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MODELING

Dependence of Yield of Cereal and Tilled Crops on Humus Reserves in Chernozems and Gray Forest Soils

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Abstract—It is established on the basis of a statistical analysis of data on the yield of cereal and tilled crops
3 and obtained regression equations that the yield on chernozems and gray forest soils is directly proportional to humus reserves in the 0–50 cm soil layer. From the standpoint of producing plant industry products, these reserves evaluate soil quality. In the case of their negative dynamics, technological expenditures will have to be increased to provide an increase in yield, a large part of which is needed for compensating the decrease in humus reserves.

Keywords: humus reserves, yield, soil quality
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Reduction of soil resources is necessitating a quantitative evaluation and prediction of their dynamics. Natural resources are evaluated by quantity and quality, and quality with consideration of the products obtained: the more products produced per unit resources, the higher their quality. The quantity of soil used for producing plant industry products is evaluated by the area of arable land and thickness of the humus horizon. In the given case, for evaluating soil quality it is suggested to use humus reserves [1–3]. This is based on the established dependence of winter wheat yield (without using fertilizers) on humus
1 2 reserves in uneroded typical chernozem [1] and on the dependence of a reduction in yield of cereal and tilled crops on a decease in humus reserves in the 0–0.5 m
3 layer of eroded chernozems and gray forest soils [4]. The purpose of the present work was to substantiate the dependence of the yield of cereal and tilled crops
1 3 on humus reserves in eroded and uneroded chernozems and gray forest soils.

METHOD

We investigated the dependence of the yield of
3 cereal and tilled crops on chernozems and gray forest soils on humus reserves in these soils in the forest-steppe and steppe zones of Russia, Ukraine, and Moldavia. We used factual data dating back to the 1960s–1980s. Since yield depends on deterministic and stochastic factors [5], the search for its dependence on humus reserves was carried out for their average values (with respect to time, soil and climate conditions, crops, and technologies). For this, mathematical statistics methods were used and the equations obtained were analyzed.

RESULTS AND DISCUSSION

The table (lines 1–4) gives data on the decrease in the yield of cereal and tilled crops on eroded cher- 3
nozems and gray forest soils [4] obtained for different technologies (with and without the use of fertilizers). The average values of the decrease in yield ($\varepsilon_{\text{yi.er}}$) and humus reserves ($\varepsilon_{\text{hum}}(H_2)$) in the 0–$H_2$ soil layer ($H_2 = 0.5$ m) can be described by a regression equation $\varepsilon_{\text{yi.er}} = a\varepsilon_{\text{hum}}(H_2)$, where $a = 0.74 \pm 0.04$. For a value of a close to one, the equation takes the form:

$$\varepsilon_{\text{yi.er}} = \frac{Y_0 - Y}{Y_0} = a\varepsilon_{\text{hum}}(H_2) \approx \varepsilon_{\text{hum}}(H_2) = \frac{G_0(H_2) - G(H_2)}{G_0(H_2)}, \quad (1)$$

where Y_0, $G_0(H_2)$, Y, $G(H_2)$ are the yield and humus reserves in the 0–0.5 m soil layer respectively for uner- 1
oded and eroded soil. From Eq. (1) follows:

$$Y_0 \approx kG_0(H_2), \quad Y \approx kG(H_2), \quad (2)$$

where k is an unknown quantity depending on the crop, soil and climate conditions, and technology.

It follows from Eqs. (2) that, for two different crops located on different slopes under different soil and climate conditions, the ratio of yields Y/Y_0 will be approximately the same provided the same ratio of humus reserves $G(H_2)/G_0(H_2)$. According to Eq. (1), the values of the decrease in yield $\varepsilon_{\text{yi.er}} = 1 - Y/Y_0$ also

