Development of a methodology for assessing the parameters of the state of crops and soil environment for crops according to remote sensing of the Earth

I M Mikhailenko and V N Timoshin
Federal State Budgetary Scientific Institution "Agrophysical Research Institute", 14, Grazhdansky Prospect, St. Petersburg, 195220, Russia

E-mail: Ilya.mihailenko@yandex.ru

Abstract. Improving the efficiency of agriculture is impossible without the use of innovative solutions, among which it is necessary to highlight information technology and the use of the capabilities of the digital economy. To the greatest extent, these opportunities are manifested in such a new technological direction as precision farming which has received a new impetus for development in connection with the expanding use of remote sensing of the Earth. However, it should be noted that the use of remote sensing means for more than twenty years has so far had little effect on the effectiveness of precision farming technologies. This is due to the insufficient development of the scientific and methodological base for the use of remote sensing in the monitoring and control of agricultural technologies. Until now, the enormous opportunities of modern remote sensing tools are reduced to the construction and study of various types of vegetation indices, according to which it is impossible to make control decisions in precision farming systems. This problem is especially acute in control systems for the processes of applying mineral fertilizers, which are the main technological operations in crop production. Here, scientific and technological progress concerned only the mechanization of soil sampling at fixed points in the field and subsequent laboratory analysis of the samples. Each sampling point is considered representative for a field plot with an area of 5 to 15 ha. Such a technology for obtaining information is not only very laborious, but also carries big errors in the subsequent justification of fertilizer doses. The aim of this work is the further development of scientific and methodological foundations and software and hardware assessment tools according to remote sensing data of the content of the main nutrients in plants and soil.

1. Introduction
One of the most promising directions for increasing the efficiency of agricultural production management is the use of information systems based on geoinformation technologies and remote sensing of the Earth (ERS). Such systems can solve the following problems:

- information support for decision making;
- planning of agricultural operations;
- monitoring of agricultural operations and the condition of crops;
- forecasting crop yields and estimating losses;
- planning, monitoring and analysis of the use of technology.
During solving these problems, all agricultural operations, the costs of their implementation are recorded, the state of crops is recorded by means of ground measurements, expert estimates of agronomists and remote sensing data (aerial and satellite images).

For monitoring, the data of the agrochemical analysis of soils for each working section of the field are important. They can be obtained in two ways:

- because of our own research using samplers and sample analysis laboratories;
- because of agrochemical surveys carried out by a specialized organization.

The use of remote sensing data in monitoring systems allows you to create electronic field maps in 3D format, as well as calculate the Normalized Difference Vegetation Index (NDVI normalized vegetation index) to efficiently fertilize crops, inventory work and protect farmland.

Today, almost all the work, one way or another related to the use of remote sensing data, is accompanied by the creation of thematic geoinformation projects (creation of thematic GIS) and thematic geoportals. All this contributes to the wide access of agricultural producers, farmers and other persons responsible for making decisions to relevant and reliable data that comprehensively describe aspects of the use of agricultural land. At the same time, the thematic tasks listed above require much more extensive information for their solution, in comparison with NDVI or other similar indexes. In [5,6], an approach based on the classical theory of estimating the parameters of the state of crops and soil environment is presented. To demonstrate its capabilities, a simple model culture was used in the form of perennial herbs used to prepare feed.

The aim of this work is the further development of the estimation methodology for cereals more complex in their morphological structure, and spring wheat sowing is used as an example to test the proposed theory.

2. Methods
As in [1, 2], a two-stage procedure is used to solve the problem of estimating soil state parameters, when at the first stage, according to remote sensing data, the parameters of the state of sowing biomass are first evaluated over the entire growing season, and at the second stage, based on the model of connection with the crop, parameters are estimated the chemical state of the soil. Thus, the construction of monitoring estimates of the parameters of the chemical state of the soil is possible only when modeling all the components of the soil-sowing system. This system includes the following blocks of mathematical models.

