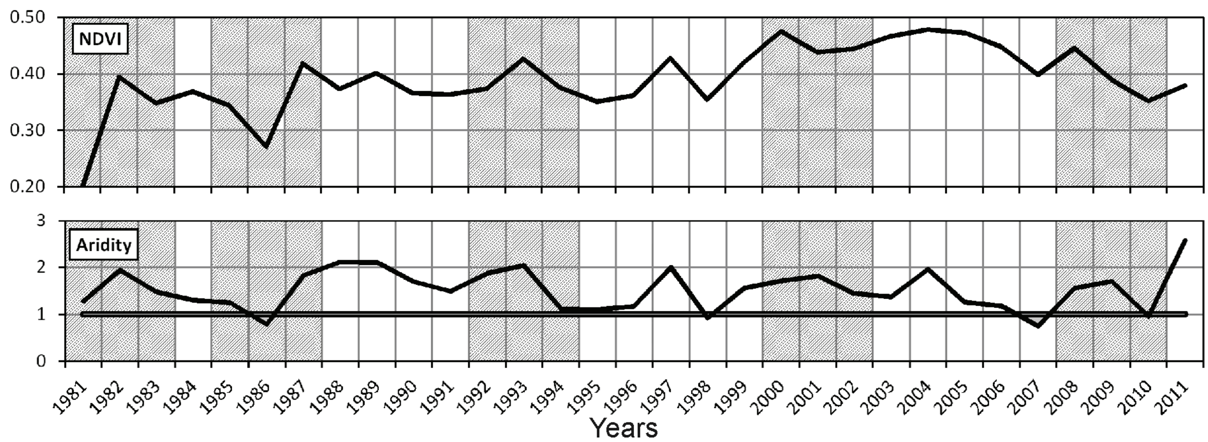

Fig. 7. Indexes for "European Region". Grey columns indicate the periods of locust mass breeding

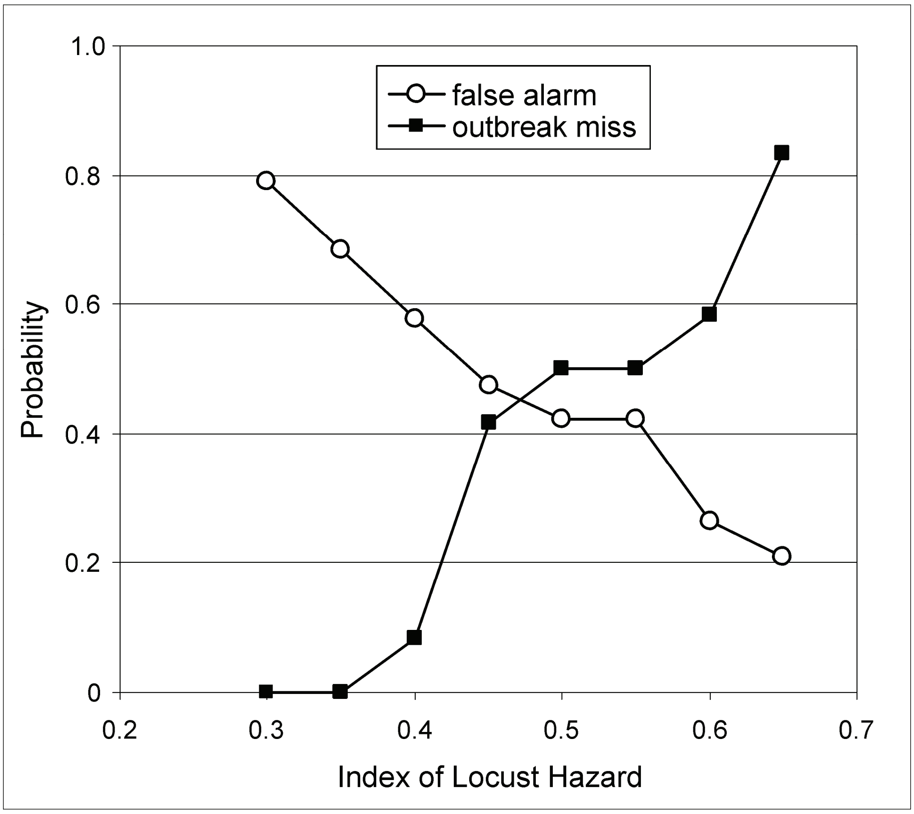

Fig. 8. Probabilities of forecast, depending on the threshold of the locust hazard index. "European Region"

3. Discussion

Statistical analysis of false alarms and missed breeding shows that the suggested index of locust hazard (1) makes it possible to predict locust outbreaks in "Siberian Region". The forecasting threshold should be chosen on the basis of economic strategy. It could be chosen as I_{LH}=0.51 (*Figs. 5*, *6*) if the main strategy is the minimization of economic losses due to a false alarm and outbreak miss.

