ISSN 1068-3674, Russian Agricultural Sciences, 2016, Vol. 42, No. 1, pp. 86–89. © Allerton Press, Inc., 2016.
Original Russian Text © T.V. Voloshenkova, Yu.I. Vasiliev, 2015, published in Rossiiskaya Sel'skokhozyaistvennaya Nauka, 2015, No. 6, pp. 40–43.

MODELING

Methodical Approaches to the Definition and Optimization of Criteria of Soil Protection Efficiency of Crop Rotation in the Regions Exposed to Deflation

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Received April 13, 2015

Abstract—This paper shows the directions of optimization and methods for determining the ecological and economic parameters that characterize the protective properties of crop rotations in areas with dust storms. The calculation algorithm, mathematical apparatus, and information-reference base are given. Their application permits crop rotations to be formed as early as the stage of design with the least loss of soil and costs for fertility restoration.

Keywords: crop rotation, soil protection efficiency, potential loss of soil, blowing of nutritional substances, costs for fertility restoration

DOI: 10.3103/S1068367416010225

The growth of the share of pure fallows in the structure of crop areas in connection with the transition from multiple-field crop rotations to short narrow specialized rotations [1] can be accompanied by increased deflation processes. This is especially dangerous to the droughty regions of the North Caucasus, Lower Volga region, and south of Russia as a whole, where dust storms took place in March 2015. Therefore, crop rotations must be formed with particular attention to their soil protection efficiency.

Methodical studies in this field are fragmentary and, for the most part, deal with the open surface of black fallow [2, 3]. Therefore, in this work, we tried to present the calculation algorithm, mathematical apparatus, and information-reference base needed to determine and optimize the ecological and economic parameters that characterize the protective properties of crop rotations.

The soil protection efficiency of crop rotation means the total prevented detriment, which must be assessed from the standpoint of both ecology and economics (Fig. 1). This makes it necessary to determine the potential loss of soil for the dust storm period, the concomitant decrease in soil fertility, as well as economic costs for its restoration to the initial level. This also gives a logical foundation for the possible fields of optimizing the ecological and economic parameters of crop rotation efficiency in deflation hazardous regions: the formation of crop rotations that ensure the minimal loss of soil in the dust storm period and reduction of costs for restoration of soil fertility.

The ecological constituent is considered with the preliminary calculation of the potential annual loss of soil for the dust storm period for each crop rotation culture (field), on average, for the yearly crop rotation and for the rotation period as well as with the estimate of the total loss of fine soil for all years of rotation.

The annual loss of soil for each crop rotation culture (P, t/ha year) can be calculated using the formula

$$P_j = P_{bj} K_{dj}, \tag{1}$$

where P_{bj} is the annual loss of black fallow soil, t/ha year; K_{dj} is the factor of deflation danger for a corresponding culture (the background); and j is the number of a crop rotation field.

The annual loss of black fallow soil can be determined based on the data on the structural composition, critical wind speeds, wind erodibility of soils for a specific crop rotation, and duration of dust storms in a studied region. The calculation methods are expounded in detail in the work by M.I. Dolgilevich et al. [2].

The average weighted loss of soil for crop rotation in the rth year of rotation (P_{cr}, t/ha year) is calculated based on the relationship:

$$P_{cr} = \sum_{j=1}^{B} (P_{cj} S_j)/S_t, \tag{2}$$

where P_{cj} is the annual loss of soil for each crop rotation culture, t/ha year; S_j is the area of the field occupied by the corresponding crop rotation culture, ha; B is the number of crop rotation fields; and S_t is the total crop rotation area, ha.

Then, the average deflation loss of soil for the entire crop rotation period (P_{rot}, t/ha year) can be found using the formula:

$$P_{rot} = \left(\sum_{r=1}^{V} P_{cr}\right)/V, \quad (3)$$

where V is the duration of crop rotation, years.

Formulas (1–3) are applicable if fields are not divided into working areas; otherwise, it is necessary to make appropriate adjustments.

Then, it is necessary to determine the amount of humus, nitrogen, phosphorus, and potassium that will be lost together with fine soil brought away during dust storms.

When determining a loss from a specific working area, which is characterized by homogenous soil conditions, it is expedient to use the methods proposed by Yu.I. Vasiliev [3]. According to these methods, the amount of humus lost due to deflation from a working area (P_{Gi}, t/ha year) is determined based on the formula:

$$P_{Gi} = P_i G_i/100, \quad (4)$$

where P_i is the loss of soil from the ith working area for the dust storm period, t/ha year; i is the number of the working area; G_i is the content of humus in the corresponding soil before blowing out, %.

