GIS-based Potential Distribution Modeling for Harmful Non-Gregarious Locusts in Agricultural Areas of Northern Kazakhstan to Improve Preventive Pest Management

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Abstract — To predict the potential distribution of harmful non-gregarious locusts efficiently, MaxEnt software based on the GIS and remote sensing data were used. The main novelty is based on results from ecological niche modelling (ENM), which was implemented using MaxEnt platform. In order to perform the ecological niches of locust pests, satellite images remote sensing data, climatic data downloaded from electronic resources, as well as ground data in selected research areas were collected. The uploaded data was recalculated to monthly averages for all years from 1999 to 2021. The innovation of this study is a versatile approach that takes into account not only environmental and climatic conditions but also the current situation with agricultural land management and pesticides application. These research results on habitat suitability and potential distribution of non-gregarious locust pests may allow prioritization of areas for risk assessment, monitoring and early prevention measures.

Keywords — non-gregarious locusts, ecological niche modelling (ENM), potential distribution, Northern Kazakhstan.

I. Introduction

A topical problem in the field of plant protection is the high risk of dangerous pests to agricultural production and food security [1]. Research on finding ways to limit pests and their impact on food security is an urgent and high priority [2].

In line with current trends in science and technology, the use of innovative technologies in phytosanitary monitoring and forecasting [3]-[5] is determining the global level of research in plant protection. With the application of innovative technologies such as GIS and GLONASS/GPS-technologies, there is an exceptional opportunity to accurately identify pest outbreaks, transmit data quickly, predict their further spread and make the right decisions to protect crops.

Northern Kazakhstan is an economically important agricultural region in the country. At the same time, the natural climatic conditions of the region are considered the most optimal habitat for locust distribution and harm of all locust species [6]. It is important to prevent damage caused by non-gregarious locusts, which in the years of mass reproduction cause no less harm than herd locust migratory species [7]-[8]. Moreover, the natural agricultural areas serve as reservoirs for the harmful grasshoppers. In this regard, the close proximity of agricultural crops to the grassland facilitates the infestation of these insects [9].

From the practical and operational point of view, all the monitoring studies on the non-pestiferous locusts are carried out simultaneously on the complex of pest locusts for agriculture. According to literature sources and our observations [10]-[12], the pest locust complex destabilizing production of agricultural plants includes 9-10 species. Of them in the agricultural areas of Northern Kazakhstan occur such species as *Dociostaurus brevicollis (EV.), Dociostaurus kraussi kraussi (INGEN.), Stauroderus scalaris (F.-. W.), Aeropus sibiricus sibiricus (L.), Pararcyptera microptera microptera (F.-W.), Chorthippus albomarginatus albomarginatus (DEG.), Euchorthippus pulvinatus (F-W.).* All of the above species occur in complex proportions at the stations.

Regions of Northern Kazakhstan are highly infested by non-gregarious locust pests, according to the prevalence rates [12]. They cause damage to crops, legumes, fodder crops and pastures. According to the Order of the Minister of Agriculture of 19.03.2020 # 100 [13], Locusts are included in the list of pests, phytosanitary measures against which are supported from public funds. This newly issued provision once again emphasizes the importance and relevance of improving phytosanitary control of these pests. In this regard, research on the improvement of phytosanitary control of non-gregarious locusts, based on modern innovative approaches such as GIS-technology and remote sensing methods, is quite relevant.

The objective of the research is to model ecological niches of non-gregarious locust pests based on GIS-technologies and remote sensing methods to identify potential distribution areas and prevent damage from dangerous pests in the agricultural areas of Northern Kazakhstan.

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Predictive modelling of geographical distribution based on the ecological niche of the study site has become an important tool in agroecology [14]-[15]. Modelling uses previous information on the spatial distribution of species in an ecosystem by constraining predictive models to the nearest ecological niche, thus generating predictions of possible occurrence areas based on environmental conditions that are similar to the identified actual infested area [16].

