Models of soil fertility as means of estimating soil quality

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Abstract: *The aim of this article is to demonstrate application of soil fertility models as an indicator of soil quality. We designed a model of soil fertility with a finite number of parameters which is important in adapting the model for use in other countries and with regard to the accessibility of various data sets of soil parameters in the countries. The main objectives were: (i) to build a model which fulfils agro-environmental requirements of separate crops to growth factors and basic laws of agriculture (law of limiting factor, law of minimum, optimum and maximum, Law of combined effect of factors of Mitcherlih-Bowle, law of the critical periods) because all of the above directly control the growth of crops and their response; (i) optimizing of ways of normalization of soil fertility parameters; and (iii) demonstrating the relationship of yield of crops and indicator of soil quality. We proposed a method of creating model of soil fertility based on generalized indicator of soil fertility based on the formula of harmonic mean, which ensures compliance of the calculations with the law of combined effect of factors and with the law of limiting factor. Compliance with other laws of agriculture and agro-environmental requirements of crops provide a right choice of weighty parameters of soil and most importantly - the specific way of their normalization. This is recalculation for individual indicators in the scale of 0-100 points for bilateral and unilateral criteria (which was shown an example winter wheat). Comparison of methods showed that they describe well the level of fertility of the soil in our experiment. The proposed model of soil fertility can be used to assess the quality of the soil, and also as an indicator of monitoring change of soil fertility, in systems of precision agriculture and more.*

Keywords: *laws of agriculture, models soil fertility, soil quality index, agroecological requirements of crops, averaging means.*

Introduction

Attempts to evaluate soil properties and their fertility were inherent for the first agricultural civilizations even in primitive society. The development of science has led to a better understanding of the relationships between quantity and quality of agricultural yields and complex of soil-climatic organizational and economic measures. This issue was and still is of great public importance; therefore several generations of scientists focused their effort on soil fertility. The result of these efforts is the past and current methods for evaluating productive and qualitative characteristics of soils in different ways, described in detail Medvedev and Plisko (2006). This usually concerns two main objectives: 1) ranking soil fertility (productivity); 2) determine their suitability for cultivation of certain crops. There are various approaches to evaluate the two aspects. This applies both to appropriate setting of the parameters involved in the assessment and to the methods of calculation and reduction to a single scale.

Most standardized methods used mathematical operations based on the arithmetic average and the linear calculation of values of indicators regarding the standards. Other methods use the averaging of factor parameters using the geometric mean (Grinchenko et al. 2008, Medvedev and Laktionova 1988) or harmonic average (Cherlinka 2001b, Smaga and Cherlinka 2005, Smaga et al. 2005, Smaga and Cherlinka 2010, 2011). A feature of these methods is more accurate account of the integrated assessment of soil. This is especially important if characteristics factor in the calculations have low numerical values that will be shown later.

One should also mention discussion on the inclusion of different groups of factors for integrated assessment of soil. Thus, current achievements, including Tihonenko et al. (2012), Medvedev and Bigun (2013) emphasize the physical and agrophysical soil parameters of soils and methods of their evaluation (Plisko et al. 2012). This is certainly correct, because agrophysical soil degradation has reached enormous proportions. For example, according to Medvedev (2013) 6.8 million hectares from 30 million ha total arable land of Ukraine is subject to the impact of this type of degradation. So agrophysical qualitative assessment of soil quality indicators is particularly important (Plisko et al. 2012, Laktionova et al. 2013). However, the situation of soil organic matter, content of macro- and micronutrients, *pH* of soils is not in much better condition. Therefore, the best way to assess the soil as a special body of nature and a production unit is incorporation as possible many factors. We conclude that the completeness of the national soil database information should be one of the priority tasks facing soil scientists. Depending on the country, the situation is changing for the better or worse. For example, in Bulgaria, Moldova, Romania, the situation is in good condition (Rousseva et al. 2015). In Slovakia (Bielek et al. 2005, Skalský and Balkovic 2002), the Czech Republic, Germany and other EU countries, it is also good (Jones et al. 2005). In Ukraine, unfortunately, it is far from ideal (Cherlinka 2015).

Presented in the literature data on the use of soil fertility models as an indicator of soil quality have vague character. Therefore, in this paper, we aim to improve the modelling of soil fertility by demonstrating how the model of soil fertility can be built from a finite number of parameters. This is important in adapting the model for use in different countries and access to various data sets of soil parameters in them. With good crop yield describe such a model can be used as an integral indicator of soil fertility. Accordingly, this study has following main objectives: including agro-environmental requirements of separate crops to growth factors; optimizing of ways of normalization of soil fertility parameters; to illustrate the relationship of yield of crops and indicator of soil quality. Based on this hypothesis we tested the ability of soil fertility models in relative units are as soil quality index.

