LAND-USE FORECASTING USING A BAYESIAN NETWORK

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Abstract. The article proposes a forecasting scenario to be used for improving the quality of land of one of the most developed industrial-agrarian regions of the European Russia – the Tula region. The purpose of the work is land-use forecasting using the Bayesian networks analysis. The networks were built by considering the most significant indicators of both the ecological state and the negative impacts on lands and, in addition, the potential indicators of the improved lands. As a result of the analysis, characteristic high rates of factor loadings were established determining the need for land management. One of the land management measures proposed within the project employed soy cultivation on 5% of the farmlands surface and of pennycress on 5% of the rest of lands for improving the ecological state and decreasing the need for undertaking land management measures from 91% to 83.5%.

Key words. Ecological state; a probabilistic-statistical analysis; environmental measures

1. INTRODUCTION

The Earth's land surface is negatively affected by human activities. As result of rapid pace of development of socio-economic sectors, such as industry, agriculture, logging, construction, the quality of lands as well as their natural recovery functions and chances of a way out from the global environmental crisis have decreased.

Concerns on changes of the ecological state of land have arisen several decades ago. Since no common conclusions on this issue have been reached yet, the problem is still debated within a series of annual world summits and regional forums. The main issue today is to find a solution to avoid the ecological crisis of territories while considering their continuous socio-economic development and increased negative impact (Botequilha and Ahern, 2002; Hong, 1999; Shapovalov *et.al.,* 2018; World Summit on Sustainable Development, 2002). The lack of a unified methodology for establishing the main indicators describing the various factors affecting the lands of different regions has accentuated this crisis.

Recent or former researches have focused on a limited number of indicators, in most of the cases applicable to a certain area (Andrejchik, 2012; Gamm and Kaliev, 2004; Rebane and Pearl, 1988; Vasil'ev, 2013). Despite the fact that the significant indicators on the ecological state of territories are estimated to hundreds, in particular situations, these could be ineffective, because*, i.e.* they do not consider the particular geographical features in the process of management decision. The precautionary principle and restoration of lands for effective and rational use should be taken into account. In this regard, the authors analyzed a number of publications dealing with techniques applied for ecological assessment of lands in relation with the need for management actions. For example, Kasimov *et al.,* 2014, by using ecological and geochemical indicators of ecosystem components, managed to identify the pollution and other impact factors on urban lands. Vershinin *et al.,* 2016; Volkov *et al.,* 2017 identified the factors describing the ecological state and the significant impacts concerning especially the agricultural lands. Methods based on environmental criteria and indicators developed to assess the environmental sustainability of the territories (World Development Indicators) were promoted within the framework of the ideas of the Trinity on development of territories (Beroya-Eitner, 2016; Homyakov, 2016; Kryukov, 2000; Skibarko, 2013).

However, in order to prevent the distortion of final results of the present study, we didn't include any of this data in our own general list of principal factors. For most of the studied territories, there is no information about the regional and geographical features because of lack of monitoring. This fact made everything much more difficult when it came to assess the present state of lands and causes of its change.

The land degradation, culminating with the loss of its restorative functions, continues, while no improvement of ecological status assessment practices have been recorded. One reason seems to be the mankind inability to take advantage of the best knowledge available at the expense of old inefficient practices. The projects in the field of land management should consider not only the past and present state of lands, but also the forecast future state.

Speaking about land management, it should be noted that there is no common international understanding of the term. In Europe (Denmark, Switzerland, France and others) development of land-use plans for environmental purposes is regulated by legislative acts, which justify and sustain the land management actions. In the United States, special state programs are dedicated to rational use and protection of land, so that the environmental measures fall under responsibility of public administration. In Russia, the land-use planning and management of resources are regulated by a large number of legislative documents including the Federal law on "Land Management".

In modern research there are many ways to yield forecast data. The Bayesian network is considered one of the most reliable methods in the world for building predictions (Ivutin and Suslin, 2011; Vieira *et al.,* 2017). In order to visualize graphically the results of the Bayesian method used in our work, the Netica software (Netica Tutorial, 2018), developed at the end of the last century, managed to offer a good representation of the probabilities rendered by our analysis.

A lot of scientific literature (Gieder *et al.,* 2014; Gutierrez *et al.,* 2015; Jiang *et al.,* 2011; Khan *et al.,* 2011) had been consulted before proposing our own algorithm for the Bayesian networks. Since the outcome of the construction of this network depends on the chosen algorithm and the arrangement of links between data blocks, we paid much attention to those already developed (Li *et al.,* 2016; Maslennikov and Sulimov, 2010; Mittal and Kasim, 2007; Stewart *et al.,* 2015).