As a result of modeling the ecological niches of the surveyed pests, with the help of GIS-technology products such as MaxEnt software, it becomes possible to allocate information about potential locust breeding areas on the digital maps of the surveyed area, where the first priority should be given to monitoring and protection efforts. If this provision can be applied in the phytosanitary monitoring practices, it might contribute to the digitalization of agriculture [15].

As the current research results in this direction show, the ecological modelling of pest niches depends primarily on environmental factors and some environmental parameters [17]- [18]. Referring to the studies of most scientists [14]-[16], as these factors and parameters, a large place is given to the vegetative cover (NDVI index), which is a forage base for pests and meteorological parameters of the studied environment, which determines favorable conditions for the habitat of certain groups of pests.

If we consider the global research on ecological niche modeling of locust pests and phytophages in general, in most cases, an enormous attention is paid to their global distribution in order to prevent infestations and mass outbreaks on a global scale [19]-[20], which is also a strategic issue for phytosanitary security of neighboring territories. At the same time, there are also studies that address the improvement of preventive pest management by modelling pest ecological niches within countries and their agricultural regions [21]. Similar studies on locust pests in Kazakhstan were carried out on Moroccan locust *(Dociostaurus maroccanus, Thunberg)* and migratory locust (Locusta migratoria L.) in its typical habitat, i.e., the southern regions of Kazakhstan [15], [22].

In our case, we propose an approach to model the ecological niches of non-gregarious locust pests using examples from four regions of northern Kazakhstan: Akmola, Pavlodar, Kostanai, and Northern Kazakhstan. It should be noted that these studies aim to improve phytosanitary control and preventive measures in the studied area in order to identify potential pest distribution areas, as well as rational planning and use of plant protection products. The proposed approaches and methods can be used by other researchers of similar fields.image to the Windows clipboard and then Edit | Paste Special | Picture (with “Float over text” unchecked).

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II. Materials and Research Methods

The objects of the study were non-breeding locust species. The survey and analysis techniques are generally accepted methods in phytosanitary monitoring and forecasting [23]-[27]. In order to identify ecological niches of the locusts under investigation and monitor their development and distribution, this project utilizes available resources of the GIS-Centre of the S. Seifullin Kazakh Agro Technical University. For that purpose, satellite remote sensing (ERS) data for multi-year period are collected in the form of satellite images, climatic data, historical data on grasshopper outbreaks, terrain elevation data, and soil data [28]-[31].

The evaluation of the phytosanitary status of crops, i.e. the detection of outbreaks of diseases, pests and weed infestation, occupies a special place. As a rule, the method of determining the difference in spectral brightness of vegetation during the vegetation period based on Normalized Difference Vegetation Index (NDVI) and Vegetation Conditions Index (VCI) [28]-[35] are used for these tasks.

As remote sensing data, satellite images from TERRA and Aqua MODIS, Sentinel, and Landsat satellites were used. Climatic data were obtained from Bioclim sources. Based on the analysis results, the criteria of meteorological parameters under which the locusts develop will be specified. The data from Landsat and Sentinel satellites are multispectral images in optical, infrared, near infrared and thermal bands with spatial resolution from 10 m to 60 m and periodicity of 3-16 days [17], [28], [30]-[31]. Hyperspectral images were downloaded from MODISTERRA and AQUA satellites, with spatial resolution of 250 to 1000 m each day.

The research requires calculation of vegetation indices matrices from spring and summer period images. This was done using ENVI, ERDAS or ArcGIS software [36].

In addition, soil moisture data at 1 km resolution are downloaded from SMOS and SMAP resources http://nsidc.org/data/smap and the ground surface temperature is calculated from Landsat images.

Based on the results, classification and index calculations, and calibrated ground data, locust habitat areas are identified as well as distribution factors. An important step in developing a methodology for phytosanitary control of non-staple locusts is the creation of ecological niche modelling using the MaxEnt software [37]-[38].