Background

Usually as a model of soil fertility understand the totality of its agronomically important features and regimes that meet a certain level of productivity of plants (Shishov et al. 1987). Among the famous models in which the productivity of crops is presented as a function of soil parameters, the most common models are based on correlation and regression analysis (Hedi and Dillon 1965, Frid 1985). Completely different from the previous simulation is the way, which is based at some type of appraisal (Bondarenko and Zheleznyj 1986). However, these approaches do not consider the requirements of specific types of crops to factors of life that is agroecological unfounded and according to some authors (Shishov 1991) cannot be regarded as integrated models of soil fertility. Moreover, most of them do not conform to basic laws of agriculture, according to which the yield formation and evolution of soil fertility is carried (Muha et al. 1994, Cherlinka 2001b).

Thus, one of the most important laws that determine the conditions of the ontogenesis of plants is the law of indispensability and equivalence factors and their lives, which was formulated by Vil'yams (1949). The essence of it is that all factors of plant life are physiologically equivalent and none of them can be replaced by another.

One of the first laws discovered in the study of plant response to different amounts of a factor was the Sprengel-Liebig Law of the Minimum (van der Ploeg et al. 1999) and revised by Narcissov (1982) whereby it is termed the law of limiting factor. In practice of agriculture often there are cases when such factors dramatically reduce the efficiency of action of other. For example, Pryanishnikov (1937) found that without the removal of acidic reaction of soil making any fertilizer makes it impossible to obtain a high yield of most crops.

Since most of the factors acting on the plant according to the law of minimum, optimum and maximum (Vil'yams 1949), then shift their values in either direction from the optimum reduces productivity of crops and in the worst case be heading to zero. This is well illustrated by the results of experiments, where nitrogen doses were tested, ranging from extreme shortage to a large surplus: the highest productivity is obtained at a dose of 7.5 *g* ammonium sulphate in container, and further its growth sharply reduced of yields (Black et al. 1968). Similar data was received in vegetation containers (Pankov 1976).

It should be noted that the whole of the permissible range of growth and development of plants accumulated very little data because researchers seldom explore the entire range of a factor from its minimum to maximum value. We have much more data about the effect of factors ranging from minimum to optimum. It was shown in several experiments how yield of wheat, canary grass, potatoes and beans changes with changing doses of potassium (Black et al. 1968). The yield increases to a certain value of potassium content, and then it remains stable, indicating the inability to further increase the impact on plants by increasing the content of this item. Very high concentration of nutrients can lead to toxic impact on the plants.

Hence the impact of nutrition factors in general can be described as parabola in Fig. 1. It shows, that each successive addition of elements ranging from minimum to optimum value accompanied by less and less increments harvest, and in the interval from the best to the maximum – progressive reduction yield (Jeffrey, 1987).

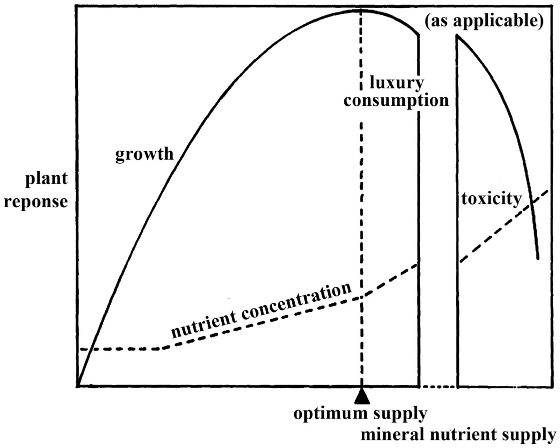


Fig. 1. *Parabolic view: plant response as a function of mineral nutrient supply (Jeffrey, 1987)*

It should be noted that abundance of available forms of nutrients is usually not observed in soils and even more of theirs amounts that result in intoxication plants (Jeffrey 1987). Similarly, affect the plants and other environmental factors, such as the equilibrium bulk density, *pH* environments, granulometric composition of and more. Several parameters of soils (or climate), adversely affect the plant organisms in case achieving sufficiently large absolute values, which is not always realistic. In such cases it is advisable to take into account only the left branch of the parabola that describes the interval factor from minimum to optimum.