Block of optical measurement models:
These models reflect the relationship between the estimated parameters of the state of sowing and soil environment with the reflection parameters on the used optical channels of the Earth remote sensing system.

Optical measurement model (ERS model) of the state of biomass of spring wheat sowing for the period before heading in vector-matrix symbolic form [2,4]

\[ Z_m(y,h) = P_m W(X_m(y,h)) \]

where: \( Z_m^T(y,h) = [z_{1m}(y,h) \ z_{2m}(y,h)] \) - a vector of reflection parameters for the spatial coordinate in the visible range (450-750 nm) \( (z_1) \) and in the near infrared range (750-900 nm) \( (z_2) \) of the optical spectrum;

\[ P = \begin{bmatrix} p_{01} & p_{11} & p_{12} & p_{13} & p_{14} & p_{15} & p_{16} \\ p_{02} & p_{21} & p_{22} & p_{23} & p_{24} & p_{25} & p_{26} \end{bmatrix} \] - matrix of model parameters,

\[ W(X_m(y,h)) = \begin{bmatrix} 1 & x_{1m}(y,h) & x_{2m}(y,h) & x_{1m}^2(y,h) & x_{2m}^2(y,h) & x_{1m}(y,h) & x_{2m}(y,h) \end{bmatrix} \] - vector-function, where the parameters are the parameters of the state of sowing: \( x_{1m} \) - sowing biomass density (crop) for
the spatial coordinate, cwt·ha\(^{-1}\); \(x_{2m}\) — density of the wet mass of the crop for the spatial coordinate cwt·ha\(^{-1}\).

Optical measurement model (ERS model) of the state of spring wheat sowing biomass for the period from the beginning of heading to ripening of the crop in a vector-matrix symbolic form

\[
Z_u(y, h) = P_u W(X_u(y, h)),
\]

where: \(Z_u(y, h) = [z_{1u}(y, h) \quad z_{2u}(y, h) \quad z_{3u}(y, h)]\) - the vector of integrated reflection parameters in the green (500-565 nm) - (\(z_{1m}\)), in red (625-740 nm) - (\(z_{2m}\)), in the near IR (750 - 950 nm) - (\(z_{3m}\)) optical spectrum;

\[
P_u = \begin{bmatrix}
p_{01} & p_{11} & p_{12} & p_{13} & p_{14} & p_{15} & p_{16} & p_{17} & p_{18} & p_{19} 
p_{02} & p_{21} & p_{22} & p_{23} & p_{24} & p_{25} & p_{26} & p_{27} & p_{28} & p_{29} 
p_{03} & p_{31} & p_{32} & p_{33} & p_{34} & p_{35} & p_{36} & p_{37} & p_{38} & p_{39} 
\end{bmatrix}
\]

- matrix of model parameters,

\[
W(X_u(y, h)) = \begin{bmatrix}
1 & x_{1u}(y, h) & x_{2u}(y, h) & x_{3u}(y, h) & x_{1u}^2(y, h) & x_{2u}^2(y, h)
\end{bmatrix}
\]

- vector function, where the

arguments are the parameters of the sowing state for the spatial coordinate (y, h): \(x_{1u}\) is the density of the sowing biomass, cwt·ha\(^{-1}\); \(x_{2u}\) — density of wet sowing mass, cwt·ha\(^{-1}\); \(x_{3u}\) is the mass density of the ears, cwt·ha\(^{-1}\).