Historical data on the pest locust outbreaks include: the number of detected larvae; the treated areas; and the place and time of locust outbreaks. Terrain elevation data will be obtained from the open-source Shuttle Radar Topography Mission (SRTM), soil data from the Automated Information System of the State Land Cadastre (AIS GZK) portal. Based on the analysis results, ecological niches and locust migrations are identified.

Modeling the ecological niches of the surveyed non-gregarious locust pests encompasses two areas:

1) developing a baseline model based on climate variables;

2) developing an ecological niche model based on remote sensing data.

The baseline model represents a set of optimal climatic parameters (monthly mean temperatures, Precipitation, hydrothermal coefficient of wetting Selyaninov HTK, etc.) for the development and reproduction of the non-staple locust pests and serves as the basis for identifying the hotspots and high density of non-staple locusts in order to improve preventive pest management measures in the agricultural areas of Northern Kazakhstan. Drying conditions of the growing season for several consecutive years are critical for mass emergence of the Nematode locusts[1], [6]-[9], [12].

III. Research results and discussion

A. Processing of climate and terrain data from electronic resources to refine meteorological parameter criteria.

In order to identify ecological niches of non-gregarious locusts, remote sensing data were collected in the form of satellite images and terrain elevation data. Remote sensing data in the form of satellite imagery and terrain data were collected and analyzed from electronic resources in order to refine the criteria for meteorological parameters under which locusts develop. Climatic data from WorldClim; Bioclim were obtained. An analysis was performed to refine the meteorological parameters under which the locusts develop.

The climate data were downloaded from https://developers.google.com/earth-engine/datasets/catalog/IDAHO_EPSCOR_TERRACLIMATE.

Terrace limited is a set of monthly climate and climatic water balance data for global land surfaces. Uses climate-supported interpolation, combining high spatial resolution climatological norms from the WorldClim dataset with coarser spatial resolution but time-varying CRU Ts4.0 and Japanese 55-year reanalysis (JRA55) data. The spatial resolution of the data is 4638.3 metres.

The images were downloaded using Google Engine. The downloaded data were converted to monthly averages for all years from 1999 to 2021 using QGIS. Further, all rasters were reduced to the same spatial segment and the same spatial resolution for modelling purposes. Also, all rasters were converted to the same projection and converted to ASCII format using ArcGIS.

Table 1 shows the data for key climatic and meteorological parameters. That are key factors such as PDSI (February-July, 1999-2021), NDVI (June, 2015-2021), NDWI (June, 2015-2021), Solar radiation (February-July, 1999-2021), Precipitation (January-December, 1999-2021), Temperature minimum (January-December, 1999-2021) and Temperature maximum (January-December, 1999-2021) were taken for processing.

TABLE I: CLIMATIC DATA DEFINED AS INPUT PARAMETERS FOR THE ECOLOGICAL NICHE MODELLING (ENM) OF THE NON-GREGARIOUS LOCUST PESTS