All known algorithms are based, either on constraints (NPC, PC algorithms), or on evaluation, or on a combination of them (partially based on constraints and random evaluation) (Nodoushan, 2018; Kuznetsova, 2016; Ranganathan *et al.,* 2014; Shin *et al.,* 2016). Some of them when used displayed randomly the links between blocks, the degree of randomness influencing the accuracy of the final result. In the case of choosing an algorithm based on constraints, the probability of correct arrangement of the structure edges of the probabilistic-static model is high. The combined Bayesian network algorithm is based on the expert opinion, hence near 80% of direct relationships between settled variables are *a priori* known.

Tula is one of the Russian Federation regions that has historically experienced a huge number of different negative events that were very little documented in terms of quantitative data recorded. A comprehensive assessment of the ecological state of the lands of the region, taking into account all factors of impact has never been carried out, so by only using the present and forecast data, without taking into account some historical patterns, is not appropriate for modeling purpose. However, from 2016 to 2018 quite a lot of material from various information sources was collected allowing us to conduct a statistical analysis for the region taking into account its natural, geographical and economic characteristics. In this regard, the purpose of this study is to prove the need for a management based on preservation, restoration and sustainable further use of lands of the Tula region, relying on the solutions offered by construction of Bayesian networks.

2. STUDY AREA

The European side of Russian Federation located in its Western part represents about 1/5 of whole country covering an area of more than 3.5 million km^2. About 80% of the population is concentrated here. The lands of the administrative regions of this territory have been experiencing huge natural and anthropogenic environmental disturbance for a long time. Agriculture and industry, mining, thick transport network have been identified among the main environmental problems.

The Tula region is located in the Central part of the European part of the country. It is bordered by Moscow, Ryazan, Lipetsk, Orel and Kaluga regions in the North, East, South and South-West and West, respectively. It is one of the most economically developed region but also one of the most polluted from the Russian Federation. The challenge posed was to integrate all areas of the Tula region, as each of them includes more than 2 negative factors of impact on land. For example, the most polluted areas are Aleksinsky, Suvorovsky, Leninsky, Novomoskovsky, Uzlovsky and Shchekinsky districts. In all of them the land used for agricultural purposes is subject to periodic enhanced mineralization and fertilization. Every region has also activities related to mining practiced for decades, so the lands in great part are contaminated with radionuclides, inclusively as result of the Chernobyl accident (Novomoskovsky, Uzlovsky, Shchekinsky districts).

3. MATERIALS AND METHODS

3.1. Dataset

Previous studies on the ecological state of agricultural land (Sukhomitskaya, 2017) and complex state of geosystems (Sukhomitskaya, 2018) of the Tula region showed that all lands have experienced negative effects to varying degrees. However, those studies did not include all possible environmental impacts and conditions, so the main variables might have not been identified. In this study, the authors supplemented the list of indicators by analyzing various state databases and reporting documents, modern cartographic materials and some archival information.

The resulting dataset was divided into two groups. The group of ecological state included the following indicators:

- Percentage of the area subject to radioactive contamination of soils, %.
- Land area with the highest degree of anthropogenic load, ha.
- Percentage of area of reclaimed land in bad state relative to the total area of reclaimed land, %.
- Coefficient of soil fertility.
- The coefficient of the relative tension.
- Anthropogenic load factor.

The group of negative natural and anthropogenic impact factors was supplemented by the following indicators:

- Area of the other land category, ha.
- Land area used by industry and for other special purposes, ha.
- Area of agricultural land, ha.
- Land area of settlements.
- The number of waste objects in the State Register.
- Number of licensed subsoil plots.
- Number of enterprises in 2016 year.
- Number of enterprises in 2018 year.
- Density of roads km / 1000 km^2.
- Number of potentially hazardous industrial facilities.
- Number of car washes.
- Water equivalence of snow cover, mm (calculated by the authors according to the generally accepted formula: *Water equivalence of snow cover* = $10 \times h \times P$ where: 10 – conversion factor in mm; h – snow depth, cm; P – the density of snow kg / m^3).
- Coefficients of humidity per year, for the active period of snowmelt and, for the vegetation season.
- Altitude difference.
- Density of the river network of the district, km / km^2.
- River length, km.
- The coefficient of anthropogenic load.
- Absolute environmental stress.
- Relative environmental stress.