3 Data for eroded chernozems and gray forest soils (mean values and their standard deviations)

No. of line	Parameter	Degree of soil erosion		
		minor	moderate	severe
3	Cereal and tilled crops on chernozems and gray forest soils of the forest-steppe zones of Russia, Ukraine, and Moldavia [4]			
1	Decrease in yield, %	18 ± 1	35 ± 1	52 ± 1
2	Sample size	149	143	120
3	Chernozems and gray forest soil in Kursk oblast [4]			
3	Decrease in humus reserves in 0–50 cm soil layer, %	26 ± 1	51 ± 1	66 ± 2
4	Sample size	163	78	26
3	Typical and leached chernozems in Kursk oblast[1]			
5	Decrease in thickness of humus horizon, %	26 ± 1	54 ± 1	67 ± 3
6	Decrease in humus reserves in 0–50 cm soil layer, %	20 ± 2	48 ± 2	58 ± 3
7	Sample size	94	39	12
2	Values calculated by Eqs. (6) and (7) for winter wheat without use of fertilizers on typical chernozem in Kursk oblast			
8	Decrease in yield[2], %	30 ± 8	54 ± 5	63 ± 4
2	Decrease in winter wheat yield[2] on typical chernozem in Kursk oblast [7], average for 1968–1970			
9	Without fertilizers	18	29	45
10	$N_{45}P_{45}K_{45}$	12	21	25
3	Typical, leached and podzolized chernozems in Kursk oblast			
11	Humus horizon, cm	55 ± 1	35 ± 1	24 ± 2
12	Humus reserve in 0–50 cm soil layer, t/ha	211 ± 4	138 ± 4	113 ± 7
13	Sample size	105	44	12
	Gray and dark gray forest soils in Kursk oblast			
14	Humus horizon, cm	37 ± 1	30 ± 2	23 ± 1
15	Humus reserve in 0–50 cm soil layer, t/ha	132 ± 4	83 ± 4	56 ± 5
16	Sample size	54	34	18

[1] Obtained from materials of the Kursk Branch of TsChOGiprozem.;
[2] The decrease in yield is equal to the decrease in humus reserves in humus horizon.

seem close. This dependence of yield on humus reserves made it possible in the statistical analysis to unite into one group the data on yield of different crops obtained under different soil and climate conditions [4].

The depth distribution of the soil humus content was taken the same as in model [6], namely: the humus content doesn't change across the depth in the $0–H_1$ soil layer ($H_1 = 0.2$ m) with density ρ_1; it decreases to zero according to a linear dependence in the $H_1–H_{hum}$ layer (H_{hum} is the thickness of the humus layer with density ρ_2. Furthermore, since the upper soil layer is tilled, therefore $H_{hum} \geq H_1$ always. From this distribution follows: the portion ($f(H_{hum})$) of humus reserves ($G(H_2)$ from the reserves in the entire humus horizon $G(H_{hum})$ is equal to 1 when $H_{hum} \leq H_2$, and when $H_{hum} > H_2$:

$$f(H_{hum}) = \frac{\rho_1 H_1 + 0.5\rho_2\left(1 + \frac{H_{hum} - H_2}{H_{hum} - H_1}\right)(H_2 - H_1)}{\rho_1 H_1 + 0.5\rho_2(H_{hum} - H_1)}. \quad (3)$$

Then Eqs. (2) for eroded and uneroded soils can be 1
written by one equation:

$$Y \approx kf(H_{hum})G(H_{hum}). \quad (4)$$

Since humus reserves change little during 10–20 years, the value of k can be estimated from the normal yield during this period: $k = Y/G(H_2)$.

The region of applicability of Eq. (2) and, as a consequence, Eq. (4) is determined by the conditions for which the yield data were used. Equation (1) was obtained from yield data with and without the use of fertilizers. For the example of the yield of winter wheat
grown on typical chernozem in the Kursk oblast, we 2
will show that the use of fertilizers leads to a decrease in the value of a in Eq. 1).

For a normal yield (Y) on this noneroded cher- 2
nozem without the use of fertilizers, G.I. Bakhirev [1] proposed an equation having the following form:

$$Y = k_1 G(H_{hum}), \quad k_1 = K_m \frac{e_{hum}}{e_{cro}} w, \quad (5)$$

where K_m is the portion of humus reserves spent on grain yield; e_{hum}, e_{cro} are the specific calorific value of absolutely dry humus and winter wheat grain crop; w is the conversion factor to grain weight at standard moisture content. For this soil we take $\rho_1 = \rho_2 = 1.2$ g/cm^3 and $H_{hum} = 0.8$ m. It follows from Eq.(3) that for these values of the parameters, $f(H_{hum}) = 0.85 \approx 1$.

It is seen on comparing Eqs. (4) and (5) that they practically coincide and $kf(H_{hum}) \approx k = k_1$. Therefore,
1 we use Eq. (5), from which follows: for uneroded soil (without the use of fertilizers), a decrease in yield ($\varepsilon_{yi,uner}$) due to a decrease in humus reserves takes the form:

$$\varepsilon_{yi,uner} = \frac{Y_0 - Y}{Y_0} = \frac{G_0(H_{0,\,hum}) - G(H_{hum})}{G_0(H_{0,\,hum})} = \varepsilon_{hum}(H_{hum}), \quad (6)$$

where Y_0, $G_0(H_{0hum})$ are the yield and humus reserves
1 1 for uneroded soil; Y, $(G(H_{hum})$ are the same for uneroded soil but the humus reserves are the same as for eroded soil; $\varepsilon_{hum}(H_{hum})$ is the relative decrease in humus reserves in the humus horizon.