#	Climatic data	Frequency, yrs.
1	PDSI Drought Index, February	1999-2021
2	PDSI Drought Index, March	1999-2021
3	PDSI Drought Index, April	1999-2021
4	PDSI Drought Index, May	1999-2021
5	PDSI Drought Index, June	1999-2021
6	PDSI Drought Index, July	1999-2021
7	NDVI June	2015-2021
8	NDWI June	2015-2021
9	Sol. Radiation, February	1999-2021
10	Sol. Radiation, March	1999-2021
11	Sol. Radiation, April	1999-2021
12	Sol. Radiation, May	1999-2021
13	Sol. Radiation, June	1999-2021
14	Sol. Radiation, July	1999-2021
15	Precipitation January	1999-2021
16	Precipitation February	1999-2021
17	Precipitation March	1999-2021
18	Precipitation April	1999-2021
19	Precipitation May	1999-2021
20	Precipitation June	1999-2021
21	Precipitation July	1999-2021
22	Precipitation August	1999-2021
23	Precipitation l September	1999-2021
24	Precipitation October	1999-2021
25	Precipitation November	1999-2021
26	Precipitation December	1999-2021
27	Minimum temperature January	1999-2021
28	Minimum temperature February	1999-2021
29	Minimum temperature March	1999-2021
30	Minimum temperature April	1999-2021
31	Minimum temperature May	1999-2021
32	Minimum temperature June	1999-2021
33	Minimum temperature July	1999-2021
34	Minimum temperature August	1999-2021
35	Minimum temperature September	1999-2021
36	Minimum temperature October	1999-2021
37	Minimum temperature November	1999-2021
38	Minimum temperature December	1999-2021
39	Maximum temperature January	1999-2021
40	Maximum temperature February	1999-2021
41	Maximum temperature March	1999-2021
42	Maximum temperature April	1999-2021
43	Maximum temperature May	1999-2021
44	Maximum temperature June	1999-2021
45	Maximum temperature July	1999-2021
46	Maximum temperature August	1999-2021
47	Maximum temperature September	1999-2021
48	Maximum temperature October	1999-2021
49	Maximum temperature November	1999-2021
50	Maximum temperature December	1999-2021

Figure 1 presents the percentages and contributions of the key inputs to the ecological niche modeling (ENM) of non-gregarious locust pests. As can be seen from the data, the most frequently used (24% out of 100% each) inputs for ENM modeling were Downfall , temperature minima and temperature maxima from 1999 to 2021. This is explained by the fact that these factors are the main ones in the study of bio-ecological features of pests [39].

As secondary factors, PDSI and Solar Radiation (each 12% of 100%) were taken for the February-July months of 1999-2021. The Drought Severity Index was added in a given study year. Since, a pattern was found between years with SCC. The PDSI (Drought Severity Index) developed in the 1960s as one of the first attempts to define droughts using more than just Precipitation data.

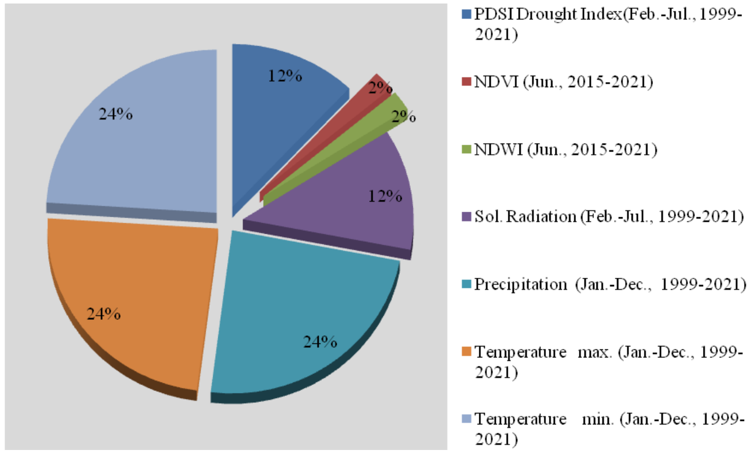

Fig. 1. Percentages and contributions between key input parameters (data input) for ecological niche modelling (ENM) of non-gregarious locust pests, 1999-2021.

Calculated using monthly temperature and Downfall data as well as information on soil moisture holding capacity. Accounts for moisture received (Downfall) as well as moisture stored in the soil, taking into account potential moisture loss due to temperature effects. For many years, PDSI was the only valid drought index, and it is still very popular around the world. According to scientists [32], [34] they also have some influence on the development and cycling of the pests studied.

The minor position is occupied by NDVI and NDWI for June, 2015-2021. These indices are also important [14]-[15], as the vegetation index and plant abundance respectively for the month of June.