3.2. Probabilistic-statistical model

The choice to create Bayesian networks for carrying out this research has been proved one of the most reliable tool to forecast the need for land management measures in the Tula region. The creation of Bayesian networks embedded only the current and prospective data, because of lack of archival information for the studied lands. The probabilistic model has been performed in 2 steps: the 1st step – selection of statistically significant indicators of factors and the 2nd step – creation of Bayesian networks on the basis of the chosen statistics.

The first step consisted of factor analysis of all indicators in the database using the factor and main components analysis provided by the software Statistica v.8.0.055. The most significant variables were considered those with values of coefficients greater than 0.7. In addition, we made a factor analysis of the districts of the Tula region to determine the weight of each statistical indicator. The characteristics of high factor loads allowed us to select the areas. Visualization of the results was carried out with QGIS software.

The second step – construction of a probabilistic-statistical model. To produce the forecast data, some of the significant indicators calculated by the authors with the Statistica program were selected and further analyzed with the Netica program based on the Bayesian method of a forecast network constructions, as well.

To build the probabilistic model, we took into consideration both the expert judgement method to set a priori dependence and arrangement of the direction of the edges of the structure of Bayesian networks by 80% and the statistically significant relationships between variables. Given that the cause -effect relationship is already known, the links between them were done based on the values of established correlation dependences. In addition, we ought to choose one of the possible negative scenarios of development in order to demonstrate how by changing it in some points with addition of possible projected data, it made possible the assessment of the feasibility of planned land management actions.

Theoretically, by adopting the option of planting soybeans and pennycress in these areas, we expect to reduce the need for land management. In this setting, the lower the reduction of percentage of the need for measures the less effective their implementation will be and vice versa.

4. RESULTS

4.1. Data factor analysis

The matrix of eigenvalues shows the squared loadings for the factors (eigenvalues), the percentage of total variance accounted for by each factor, the cumulative eigenvalues and the cumulative percentage of variance. The results of factor analysis evinced two principal factors accounting for more than 10% total variance each, which explained most of the variability observed in the state variables of the Tula region's lands (Fig. 1).