In such a case, the loss of carbon (P_{Ci}, t/ha year) and nitrogen (P_{Ni}, t/ha year) will be

$$P_{Ci} = 0.58P_{Gi} \text{ and } P_{Ni} = P_{Ci}/9.8, \quad (5)$$

and the loss of phosphorus (P_{Fi}, t/ha year) and potassium (P_{Ki}, t/ha year) will be

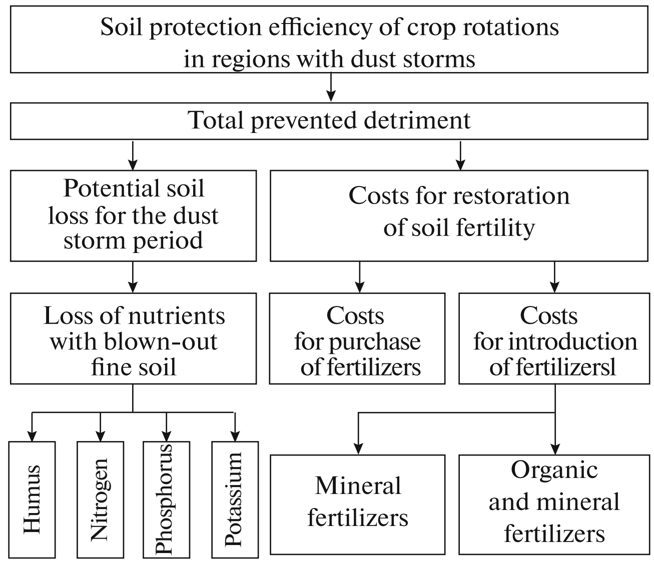
$$P_{Fi} = P_i F_i/100 \quad \text{and} \quad P_{Ki} = P_i K_i/100, \quad (6)$$

where F_i and K_i is the total content of phosphorus and potassium in the blown-out soil, %.

Then, it is necessary to determine the average weighted loss of humus and nutrients for each field (culture) and the average crop rotation loss for a year and for the entire rotation period. Since the calculation is of the same type for all elements, the average weighted annual loss for a field (culture) can be expressed in the general form by the formula:

$$P_{Mj} = \left[\sum_{i=1}^{A}(P_{Di}S_i)\right]\Big/S_j, \quad S_j = \sum_{i=1}^{A}S_i, \quad (7)$$

where P_{Di} is the loss of humus, carbon, nitrogen, phosphorus, and potassium, respectively, from the ith working area of the field, t/ha year; A is the number of working areas in the field; S_i is the size of the ith working area, ha; and S_j is the area of the jth field, ha.



Structural scheme for determining the soil protection efficiency of crop rotations.

The average weighted crop rotation loss for a year (P_{Hr}, t/ha year) is found from the relationship:

$$P_{Hr} = \left[\sum_{j=1}^{B}(P_{Mj}S_j)\right]\Big/S_c, \quad S_c = \sum_{j=1}^{B}S_j, \quad (8)$$

where r is a crop rotation year, and B is the number of crop rotation fields.

The average crop rotation loss for the rotation period (P_{Hrot}, t/ha year) is calculated using the formula:

$$P_{Hrot} = \left(\sum_{r=1}^{V}P_{Hr}\right)\Big/V, \quad (9)$$

where V is the duration of crop rotation, years.

Then, the total annual loss from the entire crop rotation area, on average, for the rotation period (P_{L0}, t/ha) will be

$$P_{L0} = P_{Hrot}S_t. \quad (10)$$

The economic constituent of the soil protection efficiency of crop rotations (see the figure) includes the costs for restoration of soil fertility to the initial level, which is possible thanks to the introduction of mineral or organic mineral fertilizers. Therefore, the structure of costs includes the costs for purchase and transport of fertilizers and costs for application of fertilizers in a deflated territory.

The costs for fertilizers must be differentiated depending on the way of making up the lost fertility—at the expense of only mineral fertilizers or organic (if an economic subject has this resource) and mineral fertilizers (in complex).

Agrochemical properties of the ploughed layer for major types of soils

Soils	Total content, %			
	humus	nitrogen	phosphorus	potassium
Podzolized black soils	4.0–8.0	0.20–0.45	0.15–0.20	2.0–2.5
Leached black soils	6.0–10.0	0.30–0.50	0.15–0.20	2.0–2.5
Typical black soils	8.0–12.0	0.40–0.50	0.15–0.25	2.0–2.5
Common black soils	6.0–10.0	0.25–0.40	0.15–0.25	1.8–2.5
Southern black soils	4.0–7.0	0.20–0.30	0.12–0.20	1.8–2.5
Pre-Azov and Pre-Caucasian soils	4.5–6.0	0.20–0.30	0.15–0.25	2.0–2.5
Dark-chestnut soils	3.0–4.5	0.20–0.30	0.12–0.20	2.0–2.5
Chestnut soils	2.5–3.5	0.15–0.25	0.12–0.20	2.0–2.5
Light-chestnut soils	1.6–3.0	0.10–0.20	0.15–0.19	1.8–2.25
Brown desert-steppe soils	1.0–2.0	0.09–0.15	0.10–0.15	1.0–2.5
Solonetz soils	1.0–3.5	0.07–0.20	0.10–0.20	1.2–2.5
Solonchak soils	1.0–5.0	0.07–0.25	0.12–0.20	1.5–3.0

