Modeling of effective soil fertility using remote sensing methods of agrocenoses

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Abstract. The presence of statistical relationships between productivity and soil properties allows one to assess soil fertility on a mathematical and statistical basis. To do this, it is necessary to substantiate a set of estimated soil properties and mathematically describe their cumulative effect on the yield. Known traditional methods of establishing relationships between soil properties and yield are time-consuming and expensive. It is practically impossible to cover large cultivated areas with these studies. Such work can be effectively performed using the means and methods of remote sensing, using imagery from satellites and unmanned aerial vehicles, which are equipped with multispectral cameras. Modern technologies provide the ability to survey a large area of the territory, uniform rules for recording the spectral characteristics of vegetation, determining the associated vegetation indices.

1. Introduction

The increase in the productivity of agricultural crops is carried out mainly as a result of improving soil fertility, as well as the selection of crops and varieties that are most adapted to the given soil-ecological, natural and climatic conditions. The main areas of research are usually associated with increasing soil fertility, since almost all agrotechnical measures aimed at increasing yields are associated with one way or another (mechanical, chemical, etc.) impact on the soil in order to improve its water-air properties, chemical and physical indicators, biological activity.

The study of soils and soil cover based on remote sensing materials has been carried out for a long time, since the middle of the last century. Modern satellites and satellite imagery technologies make it possible to obtain a picture of the state of agricultural land almost continuously, which made it possible to conduct their weekly monitoring. The disadvantages of satellite imagery associated with the impossibility of obtaining data on cloudy areas are today compensated for by the introduction of unmanned aerial vehicles that fly below the cloud level and therefore are practically independent of adverse weather conditions.

The current state of remote sensing methods for soil cover monitoring is characterized by the development of digital analysis tools, integration with GIS technologies, and the formation of an information field of open data sources. All this makes it possible to integrate information with the development of new criteria and features characterizing the state of the soil cover [1-3].
The formation of an information basis for the tasks of assessing and modeling soil fertility according to remote sensing data will allow a more accurate assessment of soil fertility, create a basis for monitoring and predicting changes in soil fertility, will contribute to the development of appropriate organizational and technical measures, the tasks of digitalization of agriculture at the regional level.

2. Materials and methods
This work is devoted to interdisciplinary research, combining the methods of geographic information systems and remote sensing of the Earth, on the one hand, and models of effective soil fertility with information-logical analysis, on the other.

Considerable attention was paid to the design and development, filling of geospatial databases with soil characteristics and data of remote sensing of territories. An example of a web interface for this kind of information is presented in figure 1. A fragment of a digital model of the Minino agricultural experimental production facility is shown here. The corresponding digital model contains relevant information about the agricultural fields, varieties, crops, soil, and particle size distribution, soil-forming rocks, conditions of occurrence on the terrain, selected multispectral satellite images. A series of technological digital maps on humus content, granulometric composition, pH, availability of mobile phosphorus, potassium, trace elements, crop rotation and cultivated crops has been prepared [4].

![Digital model](image)

**Figure 1.** Sample of agricultural system digital model user interface.

The main attention in this work was paid to soil fertility. Soil fertility is not the only factor in the yield; in addition to it, biological characteristics of plants, climate, agricultural technology, etc., affect the yield of crops. However, other things being equal, it will determine the productivity of crops.

The question of the thickness of the selected soil layer remains relevant for assessing fertility. The analysis of the characteristics of distributions and correlations between the properties of soils in the 0-20 and 20-40 cm layers and the crop yield showed the decisive role of the arable horizon for its fertility.
Therefore, for the mathematical modeling of productivity by soil properties, a layer of 0-20 cm was chosen.

3. Results and discussion
The results were obtained reflecting the properties of soils, characteristics of distributions (table 1). The calculations were carried out for a combined sample, including coupled sampling of soils and plants on gray forest and sod-podzolic soils. The results show that under the studied conditions, the range of values of wheat yield and soil properties is significant. This is explained by the significant diversity of the studied properties in space, micro- and mesorelief, which determines the heterogeneity of the distribution of nutrients, particle size distribution, and conditions of agrocenosis moistening.