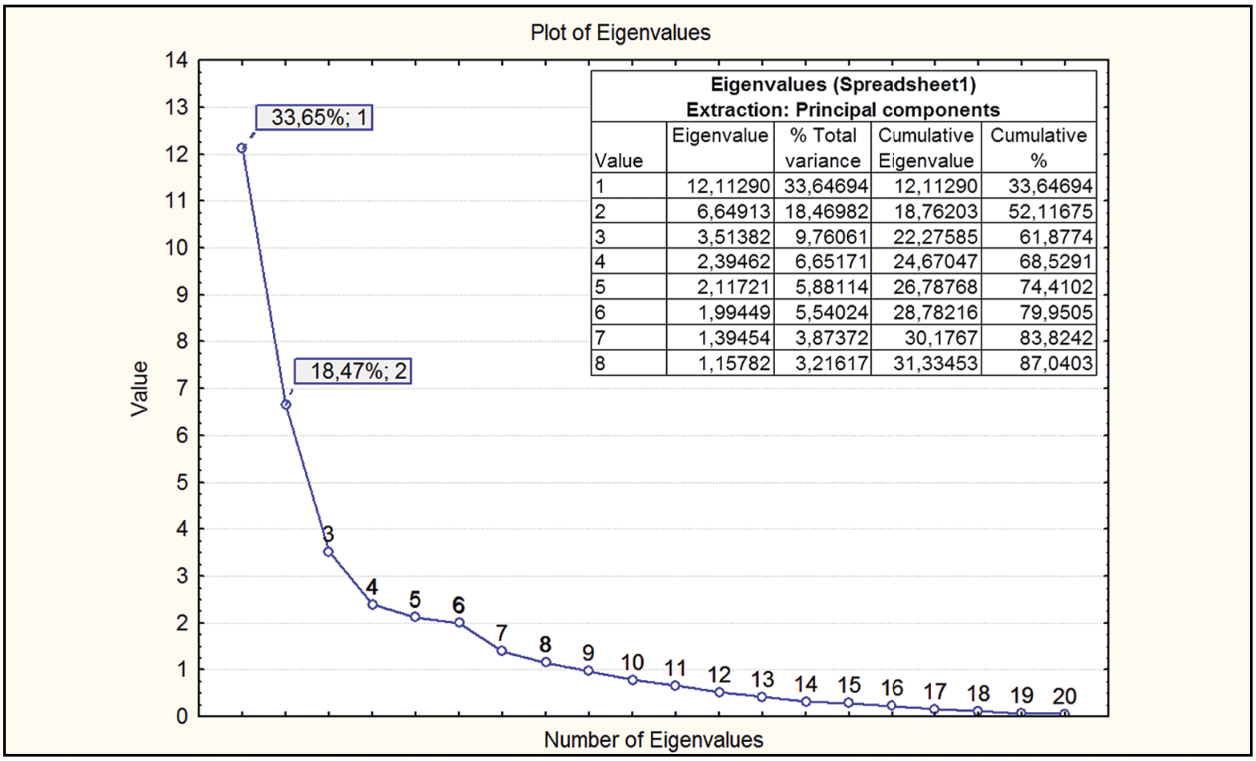

Fig. 1. The graph of scree plot of eigenvalues

Table 1. The results of the factor analysis

Factor Loadings (Unrotated) (Spreadsheet1) Extraction: Main components (Marked loadings are > 0.700000)		
Indicators	**Factor 1**	**Factor 2**
Air pollution from stationary and mobile sources, thousand tons	**0.79300**	0.124774
Coefficient of soil, in populated areas, contaminated by chemical elements	**0.79170**	0.010748
Soil susceptibility to erosion, % of the district	**0.724329**	-0.00593
S of the land with the highest degree of anthropogenic disturbance, ha	**0.95577**	-0.141689
Soil fertility rate	**-0.808603**	-0.09804
The coefficient of the relative tension	**-0.818745**	-0.35790
Population density	**0.93046**	-0.259269
Anthropogenic load factor	**0.83206**	-0.335843
S of usage of other land, ha	-0.006303	**0.86219**
S of industrial and other special purpose land, ha	-0.096881	**0.93718**
S land settlements	-0.102341	**0.88569**
Number of enterprises 2006	-0.087853	**0.94641**
Number of enterprises 2018	-0.101822	**0.94976**
Number of potentially dangerous objects	-0.211129	**0.86420**
Road density, km / 1000 km^2	0.047375	**0.78518**
Number of car washes	0.028845	**0,91769**
Share of cultivated area of total arable land, %	-0.32092	**-0.853129**

Interpretation of the obtained two factors, containing significant variables for analysis (R higher than 0.7), allowed to determine 2 groups of aggregated indicators (Table 1). The first group (Factor 1 – ecological condition) represents a set of indicators characterizing the ecological condition of lands, such as: contamination of land and air, soil fertility rate, susceptibility to land erosion, a high degree of anthropogenic pressure. The second group (Factor 2 – impact) includes a set of indicators of impact on land: population, industry, land use, vehicles, coefficient of relative tension, and the share of cultivated area of arable land. Thus, the indicators were divided between the two factors: Factor 1 – State; Factor 2 – Impact.

Interpretation of factor loads shows that the Factor 1 is a combination of the state indicators (high anthropogenic load factor, population density). Factor 2 refers to the group of impact indicators (the area of lands with negative impact, the ratio of relative tension). Further, the values of the total impact of each group in the context of all districts of the Tula region, based on the correlation indicators, were analyzed.

The results of this analysis and some indicators of the ecological status of the land are shown in figure 2. So, the highest total value (more than 1) of degradation of non-agricultural lands belongs to Aleksinsky, Suvorovsky, Shchekinsky, Leninsky, Novomoskovsky and Uzlovsky industrial areas. The highest total value of degradation of agricultural land is typical for Yasnogorsky, Zaoksky, Belevsky, Venevsky, Odoevsky, Dubensky, Chernsky, Aleksinsky, Suvorovsky areas.

Indicators of state and negative factors of impacts on the lands of Aleksinsky and Suvorovsky areas of the Tula region had the greatest weight of the total load in the two groups. In these areas, there are vast territories subjected to water and wind erosion, the highest degree of anthropogenic load, less fertile agricultural land, heavily contaminated soils with heavy metals.

4.2. Probability analysis of the statistical data

Correlation links and coefficients for all 23 areas were visualized graphically in the Bayesian network (Fig. 3).