A model of optical measurements of the chemical state of crop biomass over the entire vegetation interval in a vector-matrix symbolic form [2,4]

\[
Z_h(y, h) = P_h W(X_h(y, h)),
\]

where: \(Z_h(y, h) = [z_{1h}(y, h) \quad z_{2h}(y, h) \quad z_{3h}(y, h)]\) - vector of integrated reflection parameters in the blue (500-565 nm) - (\(z_{1h}\)), green (625-740 nm) - (\(z_{2h}\)), red (750 - 950 nm) - (\(z_{3h}\)) ranges of the optical spectrum;

\[
P_h = \begin{bmatrix}
p_{10} & p_{11} & p_{12} & p_{13} & p_{14} & p_{15} & p_{16} & p_{17} & p_{18} 
p_{20} & p_{21} & p_{22} & p_{23} & p_{24} & p_{25} & p_{26} & p_{27} & p_{28} 
p_{30} & p_{31} & p_{32} & p_{33} & p_{34} & p_{35} & p_{36} & p_{37} & p_{38} 
\end{bmatrix}
\]

- matrix of model parameters,

\[
W^T(X_h) = \begin{bmatrix}
1 & x_{1h} & x_{2h} & x_{3h} & x_{1h}^2 & x_{2h}^2 & x_{3h}^2 & x_{4h}^2 & x_{5h}^2 
\end{bmatrix}
\]

- the vector function of the parameters of the chemical state of the crop: \(x_{1h}, x_{2h}, x_{3h}\), respectively, the content of nitrogen, potassium, phosphorus and magnesium.

The block of dynamic models of parameters of the state of sowing and soil environment:

An expanded form of the model of spring wheat biomass parameters over the interval of the growing season before heading has the following form [1,2]:

\[
\begin{aligned}
&Z_u(y, h) = P_u W(X_u(y, h)), \\
&Z_h(y, h) = P_h W(X_h(y, h)),
\end{aligned}
\]
Moreover: the parameters of the biomass state are: $x_{1m}$ - average over the area of the field density of the sowing biomass (crop), cwt·ha$^{-1}$; $x_{2m}$ is the average density of the wet mass of the crop over the area of the field, cwt·ha$^{-1}$; external disturbances in both blocks are $f_1$ - daily average air temperature, °C; $f_2$ is the average daily radiation level, W·(m$^2$·h)$^{-1}$; $f_3$ is the average daily rainfall intensity, mm; parameters of the chemical state of the soil: $v_N$ - nitrogen content in the soil, kg·ha$^{-1}$; $v_K$ is the potassium content in the soil, kg·ha$^{-1}$; $v_P$ is the phosphorus content in the soil, kg·ha$^{-1}$; $v_{Mg}$ — magnesium content in the soil, kg·ha$^{-1}$; $v_4$ - moisture content in the soil, mm; $(y, h)$ – spatial coordinates, m.

Canonical vector-matrix symbolic form of the model (4)

$$
\dot{X}_m(y, h) = A_m X_m(t, y, h) + B_m V(t, y, h) + C_m F(t),
$$

$$
t \in (T_{1m}, T_{2m}), \quad X_m(T_{1m}, y, h) = 0.
$$

An expanded form of the model of spring wheat biomass parameters from the beginning of heading to the state of grain maturity has the following form [1,2]:

$$
\begin{bmatrix}
\dot{x}_{1u}(y, h) \\
\dot{x}_{2u}(y, h) \\
\dot{x}_{3u}(y, h)
\end{bmatrix}
= \begin{bmatrix}
a_{11} & a_{12} & a_{13} \\
a_{21} & a_{22} & a_{23} \\
a_{31} & a_{32} & a_{33}
\end{bmatrix}
\begin{bmatrix}
x_{1u}(y, h) \\
x_{2u}(y, h) \\
x_{3u}(y, h)
\end{bmatrix}
+ \begin{bmatrix}
b_{11} & b_{12} & b_{13} & b_{14} & b_{15} \\
b_{21} & b_{22} & b_{23} & b_{24} & b_{25} \\
b_{31} & b_{32} & b_{33} & b_{34} & b_{35}
\end{bmatrix}
\begin{bmatrix}
x_{1u}(y, h) \\
x_{2u}(y, h) \\
x_{3u}(y, h)
\end{bmatrix}
+ \begin{bmatrix}
c_{11} & c_{12} & c_{13} \\
c_{21} & c_{22} & c_{23} \\
c_{31} & c_{32} & c_{33}
\end{bmatrix}
\begin{bmatrix}
f_1(t) \\
f_2(t) \\
f_3(t)
\end{bmatrix}
$$