| Table 1. Statistical parameters of soils (gray forest and sod-podzolic). |
|-----------------|----|----|----|-----------------|----|----|-----------------|----|
| Features        | n  | Avg.| Min.| Max.| Std. deviation | Kurtosis | Std. deviation | Skewness std. deviation |
| Yields, quintal/ha | 165 | 15.6| 4.3 | 27.7 | 4.83 | -0.11 | 0.38 | 0.20 | 0.19 |
| Humus, %        | 130 | 4.2 | 0.8 | 7.4  | 1.39 | -0.39 | 0.42 | 0.35 | 0.21 |
| Thickness, cm   | 165 | 32.2| 16.0| 69.0 | 7.04 | 3.50  | 0.38 | 1.06 | 0.19 |
| P2O5 mg/100g    | 165 | 7.1 | 1.0 | 20.0 | 3.61 | 0.73  | 0.38 | 0.36 | 0.19 |
| K2O 100g        | 165 | 10.9| 4.8 | 25.6 | 3.68 | 1.46  | 0.38 | 1.04 | 0.19 |
| pH              | 165 | 5.0 | 3.8 | 6.7  | 0.55 | 0.37  | 0.38 | 0.70 | 0.19 |
| S mg/100g       | 165 | 24.7| 6.7 | 47.6 | 9.13 | -0.51 | 0.38 | -0.30 | 0.19 |
| Hr              | 165 | 4.6 | 0.8 | 9.4  | 1.96 | -0.61 | 0.38 | 0.16 | 0.19 |
| V               | 165 | 83.2| 61.0| 98.0 | 6.97 | 0.04  | 0.38 | -0.09 | 0.19 |
| Physical clay, %| 127 | 36.9| 20.0| 59.7 | 8.48 | -0.24 | 0.43 | 0.36 | 0.22 |

To establish the factors that must be taken into account in the mathematical modeling of the yield by soil properties, correlations were calculated for the indicated samples (table 2). Calculation of paired correlation coefficients between soil properties and between soil properties and productivity revealed mainly the presence of many correlating factors for the studied samples.

| Table 2. Correlation of soil properties and wheat yield (gray forest + sod-podzolic soils). |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | Yields          | Humus           | Thickness       | P2O5            | K2O             | pH              | S               | Hr              | V               |
| Yields          | 1.00            | 0.43*           | 0.53*           | 0.40*           | 0.21            | 0.35*           | 0.72*           | 0.29            | 0.30            | 0.16            |
| Humus           | 0.43*           | 1.00            | 0.54*           | 0.10            | -0.01           | -0.03           | 0.50*           | 0.49*           | -0.08           | -0.18           |
| Thickness       | 0.53*           | 0.54*           | 1.00            | 0.33            | 0.20            | 0.01            | 0.50*           | 0.50*           | 0.06            | -0.26           |
| P2O5            | 0.40*           | 0.10            | 0.33            | 1.00            | 0.70*           | -0.01           | 0.53*           | 0.42            | 0.19            | -0.25           |
| K2O             | 0.21            | -0.01           | 0.20            | 0.70*           | 1.00            | -0.11           | 0.36            | 0.36            | 0.10            | -0.03           |
| pH              | 0.35*           | -0.03           | 0.01            | -0.01           | -0.11           | 1.00            | 0.47*           | -0.57*          | 0.85*           | 0.39            |
| S               | 0.72*           | 0.50*           | 0.51*           | 0.53*           | 0.36            | 0.47*           | 1.00            | 0.23            | 0.66            | 0.54*           |
| Hr              | 0.29            | 0.49*           | 0.50*           | 0.42*           | 0.36            | -0.57*          | 0.23            | 1.00            | -0.51*          | -0.38           |
| V               | 0.30            | -0.07           | 0.06            | 0.19            | 0.10            | 0.85*           | 0.66*           | -0.51*          | 1.00            | 0.49*           |
| Physical Clay   | 0.16            | -0.18           | -0.26           | -0.25           | -0.03           | 0.39            | 0.54*           | -0.38           | 0.49*           | 1.00            |

It was determined that, according to the degree of decrease in the effect on the value of the yield, the properties of the soils are arranged in the following sequence: the sum of absorbed bases, the thickness of the humus horizon, the content of humus, the content of phosphorus, pH.
Taking into account the significant correlation of soil properties, as well as the differences from the normal distribution of some factors (in terms of asymmetry and kurtosis), which is a limitation in the use of correlation-regression analysis, information-logical analysis was used to build models of effective fertility. Its main idea is to calculate the amount of information transmitted by each factor (soil properties) to the phenomenon (yield value), to determine the logical functions of the relationship between factors and the phenomenon and to build on this basis logical models of yield [5, 6].