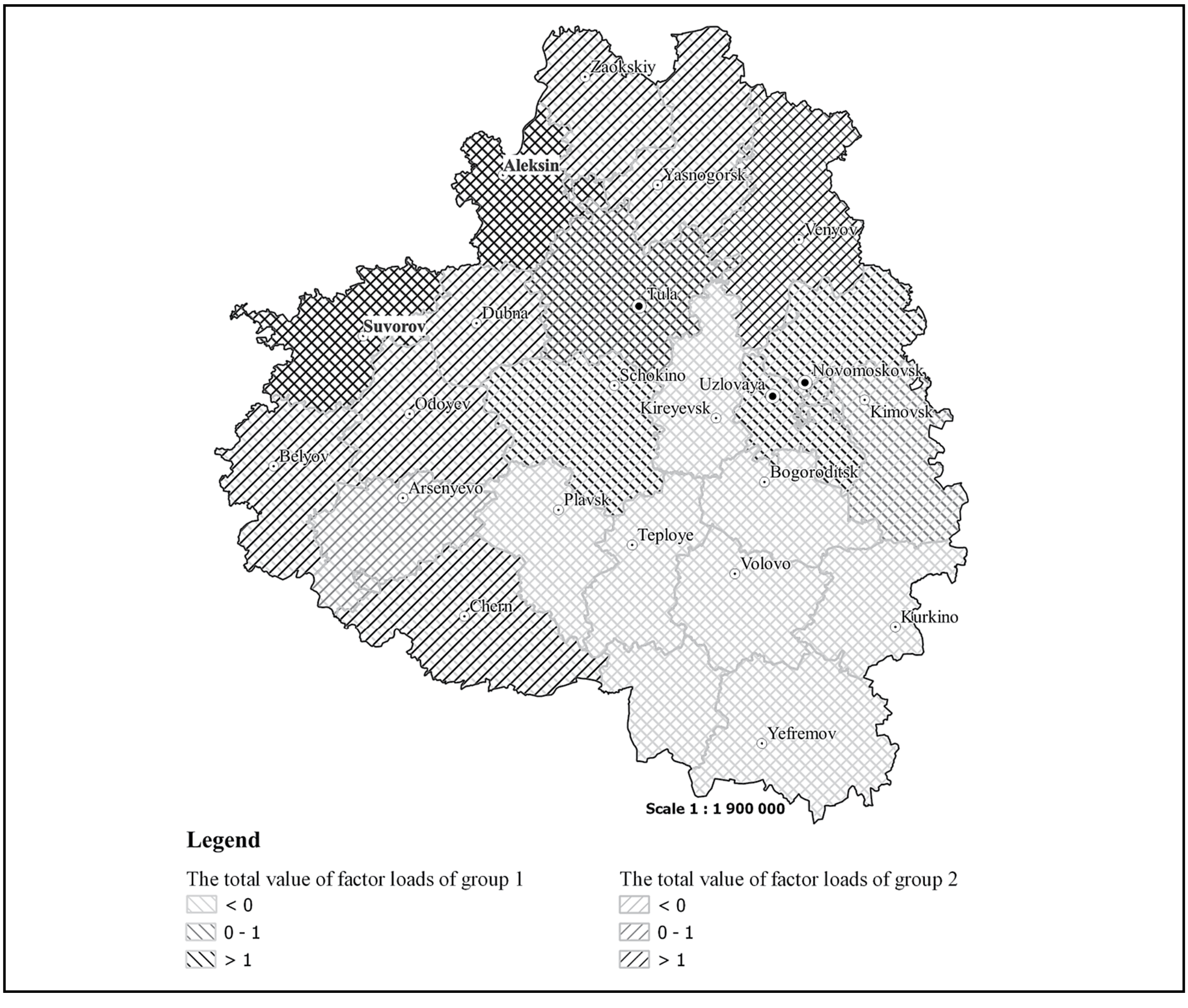

Fig. 2. The total value of factor loads for the Tula region's areas

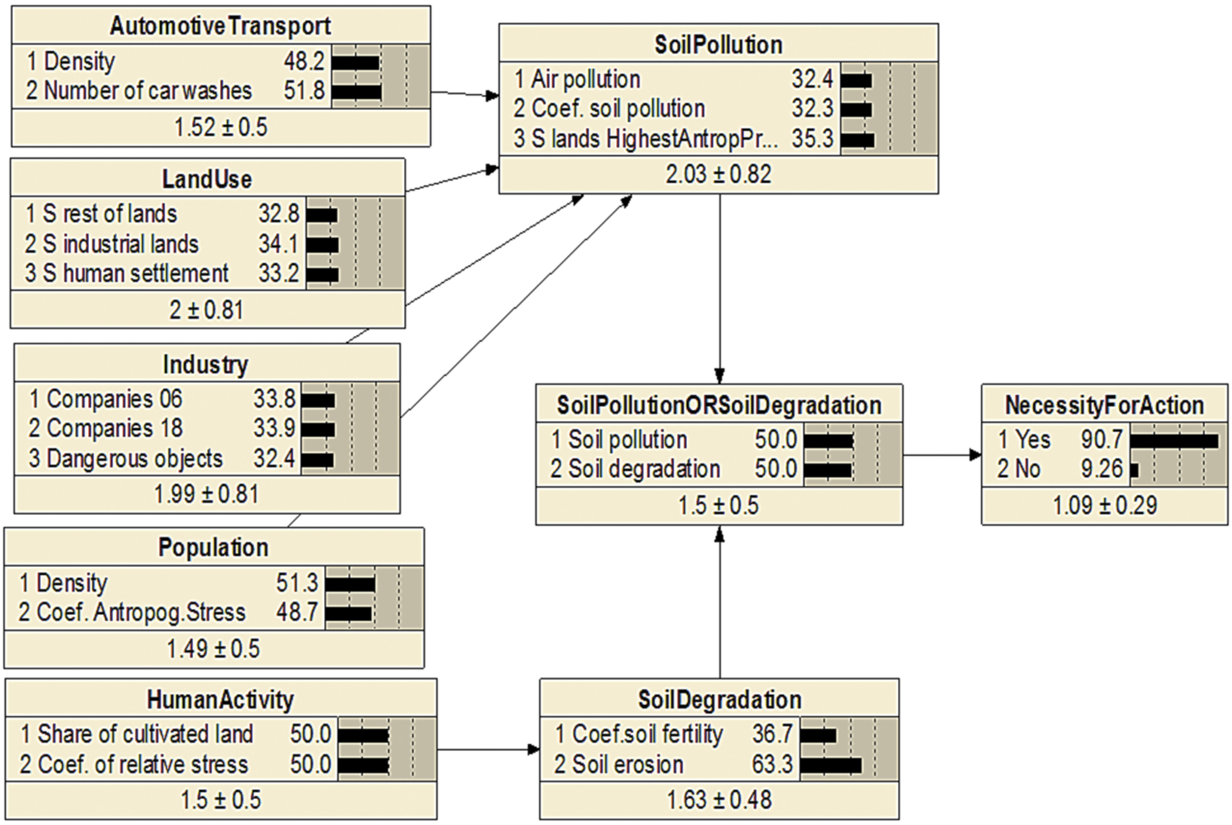

Fig. 3. Forecast of the need for environmental measures exemplified by the Bayesian network, applied for 23 areas of the Tula region

Given the fact that meaningful relationship were established between the indicators of bad state and the negative impacts on land areas of the Tula region, for further analysis, one of the negative scenarios was selected. According to available data the need for land management measures in the presence of all significant negative factors of the state and impacts was 91%.

The estimated probabilities concerning the need for undertaking environmental measures for the Aleksinsky and Suvorovsky areas in the context of two scenarios: application and not application of measures, are presented (Figs 4a and 4b). Given the characteristics of the land conditions of the considered areas (relatively low coefficients of soil fertility and relatively high rates of soil contamination in settlements), it showed that the need to adopt measures in relation to degraded land amounted to 92%.

To reduce the degradation of agricultural soils a variety of different technologies going from special methods of tillage to planting certain crops that would improve the fertility of the land, need to be used. Planting soybeans is one of these technologies, which helps at restoration of agrophysical properties of soils. When using 5% of the farm field for a while to cultivate white soybeans adapted to given climatic conditions, the probability of need for land management measures for these areas will be reduced by 7. 5%.

Figures 4c and 4d show similar trends in reducing probabilities for the same areas, but with different features of the ecological state of the land (soil pollution coefficients and the area subject to erosion). Under these settings, the necessity of application environmental protection measures against the contaminated soil, amounted to 83.7%.

The proposed algorithm for building the Bayesian networks is based on the statistical analysis of indicators. The results of built Bayesian networks that justify the land management necessity confirm the findings of similar studies (Gamm and Kaliev, 2004; Li *et al.,* 2016; Ranganathan *et al.,* 2014; Vershinin *et al.,* 2016). In addition to the reviewed papers, the article brings a significant and original contribution to global knowledge of the Bayesian networks. Namely, the results of the current study demonstrate that Bayesian models can be used to make predictions by using a reliable structure, without necessarily taking into account any temporal data.