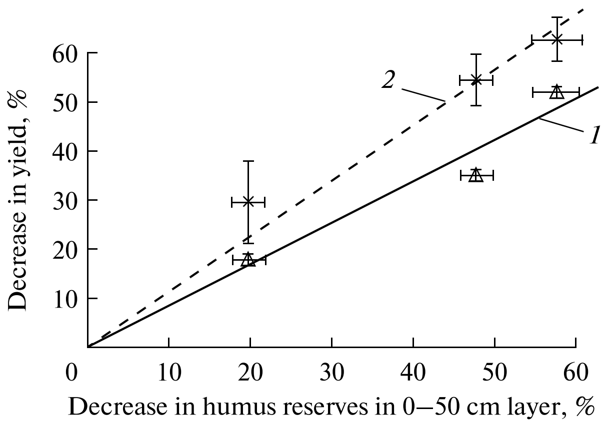
It follows from (6) that $\varepsilon^{yi,uner} = \varepsilon_{hum}(H_{hum})$. In this case the decrease in yield on eroded soil ($\varepsilon_{yi,er}$) should
1 be greater than on uneroded, that is, $\varepsilon_{yi,er} > \varepsilon_{yi,uner}$. One cause is sufficient for this: slope runoff of water in the zone of insufficient moistening leads to an additional reduction of yield.

For Eq. (5) the error with which it was obtained is not given. Therefore. we estimate the error of $\varepsilon_{yi,uner}$ in(6), using the standard deviation for the mean yield σ_{mean} (absolute error). It is shown in [5] that, for the conditions of applicability of Eq. (5), the winter wheat yield during 20 years (without fertilizers) can be described by a normal probability distribution with a mean value $Y = 2.9$ t/ha and coefficient of variation $C_v = 0.26$. We will take the value of C_v also for the yield on soil with other humus reserves. The standard deviation for the mean value of the yield $\sigma_{mean} = C_{v,mean}Y$, $C_{v,mean} = (C_v/n)^{1/2})$, $n = 20$ years (sample size); then Eq. (6) with consideration of errors can be written in the following form:

$$\varepsilon_{yr,uner} \pm \Delta\varepsilon_{yr,uner} = 1 - (1 - \varepsilon_{yr,uner})\frac{1 \mp C_{v,\,mean}}{1 \pm C_{v,\,mean}}. \quad (7)$$

We estimate the absolute error $\Delta\varepsilon_{yi,uner}$ from the condition: $\Delta\varepsilon_{yi,uner} = 0.5[\mathrm{Max}(\varepsilon_{yi,uner} \pm \Delta\varepsilon_{yi,uner}) - (\mathrm{Min}(\varepsilon_{yi,uner} \pm \Delta\varepsilon_{yi,uner})]$, where Max, Min are respectively the maximum and minimum value of the expression in parentheses.

The calculated values of $\varepsilon_{yi,uner} \pm \Delta\varepsilon_{yi,uner}$ are given in the table (line 8). For calculating the values of $\varepsilon_{yi,uner} = \varepsilon_{hum}(H_{hum})$ we used the data for eroded typical and
2 1 leached chernozem (table lines 5–7). For this uneroded soils the thickness of the humus horizon $H_{hum} = 0.75 \pm 0.01$ m, humus reserves in the 0–0.5 m layer $G(H_2) = 268 \pm 3$ t/ha (sample size, 173). We used the function $f(H_{hum})$ for convrting from humus reserves in the 0–0.5 m layer to reserves in the humus horizon.



Dependence of the decrease in yield on the decrease in humus reserves in typical and leached chernozems in the 3
Kursk oblast: (*1*) actual data (cereal and tilled crops on eroded soil); (*2*) calculated data (winter wheat on uneroded soil with the use of fertilizers); the vertical and hori- 1
zontal segments are the errors.

The figure shows the dependences of the decrease in the yield of cereal and tilled crops on the decrease in humus reserves in the 0–0.5 m soil layer. The calculated data (without the use of fertilizers) can be described by the equation $\varepsilon_{yi,uner} = 1.1\varepsilon_{hum}(H_2)$ (dashed line in figure), and the actual data (both with and without fertilizers) by the equation $\varepsilon_{yi,er} = 0.83\varepsilon_{hum}(H_2)$ (solid line). It follows from these equations that $\varepsilon_{yi,er} = 0.8\varepsilon_{yi,uner}$, for the same decrease in humus reserves, the decrease in yield on eroded soil is less than on uneroded without fertilizers ($\varepsilon_{yi,er} <$ 1
$\varepsilon_{yi,uner}$). Although this difference is small, it nonetheless exists since it falls outside the error limits. Without the use of fertilizers, it should be that $\varepsilon_{yi,er} > \varepsilon_{yi,uner}$. This seemingly contradiction can be explained by the effect of using fertilizers.