But in assessing the impact of various factors on the plant one should not forget none of them affects separately, and there is their integral effect, reflecting the combined effect of factors. This law was open at late 19th century by the German botanist Libsher. Confirmation of it is the conclusion Ziganshin and Sharifullin (1974) that the optimization of factors of life of plants can more efficiently use not only those who are at the minimum, but those that are present in sufficient quantity. Consideration of plant productivity as a function of several factors, one of which varies widely, enables describing the present moment both mathematically and graphically Mitcherlih (1931), Dickson (1942). Muha et al. (1994) supplemented the definition of this law and have expressed it mathematically:

$$\frac{\partial y}{\partial x} = (A - Y) \cdot C,$$

where *A* is a maximum yield attainable and *C* – is a proportionality factor. From Fig. 2 it can be seen that crop of plants (*Y*) increases with the increasing influence of a growth factor (X_n) proportional to the harvest, which do not enough to maximal crops.

Currently established that depending on the factor of plant growth and development, empirical formula was derived by E. A. Mitcherlih and improved B. Bowle has a certain variability, which, however, correctly describes the general nature of the changes in plant productivity (Sorensen 1983). In our opinion existence of mathematical calculation method, which will provide a result closely matching to the law of Mitcherlih-Bowle has a right on existence and on the use in science and practice.

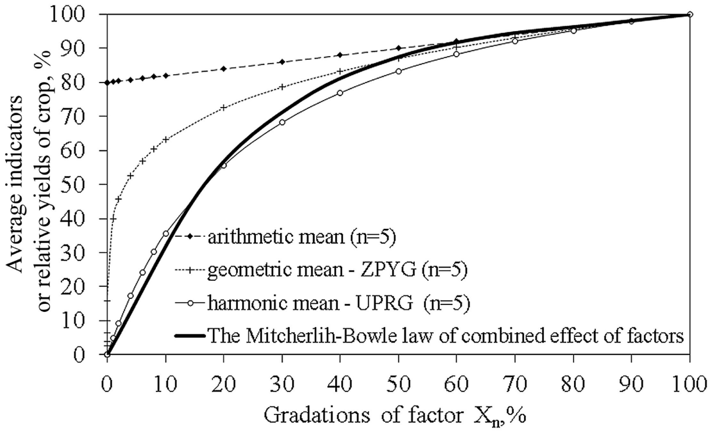


Fig. 2. *Variability of integrated assessment of soils in case of application of different averages compared with Law of combined effect of factors of Mitcherlih-Bowle*

The development of plants and their productivity depends primarily from providing all the necessary factors of life in sufficient quantities during the critical periods mainly allocated to water, temperature, nutrients, etc. (Zubenko et al. 1991). This expectation meets law of the critical periods (Suslov 2012). In some cases, the possible impact of toxic factors on plants is in their influence on plant development/growth which is slightly different from the parabolic regularity (Fig. 3). With their growth or achievement of certain critical value is reduced productivity and the loss of plants (Nikitin 1981). As an example, take the content of mobile forms of aluminium in soils that violate phosphate metabolism in plants, reduce the formation of chlorophyll and activity of various enzymes (Kulakovskaya et al. 1984, Nazarenko 1981).

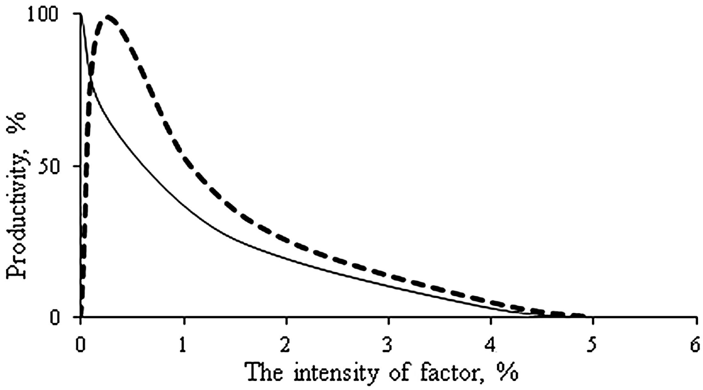


Fig. 3. *Influence of toxic factors on plant productivity; Source: Cherlinka (2001a)*

The above-mentioned basic laws of agriculture (law of limiting factor, law of minimum, optimum and maximum, Law of combined effect of factors of Mitcherlih-Bowle, law of the critical periods) directly affect the growth of crops and their response. So theirs incorporation in soil fertility models are necessary and therefore it has been given such attention. Model fertility of soils, which will take into account these laws, in our opinion, have a much higher precision and a certain rationale compared with those not counted. Be noted that crops according to their biological characteristics require different conditions for growth and development, so in one model is difficult and often impossible to combine various (sometimes contradictory) requirements. Accordingly, we have to create more than one model, and their set that comprehensively describe soil requirements of regarding the entire set of cultural species.