The pollution of lands in industrial areas is the result of past and present activities of enterprises, population, vehicles, irrational use of land. It can be combated by grassing or by cultivation of these lands with different types of vegetation. For example, pennycress – is one of these plants, which cleanses the soil of harmful chemical elements, in particular of heavy metals. Annual planting can have a positive impact

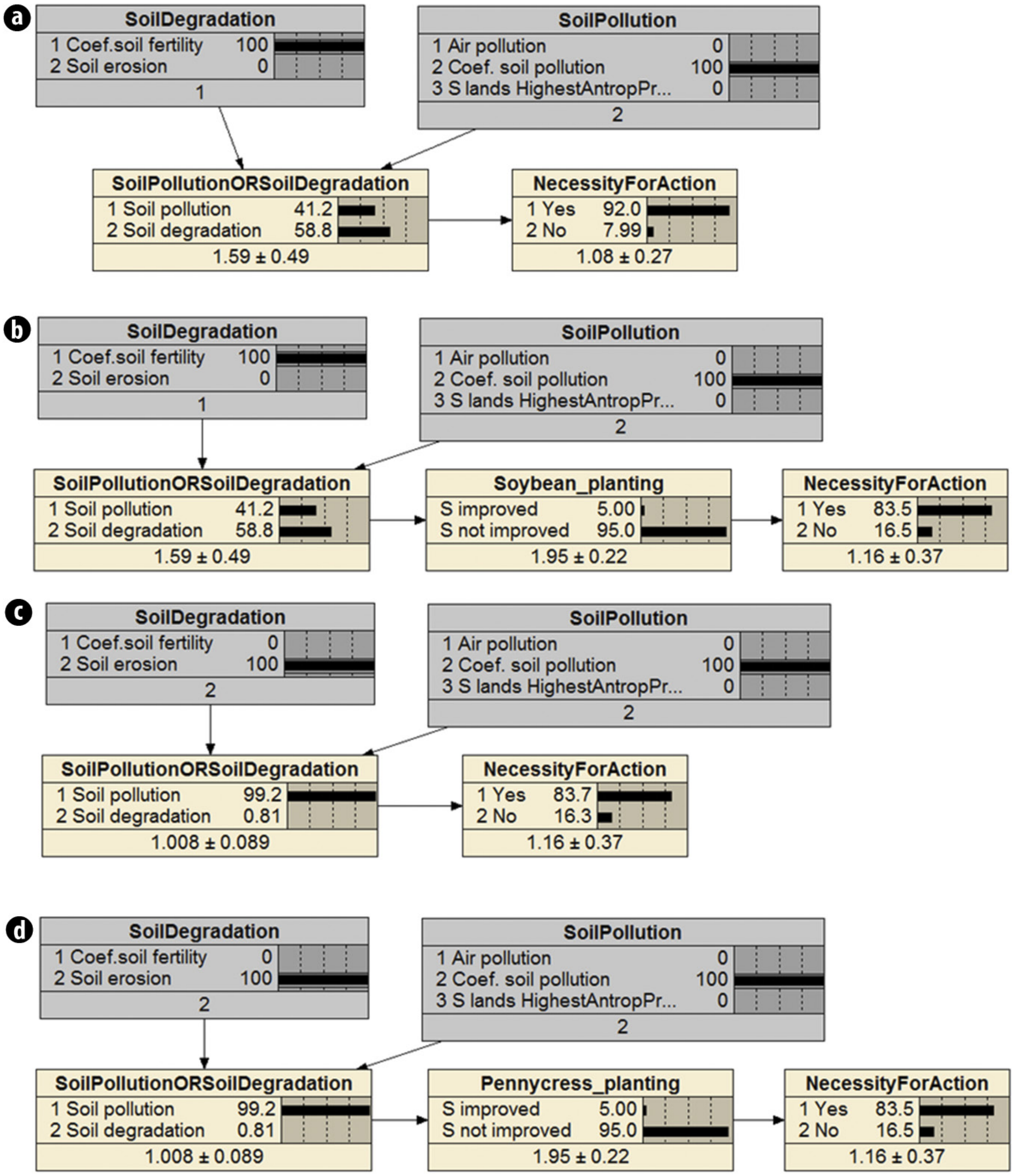

Fig. 4. Forecast of the need for environmental measures using the Bayesian network applied to Aleksinsky and Suvorovsky areas (**a**, **c**) without land management measures; (**b**, **d**) with land management measures; (**a**, **b**) towards the degradation of agricultural lands; (**c**, **d**) non-agricultural lands.

on the geochemical properties of the soils of Aleksinsky and Suvorovsky districts. If during a year round, the pennycress would be cultivated on 5% of the land area of settlements located close to roads, industrial enterprises and other sources of negative impact on the environment, the probability of need for undertaking environmental measures will be of 83.5%.