We'll examine the slope on which the same dose of fertilizers (D) is applied. The average yield for uner- 1
oded soil will be $Y_0 = Y_{0,wo/f} + k_{0,fe}D$; for eroded, $Y = Y_{wo/f} + k_{fe}D$, where the subscript "wo/f" shows the yield without the use of fertilizers and $k_{0,fe}$ and k_{fe} shows the efficiency of fertilizers (yield gain per their unit dose) respectively on uneroded and eroded soil. 1
The decrease in yield with the use of fertilizers ($\varepsilon_{yi,w/f}$) can be written as

$$\varepsilon_{yi,w/f} = \frac{Y_{0,\,w/f} - Y_{w/f}}{Y_{0,\,w/f}} = \frac{(Y_{0,\,wo/f} - Y_{wo/f}) - (k_{fe} - k_{0,\,fe})D}{Y_{0,\,wo/f} + k_{0,\,fe}D}, \quad (8)$$

where the subscript "w/f" shows that fertilizers are used.

The decrease in yield without fertilizers ($\varepsilon_{yi,wo/f}$) is determined also by Eq. (8) but for $D = 0$. From (8) follows: the inequality $\varepsilon_{yi,wo/f} > \varepsilon_{yi,w/f}$ is feasible under the condition when

$$k_{fe} > k_{0,\,fe}\frac{Y_{wo/f}}{Y_{0,\,wo/f}}. \quad (9)$$

This condition is fulfillable for eroded slopes since $Y_{wo/f} < Y_{0,wo/f}$ and fertilizer efficiency is higher ($k_{fe} > k_{0,fe}$) [7]. The effect of using fertilizers explains whey the inequality $\varepsilon_{yi,uner} > \varepsilon_{yi,er}$, which the data in the figure satisfy. Thus, the use of fertilizers on eroded soil can give a greater yield gain than its decrease caused, for example, by a decrease in moisture available to plants due to slope runoff; moreover, condition (9) is valid for any soils.

The examined effect is confirmed by the experimental data [7], which are given in the table (lines 9–10). It follows from them than the decrease in winter wheat yield without the use of fertilizers is greater than with their use. Consequently, the value of a in Eq. (1) would be greater than 0.74 if all yield data used were obtained without the use of fertilizers.

Let us compare the thicknesses of the humus hori-
3 zon and humus reserves in the 0–0.5 m layer for cher-
nozems and gray forest soils. These data were obtained
from the materials of the Kursk Branch of the State
2 Central Chernozem Land Management Planning and
Research Institute (TsChOGiprozem) during the
1 3 1970s–1980s. For uneroded chernozems $H_{hum} = 0.74$
± 0.01 m, $G(H_2) = 267 \pm 3$ t/ha (sample size, 195), and
for gray forest soils $H_{hum} = 0.49 \pm 0.02$ m, $G(H_2) = 185$
± 4 t/ha (sample size, 94). The data for eroded soils are
given in the table (lines 11–16). Their analysis shows:
soil reserves and humus reserves in it, normalized per
unit area of arable land, for gray forest soils are consid-
3 erably less than for chernozems. In both cases, these
reserves declined substantially as a result of erosion.
During 200 years (since the time of intensive develop-
2 ment of virgin lands in the Central Chernozem
1 Region, the humus content in the plow layer of uner-
3 oded chernozems decreased from 10–12 to 5–6% [8,
9[, or by about half. These data on humus reserves
3 (content) in chernozems and gray forest soils charac-
terize also the yield of crops on these soils.

As the prediction results showed [6], in the Central
2 Chernozem Region with the existing land use, the
3 resources of chernozems, normalized per unit area of
arable land, will continue to decline and it's important that it is practically impossible to recover these losses. It is necessary to develop a state strategy for the efficient use of the soil resources that remain. When determining soil humus content, at first it is necessary to determine the content of organic carbon and multiply this quantity by 1.724 [10]. Therefore, the conclusions made relative to humus are valid also for organic carbon thus determined.

For the examined conditions, the yield is directly proportional to the humus reserves in the 0–50 cm layer. Consequently, these reserves in a first approximation evaluate soil quality. In the case of negative dynamics of humus reserves, technological expenditures will have to be increased to provide an increase in yield, a part of which will increase constantly to compensate the decrease in humus reserves. This will involve an increase in prices for plant industry products and a decrease in the competitiveness of producers.

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SPELL: 1. uneroded, 2. chernozem, 3. chernozems