The technique of the locust outbreak prediction was developed in 2007, with the amount of data constantly increasing since that time, extending the time series shown in *Fig. 5*. As one can see (*Fig. 5*), the index of locust hazard overcame the threshold in 2011. Mass breeding of the Italian Locust was actually detected in 2012 in Novosibirsk Oblast' and in Altaiskii Krai of Western Siberia [2]. This example shows that the method makes it possible to predict locust outbreaks not only retrospectively, but also practically.

Let us call the locust outbreak forecast, following the previous outbreak, a long-term prediction, and the forecast of locust outbreak after the spring egg pods accounts, a short-term prediction. In these terms, our forecast can be considered a medium-term forecast.

The locust outbreak prediction, carried out on the basis of the index of locust hazard, produced an inevitable level of errors for the European Region (*Fig. 8*). We advanced a hypothesis that the reason for this unacceptable result is the size of the region and the mosaic structure of landscapes. "European Region" is about 10 times larger than "Siberian Region", has frequent climatic variations and consists of several biomes.

Figure 9 exhibits a steady decrease of ETWL during the period of 2006 – 2009. Moreover, one can conclude that the water supply at Sholohovskii & Bokovskii administrative areas (site No.1) was higher than at Bykovskii administrative area (site No.2) and Gorodischenskii & Svetloyarskii administrative areas (site No.3). Therefore, during the last two years (before 2009, when the Italian locust mass breeding occurred) conditions for locust egg survival were better on sites No.2 and No.3. According to the classical concept [5] this should have caused the locust mass breeding. In reality, mass breeding was observed in 2009 (*Fig. 10*). The highest density of the locust population was on site No. 2. On the other hand, the locust mass breeding was not recorded on site No.1, where ETWL was the highest of all the sites during the last 2 years. Site No.3 had an intermediate state. The locust mass breeding was recorded in the Southern part of this site. It correlates with the intermediate quantities of ETWL of site No. 3.

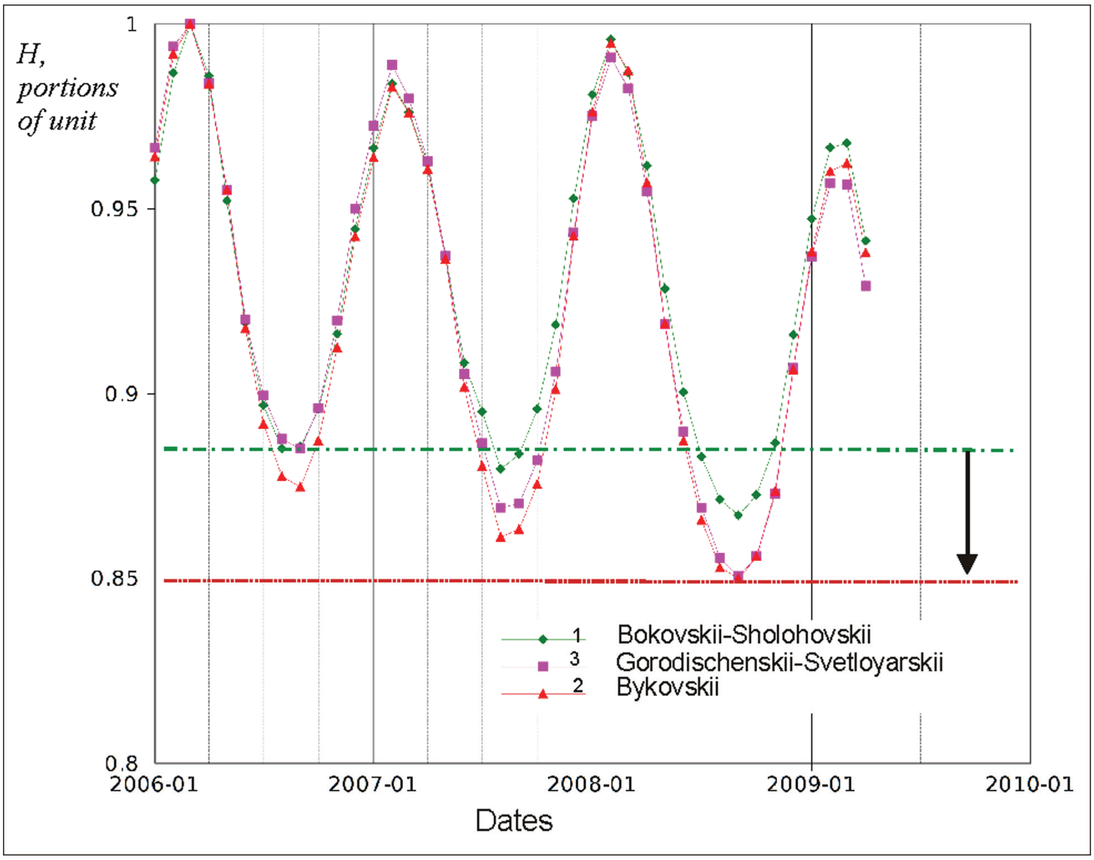

Fig. 9. ETWL variations for three test sites in Volgograd and Rostov Oblast's (Fig. 2). Legend: 1, 2, 3 denote sites as per Fig. 2