The June was chosen because the larval stage of the major non-gregarious locust species occurs in this month in the regions of Northern Kazakhstan and all control measures should be carried out before the locusts fledge [7]-[8], [12].

In addition, land cover layer data processed by Copernicus from the GEE service were downloaded (Figure 4). Land cover data are presented for the period 1999-2021 across the globe, derived from the PROBA-V time series with a spatial resolution of 100 m.

The land cover layers are a very important criterion in establishing the preferred habitat for the non-gregarious locust pests because these data show the vegetation, which is the prey base for the surveyed pests.

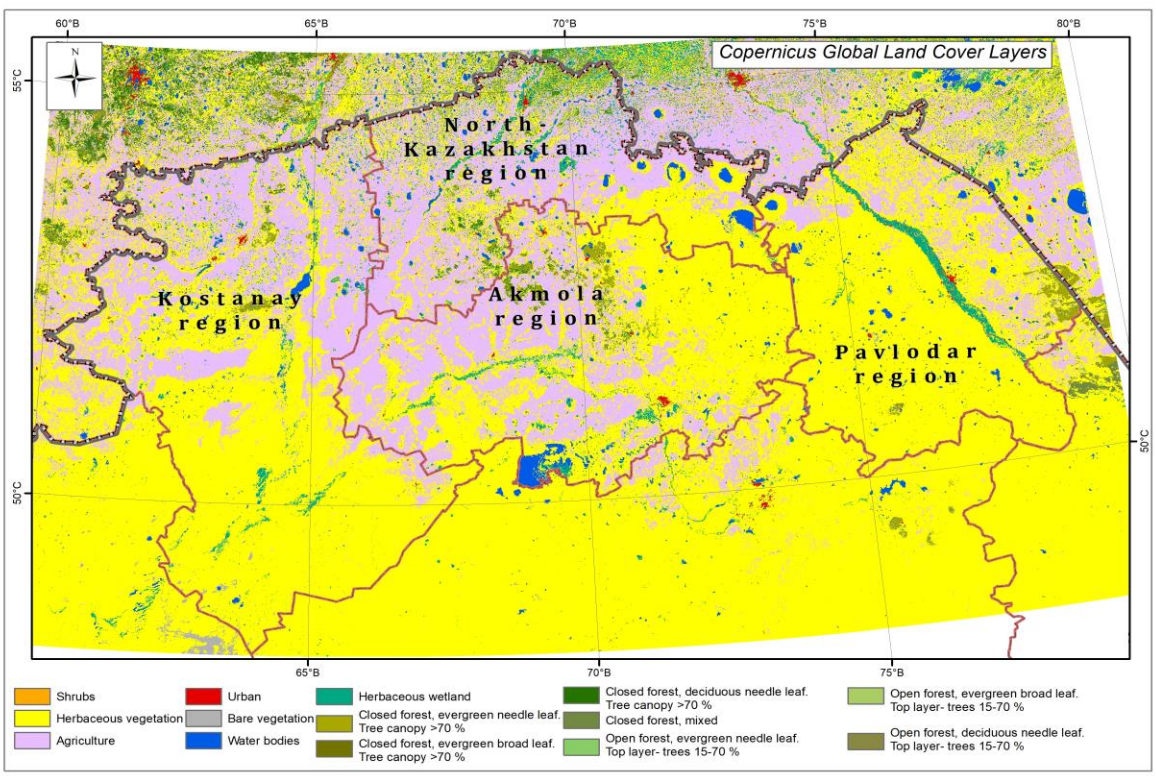

Fig. 2. Layers of the Earth cover according to Copernicus, 2021.

As can be seen from the data, the selected areas are mostly represented by grassy vegetation and arable land which is a very suitable habitat for locust pests.The baseline database of high-quality land cover plots and several auxiliary datasets achieves an accuracy of 80% (Copernicus Global Land Cover Layers: CGLS-LC100 collection). Figure 2 shows the classes of the study area.