$$
t \in (T_{1u}, T_{2u}), \quad x_{1u}(T_{1u}, y, h) = x_{1u0}(y, h), \quad x_{2u}(T_{1u}, y, h) = x_{2u0}(y, h), \quad x_{3u}(T_{1u}, y, h) = x_{3u0}(y, h);
$$

where: the parameters of the state of biomass are: $x_{1u}$ - the average density of the sowing biomass over the field area (crop), cwt·ha$^{-1}$; $x_{2u}$ is the average density of the wet mass of the crop over the area of the field, cwt·ha$^{-1}$; $x_{3u}$ - the average field density of the mass of ears of sowing (crop), cwt·ha$^{-1}$.

Canonical vector-matrix symbolic form of the model

$$
\dot{X}_u(y, h) = A_u X_u(t, y, h) + B_u V(t, y, h) + C_u F(t),
$$

$$
t \in (T_{1u}, T_{2u}), \quad X_u(T_{1u}, y, h) = X_{u0}(y, h).
$$
An expanded form of a model of the parameters of the chemical state of the soil in a daily time scale for the entire growing season [1,2]:

\[
\begin{bmatrix}
\dot{v}_N \\
\dot{v}_K \\
\dot{v}_p \\
\dot{v}_Mg \\
\dot{v}_5
\end{bmatrix} = \begin{bmatrix}
a_{11} & 0 & 0 & 0 & a_{15} \\
0 & a_{22} & 0 & 0 & a_{25} \\
0 & 0 & a_{33} & 0 & a_{35} \\
0 & 0 & 0 & a_{44} & a_{45} \\
0 & 0 & 0 & 0 & a_{55}
\end{bmatrix} \begin{bmatrix}
v_N \\
v_K \\
v_p \\
v_{Mg} \\
v_5
\end{bmatrix} + \begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
d_N(t) \\
d_K(t) \\
d_p(t) \\
d_{Mg}(t) \\
d_5(t)
\end{bmatrix} +
\begin{bmatrix}
0 & 0 & c_{13} & 1 \\
0 & 0 & c_{23} & 1 \\
0 & 0 & c_{33} & 1 \\
0 & 0 & c_{43} & 1 \\
0 & 0 & c_{51} & c_{52}
\end{bmatrix} \begin{bmatrix}
f_1(t) \\
f_2(t) \\
f_3(t) \\
f_4(t) \\
f_5(t)
\end{bmatrix} + \begin{bmatrix}
m_{11} & 0 \\
m_{21} & 0 \\
m_{31} & 0 \\
m_{41} & 0 \\
m_{51} & m_{52}
\end{bmatrix} \begin{bmatrix}
x_{1m}(t) \\
x_{2m}(t)
\end{bmatrix},
\]

or compact character form

\[
\dot{X}_n = A_{hx} X_n(t) + B_{hx} d_{Nv}(t) + M_{hx} V(t) + c_{hx} f_2(t),
\]

where: \(d_{Nv}\) - doses of foliar top dressings with nitrogen, kg \(\cdot\) ha\(^{-1}\).

An expanded form of a model of the parameters of the chemical state of sowing biomass for the entire growing season [1,2]