In the first variant of making up losses, the loss of N, P, and K is initially determined in terms of the equivalent amount of fertilizers. For this purpose, the following expression can be used:

$$P_{Ui} = P_{Qi} \times 100/K, \quad (11)$$

where P_{Ui} is the loss of nitrogen, phosphorus, and potassium, respectively, in terms of an applied fertilizer, t/ha year; P_{Qi} is the loss of nitrogen (P_{Ni}), phosphorus (P_{Fi}), and potassium (P_{Ki}) with the blown-out fine soil, t/ha year; and K is the content of a corresponding substance in the fertilizer, %.

According to Yu.I. Vasiliev's methods [3], one of the variants to make up losses is to introduce only organic fertilizers. For this purpose, the required amount of manure is calculated for the element whose loss is maximal. However, in this case, there is a risk to introduce an excessive amount of other elements, which may lead to a disturbed ratio of nutrients in the soil and to additional material and financial expenses.

From the standpoint of optimizing the ecological and economic parameters of the soil protection efficiency of crop rotations, it is more expedient to make up losses in complex—by means of organic and mineral fertilizers. In this case, it is first necessary to determine the amount of manure (H_m, t/ha year) required to compensate for the nitrogen loss:

$$H_m = P_{Ni}/N1, \quad (12)$$

where P_{Ni} is the nitrogen loss, t/ha year, and N1 is the content of nitrogen in 1 t of manure (t).

Then, the amount of phosphorus (F_m, t/ha year) and potassium (K_m, t/ha year), which will be introduced into the soil, is calculated as:

$$F_m = N_m F1, \quad K_m = N_m K1, \quad (13)$$

where F1 and K1 in the content of phosphorus and potassium in 1 t of manure, respectively (t).

The amount of phosphorus (F_a, t/ha year) and potassium (K_a, t/ha year) needed to completely make up the losses of these elements in the soil is respectively:

$$F_a = P_{Fi} - F_m, \quad K_a = P_{Ki} - K_m. \quad (14)$$

In terms of the equivalent amount of mineral fertilizers, the amount of phosphorus (F_{aa}, t/ha year) and potassium (K_{aa}, t/ha year) fertilizers, which must be applied in addition to manure, is respectively:

$$F_{aa} = F_a \times 100/K, \quad K_{aa} = K_a \times 100/K. \quad (15)$$

The costs for purchase of fertilizers consist of their market price and expenses for delivery. The total cost of fertilizers (Z, rubles) is calculated as

$$Z = Cn, \quad (16)$$

where C is the cost of 1 t of a fertilizer, and n is the number of tons of the applied fertilizer.

The expenses for delivery are actual costs, and they may be included in the cost of fertilizers.

In order to determine the loss of humus and major nutrients in the dust storm period, it is necessary to know their initial content in soil before the beginning of deflation. These parameters are contained in the cartogram of an agrochemical land use survey. If the survey was not made, or these data are absent for some reason, it is possible to use the averaged parameters for a corresponding type of soil (the table) [4–6]. The data on the chemical composition of manure can be obtained in case of need at zonal agrochemical laboratories or from literature sources [6–8].

Analysis of the policy pursued by the first-rate companies specialized in selling mineral fertilizers [9–11] has shown that their cost fluctuates within a rather wide range depending on region, supplying company, and loading point. Therefore, when calculating the expenses, the cost of fertilizers must be compared with the current price lists of the leading companies.

The expenses for introduction of fertilizers into soil must be taken into account in addition to the costs for their purchase and delivery in the total amount of costs for restoration of soil fertility. For this purpose, "the technological maps for application of organic and mineral fertilizers in deflated territories" (TMs) must be developed in advance. The TMs must reflect the major types of works, their volume, the structure of aggregates, operating personnel, standards of output, expenses of labor, equipment, and fuel for the performed works [12–14]. The average weighted costs for restoration of soil fertility for fields and crop rotations are also calculated as losses of nutrients (formulae 7–10).

Consequently, the developed theoretical and methodological positions enable the effective determination of a set of parameters that characterize the soil protection efficiency of crop rotations in regions with alert wind conditions. This makes it possible to form crop rotations as early as the stage of design in order to ensure the minimal loss of soil in the dust storm period and the least costs for restoration of lost fertility.

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Translated by L. Solovyova