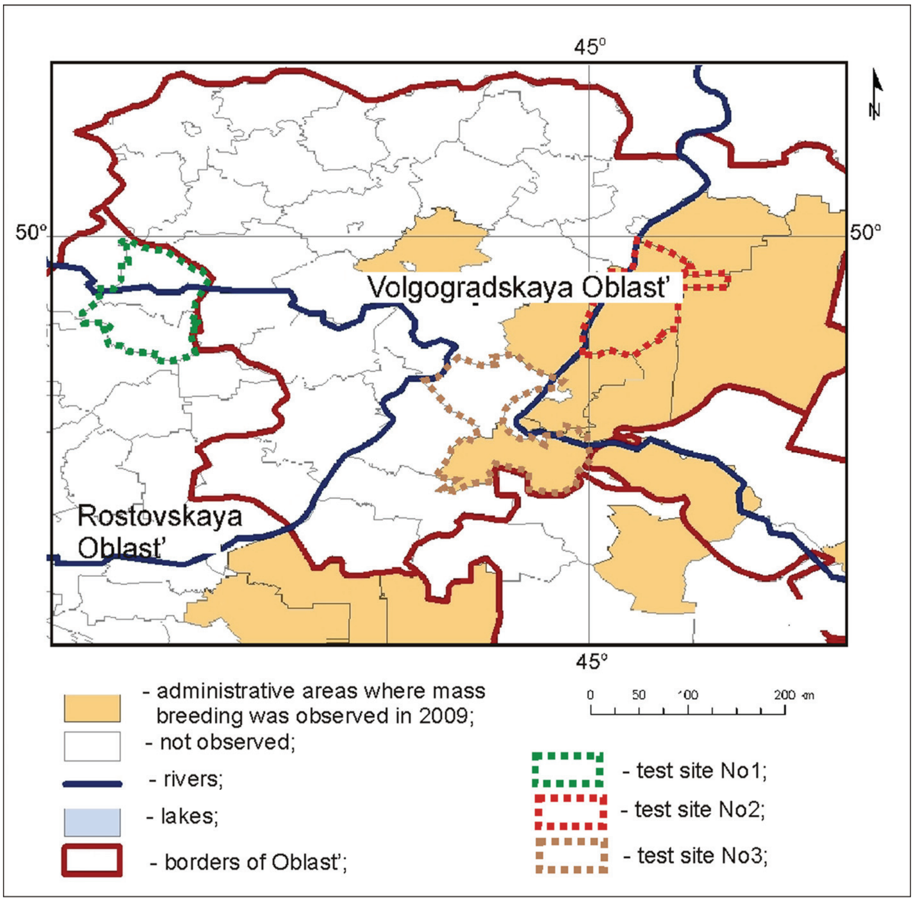

Fig. 10. The scheme of areas in the Lower Volga Region ("European Region"), where the information about the locust mass breeding in 2009 was published. Legend: sites 1, 2, 3 denote sites as per Fig. 2

Additionally, the spatial distribution of NDVI was also analyzed (*Fig. 11*), using quantities of NDVI averaged for each site, as the spatial resolution of GRACE data is very low (~ 150x150 km), while the spatial resolution of NDVI (250 m) is much better. For this reason, it is very difficult to compare the original spatial resolution NDVI and ETWL. The highest quantity of NDVI was recorded on site No.1, and the lowest was on site No. 2. The NDVI on site No.3 had intermediate quantity, again (*Fig. 11*). The distribution of NDVI can be explained by two reasons. First of all, the drought in 2009 was more severe in the Eastern part of the investigated territories (sites No. 2 and No. 3). The second possible reason is the impact of the locust.

Thus, GRACE data may be quite promising for the locust mass breeding prognosis, and that GRACE data can be used in the future for aridity index monitoring. In the framework of this paper, precipitations measured at weather stations are used for aridity index calculation. Localized in space and time, these data have significant deficiency. Besides, GRACE project provides water supply, averaged over the investigated area and within a period of time. Moreover, GOCE, the next generation of satellite for gravity force measurement, was launched. It measures the field of Earth's gravity force with better sensitivity by one order of magnitude.