The accurate forecast of the Bayesian networks (Fig. 5) is based on correctly defined positive and negative answers (more than 80). Out of 1728 observations, only 161 of the first network were classified wrong. In comparison, in the second one, only 23 of 288 observations were mistaken. The third reported only 569 from 3456, the fourth network found out 47 of 288 and the fifth were only 95 of 576.

a
```
Read 1728 cases, and used 1728 of them to test net.

For NecessityForAction:
----------------------

Confusion:
 ...Predicted..
 1 Yes   2 No   Actual
 ------  ------  ------
    91      0   1 Yes
     9      0   2 No

Error rate = 9.257%
```

b
```
Read 288 cases, and used 288 of them to test net.

For NecessityForAction:
----------------------

Confusion:
 ...Predicted..
 1 Yes   2 No   Actual
 ------  ------  ------
    92      0   1 Yes
     8      0   2 No

Error rate = 7.993%
```

c
```
Read 3456 cases, and used 3456 of them to test net.

For NecessityForAction:
----------------------

Confusion:
 ...Predicted..
 1 Yes   2 No   Actual
 ------  ------  ------
    84      0   1 Yes
    16      0   2 No

Error rate = 16.46%
```

d
```
Read 288 cases, and used 288 of them to test net.

For NecessityForAction:
----------------------

Confusion:
 ...Predicted..
 1 Yes   2 No   Actual
 ------  ------  ------
    84      0   1 Yes
    16      0   2 No

Error rate = 16.34%
```

e
```
Read 576 cases, and used 576 of them to test net.

For NecessityForAction:
----------------------

Confusion:
 ...Predicted..
 1 Yes   2 No   Actual
 ------  ------  ------
    84      0   1 Yes
    16      0   2 No

Error rate = 16.46%
```

Fig. 5. Error rate for the target hub "Need for action" for 5 Bayesian networks

5. DISCUSSIONS

The expanded list of indicators on ecological condition of the lands in Tula region and of factors influencing them as resulted from the previous works allowed us to analyze as many as possible of the available factor loadings characterizing these lands. However, this does not allow us to say that the significant variables identified in the statistical analysis are constant, because the addition of other initial indicators can change the set of significant variables and the final result of the probabilistic analysis.

The results of the statistical test for the target "need for environmental measures" partially confirm the results obtained by the international practices for improving the quality of land (Yulnafatmawita *et al.,* 2017). The cultivation of white soybean on the arable lands of Aleksinsky and Suvorovsky districts will lead to increases of agricultural land fertility and to decreasing of the need for taking measures from 92% to 83.5 %.

Pennycress planting nearby the settlements will lead to a reduction in chemical contamination of the land. However, the need for land management measures would be reduced by only 0.2%. Therefore, only by accompanying this measure with other measures would make sense its application to the considered areas.

It should be noted that the constructed models of Bayesian networks for forecasting the land management options revealed the expected changes only after statistical analysis of data. However, in comparison with other researches, our results cannot be considered 100% reliable. For example, the quality of the forecast of one of the studied works (Plant, 2016) has been checked against to and improved by considering the dynamics of certain processes documented in available archival data. The latter were also analyzed by creation of Bayesian networks. Similar work could not be carried out in the current research because of lack of such data on Tula region.

Thus, the proposed method allows us to use forecasting to predict the necessity of undertaking measures to improve the land management in Tula region. However, there is no practical proof of its correctness or applicability since no field studies have been conducted in these areas to identify the changes in the characteristics of the lands. The lack of historical data makes impossible a hindcast prediction in order to further verify the need for land management measures. The lack of indicators of environmental sustainability of the territories also does not allow forecasting of possible sustainable development of the territories. Nevertheless, the use of this technique on the basis of statistical and probabilistic analysis of modern indicators can be used to develop certain recommendations for the protection of land.

6. CONCLUSIONS

The research allowed substantiating the development of recommendations aimed at improving the ecological status of agricultural and non-agricultural lands of the Tula region. By planting soybean and pennycress as proposed within this study, as a land management good practice, the probabilistic forecast showed a potential reduction of surface of degraded areas.

The method developed by authors can be applied in similar researches, in the field of public administration and protection of lands anywhere in the world where lands are subject to degradation. A part of the study can be also used to determine key indicators of various factors and to identify territories with characteristic large weight of factorial loadings.

Besides, the results of the statistical analysis of indicators representing negative factors of influence and the ecological state of lands can be included among the control indicators used in monitoring of lands for comprehensive assessment of their ecological state.

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