Land cover layers are a very important criterion in determining the preferred habitat for the non-gregarious locust pests because this data indicates the vegetation which is the foraging ground for the surveyed pests. As can be seen from the data, the selected study areas are mostly represented by grassy vegetation and arable land, which is a very favorable habitat for locust pests. These criteria were subsequently incorporated into the ecological niche modeling of the surveyed pests by comparing the vegetation cover with a ready-made model of pest preference.

B. Ecological modelling of non-gregarious locusts' niches using remote sensing techniques.

The maximum entropy method, is an SDM specifically designed for cases in which points of presence of a species are known, but no exact data on its absence in a certain area are available.

The Ecological Niche Model (ENM) is performed in much the same way as the SDM, but includes an extended set of factors [37]-[38].

The inputs to the model were randomly generated point coordinates based on ground survey reports for the study areas. We ranked (from 1 to 6) the districts of the regions based on the area reports of non-gregarious locusts' larval infestations [40]. Based on the ranking of the districts, points were randomly generated for model training.

The model was run with the basic settings (Figure 5). The optimal model is selected in steps, with the number of steps (maximum iterations) set to 500 by default. This value is most often appropriate only for simple models or for estimation analysis. For complex models with many factors, it is necessary to increase the number of steps.

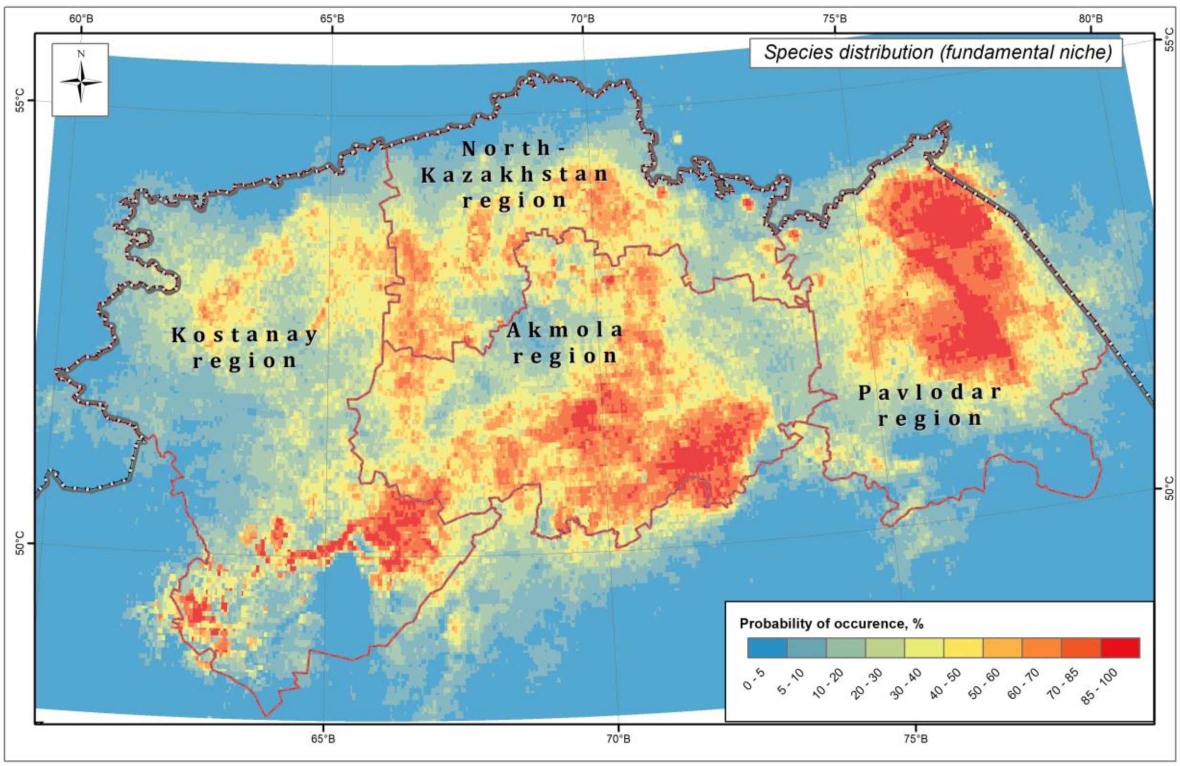

Fig. 3. Modelling result: Fundamental niche of the non-gregarious locust pest's infestation, 2021.