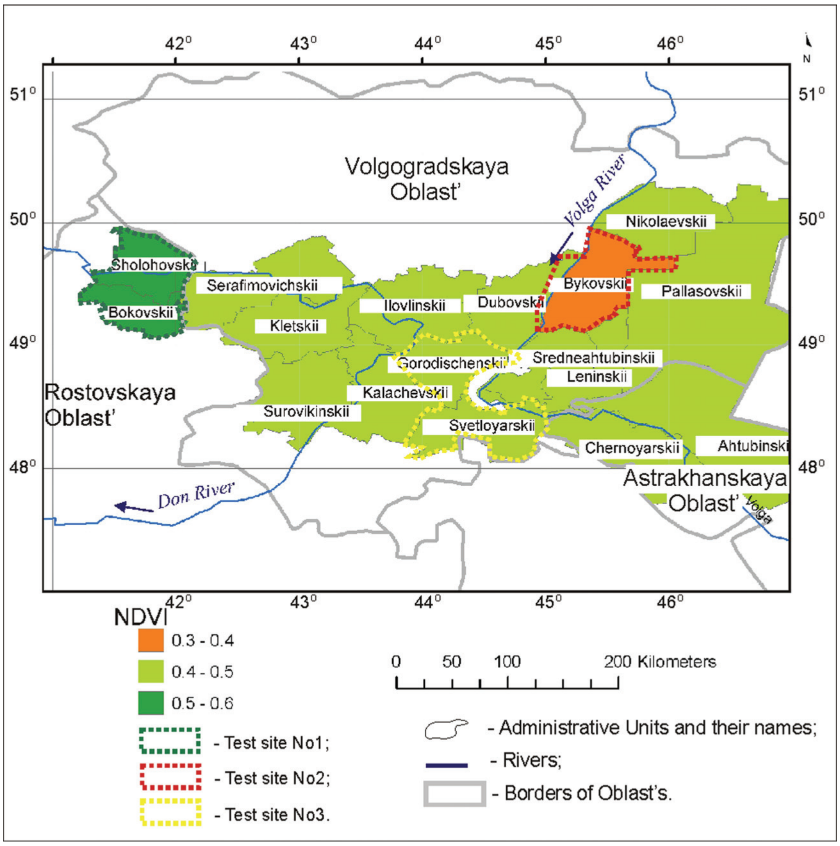

Fig. 11. The scheme of NDVI for the Lower Volga Region ("European Region"). Legend: 1, 2, 3 denote sites as per Fig. 2

4. Conclusions

1. A very simple and inexpensive method of locust outbreak prediction using satellite and meteorological data has been developed and verified for "Siberian Region".

2. Precipitation information is critical for this method. Ground meteorological information cannot be replaced with the satellite data for a temperate zone. One of the promising approaches to resolve this problem is to use satellite gravimetric data (GRACE, GOCE).

3. The size, landscape and climate variability of the test site is also quite significant. Applying the method developed for "Siberian Region" directly in "European Region" produced inappropriate results, the reasons for this being a large area and the complexity of the new test site. It should be split into several parts according to the ago-climatic areas, and the method should be applied to each part separately.

5. Acknowledgments

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Прогнозирование вспышек саранчовых на основе материалов спутниковых съемок

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Участившиеся в последние годы в России вспышки численности саранчовых вызвали значительный интерес к применению дистанционных методов для их прогнозирования. Жизненный цикл саранчовых зависит от таких экологических условий как температура, влажность почвы и воздуха, пищевая база, тип почвы. Несколько дистанционных методов позволяют восстановить количественные характеристики, отражающие эти условия. В наших исследованиях использованы материалы съемок спутниками NOAA (AVHRR) и EOS

(MODIS). По этим данным для южной части Западной Сибири и юга европейской части России построены и проанализированы многолетние ряды вегетационного индекса NDVI, индекса аридности, числа солнечных пятен. Предложен комплексный индекс саранчовой опасности. Показано, что для Западной Сибири риск вспышки численности итальянского пруса может считаться высоким, если индекс саранчовой опасности равен или превышает 0,51. В то же время, для юга Европейской части России не выявлена связь между вспышками численности саранчовых и этим индексом. Это явилось причиной для дальнейших исследований, основанных на использовании материалов спутника GRACE, измеряющего вариации поля силы тяжести. По результатам съемок этим спутником восстанавливается толщина эффективного слоя воды. В результате показано, что индекс саранчовой опасности для природных условий юга Европейской России должен быть районирован.

Ключевые слова: Итальянский прус, многоразовые спутниковые съемки, вспышки численности саранчовых, индекс саранчовой опасности, Западная Сибирь, Европейская часть России.

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