Modeling was carried out in the following order:

- calculation of communication channels and ranking of factors according to the degree of their decrease per crop;
- determination of specific states of yield through communication channels;
- drawing up a model;
- inverting the file, i.e. replacing the initial data X with specific ranks Y;
- definition of functions by which X interact with each other [7].

In accordance with this procedure, models were compiled and their predictive effect was carried out by comparing the calculated and actual yield for a sample of gray forest soils and for a combined sample of gray forest and soddy-podzolic soils (table 3).

**Table 3. Information-logical models of yield.**

| №   | Models                                      | Recognized, % |
|-----|---------------------------------------------|---------------|
|     |                                             |   Total       |
|     |                                             | including rank to rank |
|     | For gray forest soils of subtaiga            |               |
| 1   | Y=H ∨ (T ∨ (pH ∨ PC))                       | 70            |
| 2   | Y=H ∨ (pH ∨ (T ∨ PC))                       | 72            |
| 3   | Y=H ∨ (pH ∨ (PC))                           | 69            |
| 4   | Y=H ∨ (T ∨ (pH ∨ P))                        | 72            |
| 5   | Y=H ∨ (pH ∨ (PC ∨ T))                       | 72            |
|     | For gray and soddy-podzolic soils of forest-steppe and subtaiga |               |
| 6   | Y=H ∨ (PC ∨ pH)                             | 70            |
| 7   | Y=T ∨ (PC ∨ (H ∨ pH))                       | 71            |
| 8   | Y=S ∨ (T ∨ (PC ∨ (P ∨ (H ∨ pH))))           | 72            |
| 9   | Y=H ∨ (T ∨ (PC ∨ (pH ∨ P)))                 | 62            |
| 10  | Y=H ∨ (pH ∨ (P ∨ K))                        | 68            |
| 11  | Y=T ∨ (pH ∨ (P ∨ K))                        | 63            |
| 12  | Y=H ∨ (PC ∨ (pH ∨ PC))                      | 70            |
| 13  | Y=pH ∨ (P ∨ K)                              | 67            |
| 14  | Y=H ∨ (pH ∨ (T ∨ P))                        | 77            |
| 15  | Y=H ∨ (K ∨ pH)                              | 71            |
| 16  | Y=H ∨ (pH ∨ (T ∨ PC))                       | 70            |
| 17  | Y=H ∨ (T ∨ (pH ∨ PC))                       | 78            |

The models were compiled on the basis of the informativeness of the factors: H – humus, T – the thickness of the humus horizon, S – the sum of absorbed bases, P – the content of mobile phosphorus, K – the content of mobile potassium, pH – acidity, PC – physical clay. These indicators are arranged in the formulas in descending order of impact on the yield.

To assess the level of fertility of gray forest soils, the most acceptable model is

\[ Y=H ∨ (T ∨ (pH ∨ P)) \]
with a predicting effect of 72%. For a combined assessment of the level of fertility of gray forest and soddy-podzolic soils, the most effective models are:

\[ Y = H \lor (T \lor (pH \lor PC)) \quad \text{and} \quad Y = H \lor (pH \lor (T \lor P)). \]

For both samples, they have the greatest predictive effect of about 77-78%. This accuracy is acceptable for soil assessment [6].

Thus, in all models with a high degree of recognition, the first place is occupied by humus, which is logical for the soils of the non-chernozem zone. The thickness of the humus horizon has a high rank, but this is an unregulated or limitedly regulated factor, just like the content of physical clay. The presence of pH and P in the models indicates the possibility of an increase in yield due to a change in acidity and an increase in the content of P2O5 in sod-podzolic and gray forest soils.

4. Conclusions

The use of methods of remote sensing of the Earth will provide an opportunity to carry out work on modeling soil fertility in large areas, which will significantly intensify technological processes in crop production. According to the vegetation index NDVI, it is possible to predict with a sufficiently high accuracy the value of the formed yield, according to which, using the above results and using the NDSI (Normalized Difference Soil Index) soil index, it will be possible to build soil fertility models.

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