\[
\begin{bmatrix}
\dot{x}_{1n} \\
\dot{x}_{2n} \\
\dot{x}_{3n} \\
\dot{x}_{4n}
\end{bmatrix} = \begin{bmatrix}
a_{11} & 0 & 0 & 0 \\
0 & a_{22} & 0 & 0 \\
0 & 0 & a_{33} & 0 \\
0 & 0 & 0 & a_{44}
\end{bmatrix} \begin{bmatrix}
x_{1n} \\
x_{2n} \\
x_{3n} \\
x_{4n}
\end{bmatrix} + \begin{bmatrix}
b_1 \\
0 \\
0 \\
0
\end{bmatrix} + \begin{bmatrix}
m_{11} & 0 & 0 & 0 \\
0 & m_{22} & 0 & 0 \\
0 & 0 & m_{33} & 0 \\
0 & 0 & 0 & m_{44}
\end{bmatrix} \begin{bmatrix}
v_N(t) \\
v_K(t) \\
v_p(t) \\
v_{Mg}(t)
\end{bmatrix} +
\begin{bmatrix}
c_1 \\
c_2 \\
c_3 \\
c_{44}
\end{bmatrix} \begin{bmatrix}
f_2(t)
\end{bmatrix},
\]

or compact character form

\[
\dot{X}_n = A_{hx} X_n(t) + B_{hx} d_{Nv}(t) + M_{hx} V(t) + c_{hx} f_2(t),
\]

where: \(d_{Nv}\) - doses of foliar top dressings with nitrogen, kg \(\cdot\) ha\(^{-1}\).

### 3. Results

The general estimation algorithm consists of two stages. At the first stage, which can be called preparatory, the mathematical base is prepared for the assessment procedure. This step includes the following steps.

**Step 1.** Periodically, with an interval of 3-5 days, samples are taken from test sites (the number of which is 12-15, and each area is 20-30 m\(^2\)) and the following system status parameters are recorded:
reflection parameters of the state of sowing biomass: in the visible range \((z_1)\) and in the infrared range \((z_2)\);

reflection parameters of the parameters of the chemical state of the crop biomass: \(z_{1h}, z_{2h}, z_{3h}\) - reflection parameters in the most informative channels relative to the parameters of the chemical state of the plant biomass;

parameters of the state of sowing biomass: \(x_{1m}\) is the average density of the sowing biomass over the field area (yield); \(x_{2m}\) is the average density of the dry sowing mass over the area of the field;

parameters of the chemical state of the crop biomass: \(x_{1h}, x_{2h}, x_{3h}\) - respectively, the content of nitrogen, potassium and phosphorus;

parameters of the chemical state of the soil: \(v_{pH}\) is the indicator of soil acidity, \(v_N\) is the nitrogen content in the soil, \(v_K\) is the potassium content in the soil, \(v_P\) is the phosphorus content in the soil, \(v_5\) is the moisture content in the soil;

external disturbances: \(f_1\) - daily average air temperature; \(f_2\) is the average daily radiation level; \(f_3\) - average daily rainfall;

parameters of control actions: \(d_N(t)\), \(d_K(t)\), \(d_P(t)\), \(d_{Mg}(t)\) - dose of nutrients, respectively, of nitrogen N, potassium K, phosphorus P, magnesium Mg; doses of foliar top dressings with nitrogen - \(d_N\), doses of foliar top dressings with nitrogen, \(d_5\) - irrigation rates.

Step 2. Based on the operational information obtained by sampling and measuring external disturbances and controls, the parameters of models (1) - (9) are refined. In this case, the identification time interval is variable from the third measurement to the current time instant \(\tau = 3.4, \ldots, t\).

The second stage includes the procedures for assessing the parameters of the state of sowing and soil environment in the daily time scale and includes the following steps.

Step 1. initial assessment conditions are introduced:

- parameters of the state of sowing biomass: \(x_{1m}, x_{2m}; X_m(0)\),
- parameters of the chemical state of the crop: \(x_{1h}, x_{2h}, x_{3h}; X_h(0)\),
- parameters of the chemical state of the soil: \(v_{N}, v_{K}, v_{P}, v_{Mg}, v_5; V(0)\).

Step 2. Remote sensing data is entered at time \(t\):

- for the state of sowing biomass: \(z_{1m}, z_{2m}; Z_m(t)\),
- chemical state of sowing: \(z_{1h}, z_{2h}, z_{3h}, Z_h(t)\).