In our study, the number of steps was set to 5000. Also, a cumulative result was established, which is most useful for finding species distribution boundaries. This type of result is proportional to the probability that the species is present, subject to a number of additional conditions.

Figure 3 presents the implemented niche obtained as a result of the modeling exercise. In the second year of the study, the simulations of the ecological niches of the non-gregarious locusts under investigation were performed in order to forecast their distribution based on GIS-technology, using MaxEnt software; in particular, the mechanistic model (ENM-fundamental niche model) was implemented. In the current year 2021, the number of climatic factors was increased in this work, which made it possible to carry out mechanistic modelling of the fundamental niche. The inputs were considered for all areas and the inputs were taken from 1999-2021.

During the modeling of the ecological niches of the non-gregarious locust pests, the following class boundaries were defined for the transition from quantitative to qualitative indices:

- I (85-100%) - zone of very high pest settlement probability;
- II (70-85%) - zone of high pest settlement probability;

- III (50-70%) - zone of medium pest settlement probability;
- IV (0-50%) - zone of pest settlement probability.

In terms of phytosanitary security, we are interested in the first two zones (I and II), as the remaining zones pose no risk to agricultural areas.

According to the running ENM model (Figure 3), high infestation rates are found in the central and northern parts of the Pavlodar region. Here, the ecological niche modeling for the majority of the area yields a 1:1 probability of infestation for the non-gregarious locusts of zones I and II (zones equal) in a slightly arid, moderately warm agroclimatic zone.

In the southern part of the Kostanay region, the ENM model predicts for the most part a 1:2 probability of infestation of zones I and II (zone II is dominant) in the moderately arid and warm agroclimatic zone of the region. In the southern and south-eastern part of Akmola region, the model predicts a 1:3 probability of settling zone I and zone II (zone II is super-dominated) in the slightly humid, moderately warm agro-climatic zone of the oblast. Zone I and II are not observed in North-Kazakhstan oblast. Therefore, the region could be considered one of the least prone to infestations by non-gregarious locust pests.

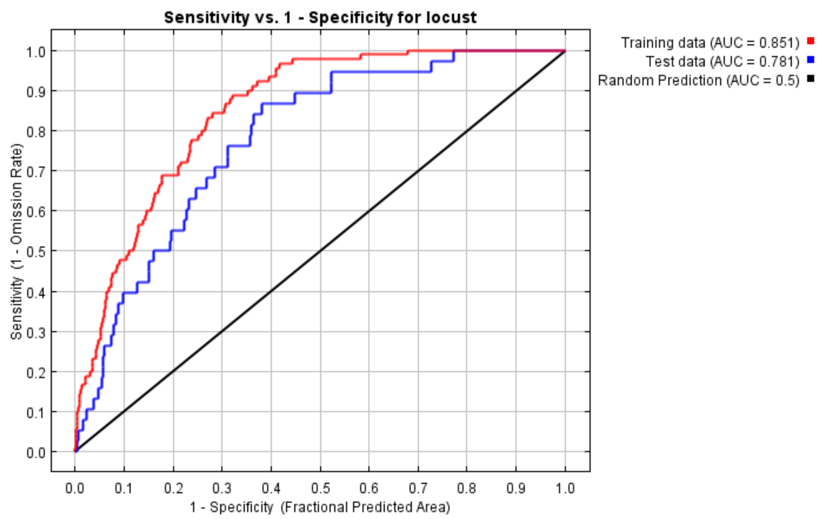

Fig. 4. ROC-curve of errors in mechanistic model validation (ENM)