Step 3. Sowing biomass parameters are estimated at time \(t\) [2,3]:

\[
\dot{X}_m = A_m \dot{X}_m(t) + B_m \dot{V}(t) + C_m F(t) + R_m(t) P_m \frac{\partial W^T(X_m)}{\partial X_m} K_m^{-1} (Z_m(t) - P_m W(X_m(y, h))),
\]

\[
\dot{R}_m = R_m(t) A_m^T + A_m R_m(t) - R_m(t) P_m \frac{\partial W^T(X_m)}{\partial X_m} K_m^{-1} \frac{\partial W(X_m)}{\partial X_m} P_m^T R_m(t),
\]

\[
\dot{X}_m(0) = X_m(0), \quad R(0) = K_m.
\]

Step 4. The parameters of the chemical state of the sowing biomass at time \(t\) are estimated:
\[
\dot{X}_h = A_{hx} \dot{X}_h(t) + B_{hx} d_{X_h}(t) + M_{hx} \dot{V}(t) + c_{hx} f_z(t) + \\
+ R_{h} P_{h} \frac{\partial W^T(\hat{X}_h)}{\partial \hat{X}_h} K_{ch}^{-1}(Z_h(t) - P_h W(X_h(y,h)))
\]

\[
\hat{R}_h = R_h(t) A_{hx}^T + A_{hx} R_h(t) - R_h(t) P_{h} \frac{\partial W^T(\hat{X}_h)}{\partial \hat{X}_h} K_{hx}^{-1} \frac{\partial W(\hat{X}_h)}{\partial \hat{X}_h} P_{h}^T R_h(t), \\
\hat{X}_h(0) = X_h(0), R_h(0) = K_{hx}.
\] (13)

**Step 5.** The parameters of the chemical state of the soil are estimated:

\[
\dot{V} = A_{hp} \dot{V}(t) + B_{hp} D(t) + C_{hp} F(t) - M_{hp} \dot{X}_m(t) - N_{hp} \dot{X}_h.
\] (14)

**Step 6.** The evaluation quality criterion is calculated

\[
J(t) = (Z_h(t) - \hat{X}_h(t))^T(Z_h(t) - \hat{X}_h(t))
\] (15)

If \( J(t) \leq \delta \), then STOP, otherwise go to step 3.

**4. Discussion**

The graphs in figures 1, 2 show the dynamics of the estimates of the biomass parameters for sowing spring wheat. In this and subsequent figures, the parameter estimates are shown by continuous lines, and the measured parameter values are indicated by geometric icons. The sufficiently high accuracy of the estimates makes it possible to use this information about the state of sowing for the formation of real-time agrotechnological controls.

**Figure 1.** Estimates of the biomass parameters of spring wheat sowing in the vegetation interval to the ear stage.

The graphs in figures 3, 4 show the dynamics of estimates of the parameters of the chemical state of spring wheat sowing over the entire vegetation interval. This information does not have independent significance, but is intermediate in the procedure for generating estimates of the parameters of the chemical state of the soil environment, the dynamics of which are presented in figure 5. Here, jumps in parameter values reflect fertilizer doses. These parameters should be considered when forming the sizes
of technological operations in real time, which is a guarantee of obtaining a predetermined crop yield and eliminating the excessive consumption of fertilizers and water during irrigation.

**Figure 2.** Estimates of the biomass parameters of spring wheat sowing in the vegetation interval from the heading phase to the grain ripening phase.

**Figure 3.** Estimates of the parameters of the chemical state of spring wheat sowing biomass in the vegetation interval in the interval to the earing phase.

**Figure 4.** Estimates of the parameters of the chemical state of spring wheat sowing biomass in the vegetation interval from the earing phase to the grain ripening phase.
5. Conclusion
The development of the theory of estimating the state parameters of crops and soil environment based on a combination of mathematical models and Earth remote sensing data is proposed. This development is associated with the transition to crops with a more complex morphological structure. For this, spring wheat sowing was considered as a methodological example.

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