The basic measure of model quality in MaxEnt is the area under the ROC curve (AUC) (Figure 4). This predictive ability measure is interpreted as the probability that randomly selected coordinates are predicted better than randomly selected background coordinates. Based on the AUC value, modelling quality can be roughly divided into five categories [38]: 0.9-1 is 'excellent', 0.8-0.9 is 'good', 0.7-0.8 is 'fair', 0.6-0.7 is 'poor' and <0.6 is 'very poor' (modelling failed). Figure 3, shows the error curve from the simulation. AUC= 0.851. Thus, the resulting mechanistic model for ecological niche modelling is satisfactory (adequate).

IV. Conclusion

In line with current trends in science and technology, the use of innovative technologies in phytosanitary monitoring and forecasting is driving global research in plant protection and quarantine. With the application of innovative technologies, such as GIS and remote sensing technologies, an exceptional opportunity opens up for precise identification of pest species outbreaks, rapid data transfer, and correct and effective crop protection decisions. The proposed ecological niche modelling (ENM) approach to non-gregarious locusts is one of the innovative approaches in predicting crop pest development and distribution. Because with the help of this approach, the preferred locations and the potential distribution zones of locust pests can be established, especially in the Northern part of Kazakhstan where the economically important crops and agricultural lands are located. Further, the validation and verification studies of the running ecological niche model on non-gregarious locust pests are in progress and the results will be published in one of the scientific publications.

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- from 2009 to the present, he has been the responsible executor of the contractual topic 41X "Registration and production tests of pesticides (insecticides) on the territory of the Republic of Kazakhstan".

- executor of the scientific and technical program of the Ministry of Agriculture of the Republic of Kazakhstan "Transfer and adaptation of technologies for point agriculture in the production of crop production on the principle of "demonstration farms" (landfills) in the North Kazakhstan region" for the 2018-2020 years as part of the research group on the direction "Plant Protection".

- executor of the scientific and technical program of the Ministry of Agriculture of the Republic of Kazakhstan "Development and improvement of integrated pest management for fruit, vegetable, grain, fodder, legumes and quarantine plants", for the 2021-2023 years.

Mr. Baibussenov had the following internship courses and awards

- In 2016, completed a scientific internship on integrated plant protection system (IPM) at the University of California (Davis, USA).

- In 2018, completed a foreign internship at the Indian Institute of Remote Sensing of the Earth on Geoinformstics (Dehradun, India).

- He is the holder of the scientific scholarship of young scientists of the Ministry of Education and Science of the Republic of Kazakhstan for 2020.

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- Transfer and adaptation of technologies on precision farming in crop production according to the principle "Demonstration farms (polygons)" in the North Kazakhstan region (2020). Yield modeling with regression analysis in SPSS;

- ADB consultant National Water Expert—Drone and Remote Sensing Technologies (2020). Surface Energy Balance modelling with UAV data in Erdas;

-FAO consultant Remote Sensing Technologies (2021). Agricultural Drought monitoring using CDI

-Interpretation of high-resolution satellite images of the territory of the green belt of Nur-Sultan using GIS technologies and their correlation with the obtained ground survey data in 2021. Tree species identification using Planet data and random forest classification in Python.

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Mr. Azhbenov, under an agreement with the Ministry of Agriculture of the Republic of Kazakhstan "Services for scientific guidance for selective monitoring surveys during the mating and egg laying of locusts" locust expeditions were carried out in Akmola, Kostanay, Aktobe, Atyrau and West Kazakhstan regions. Пuidelines "Memo to the participant of the locust expedition", "Summary report of monitoring surveys of an expeditionary nature in Akmola, Kostanay, Aktobe, Atyrau and West Kazakhstan regions on locust pests" has been prepared.