Methods and Data

The objective existence to each culture optimum of fertility parameters necessitates their incorporation when calculating processes in the system of soil-plant (Savich et al. 1988), therefore we consider it appropriate allotment of partial models for each culture. Another way, which is to establish only one model for all cultures, requires a large number of constraints leads to its excessive complexity. Therefore, in our view, only in system of "partial" models can be fully or to a large extent taken into account most of the agroecological requirements crops to the environment and made possible characterize the level of fertility of soils.

Creating a model is a complicated and laborious process. For his alleviate Neujmin and Solomenko (1984) developed clearly algorithmic scheme that made it possible to build a model in respect of defined criteria. Based on the this scheme, we have formulated the problem, which is to establish models soil fertility that meets the requirements; have defined ultimate goal – the ability of the model to predict the fertility status and its changes and was selected criteria of quality - ability to satisfy target with the required accuracy. In the classification Frid (1985) formed models belong to the class models state of fertility.

According to the task we chose the objects of study, including methodology of calculation of soil quality, which can be seen as a model of state of fertility. In particular, it is standardized method of calculating the agrochemical and ecological-agrochemical scores points (Demidov et al. 2013) and its alternatives of similar direction (Grinchenko et al. 2008) – method of calculation aggregate metrics of soil quality (ZPYG) and generalized indicator of soil fertility – UPRG (Cherlinka 2001a, b, Smaga et al. 2007).

At their consideration should clearly delineate the notion of averaging and normalization of indicators. Under the normalization by us understood getting mark estimation of specific soil parameters, which actually enables them following obtaining of averaging and integrated assessment. Comparison of different averages, which have spread in the techniques obtaining estimates of integrated soil quality (Fig. 2) shows a clear differentiation between them. In this case, in order to formalize task by us was made that the indicators from one to fifth have 100 scores (the maximum of possible), and one of them varies from 0 to 100 points. Obviously, formula of the arithmetic mean

$$Y = \frac{\sum_{i=1}^{n} X_i}{n},$$

where Y is an integrated assessment in relative units, X_i is a normalized parameters of soil and *n* is a total number of parameters) is the least adapted to obtain reliable results, because it gives overestimated integrated assessment for low values of variable parameters. This can be demonstrated by virtual experiment in which, for example, the *pH* varies from value of 7.0 (neutral reaction, significance in points is 100) to *pH*=3.0 (very acidic soil, the reaction corresponds to approximately 0.1 normal acetic acid, significance in points – 0). In extreme meanings *pH* integrated indicators based on of the arithmetic mean will be shown result ≈80 scores, which obviously is not fully correct because productivity of crops under these conditions is almost impossible and equal to zero. As such a widely varied parameter can be any factor, and according to the Shelford's law of tolerance (who in turn extends the well-known law of minimum of Libih) will obtained similar results.

With this approach more correct of integrated assessment gives formula of geometric mean

$$Y = \sqrt[n]{X_1 \cdot X_2 \cdot \ldots \cdot X_n},$$

adopted as a basis in the method by force (Grinchenko et al. 2008). However and it gives a fairly significant deviations from the law of combined effect of factors (Fig. 2) at the values of factor less than 40 points. It is necessary noted that despite this, this techniques ability of to take account low value of components in which the productivity of plants practically equal zero, it is an undeniable advantage over methods based on of the arithmetic mean. However, detailed analysis Fig. 2 leads to the conclusion that similar character of curves in law of combined effect of factors and line of harmonic mean

$$Y = n / (1/X_1 + 1/X_2 + \ldots + 1/X_n)$$

are some precondition to use the latter as a basic summary measure, as is customary in the method of calculation UPRG (Cherlinka 2001a,b, Smaga et al. 2007) and has a clear advisability and reasonableness.

The area of research and modelling of soil fertility located in western Ukraine, and is confined to the territory between the rivers Prut and Dniester. This area is belonging to the administrative district Kitsman of Chernivtsi region of Ukraine (Fig. 4) and is represented in the coordinates system Pulkovo 1942/Gauss-Kruger zone 5 (EPSG: 28405).

The dataset about yields of winter wheat and soil parameters covering the period 1992-2000 years are presented by Kitsman State station for research of varieties of crops. Soil samples data was selected according to ISO 10381-(1-5) with such parameters as: *pH(KCl)* (ISO 10390); organic matter in terms of humus, % (ISO 10694); nitrogen, mg/100 g (GOST 26488-26489, ISO 11261); mobile phosphorus, mg/100 g (ISO 11263); exchangeable potassium, mg/100 g (GOST 26207); depth of horizon with humus content, cm; equilibrium bulk density of soil, t/m^3 (ISO 11272).

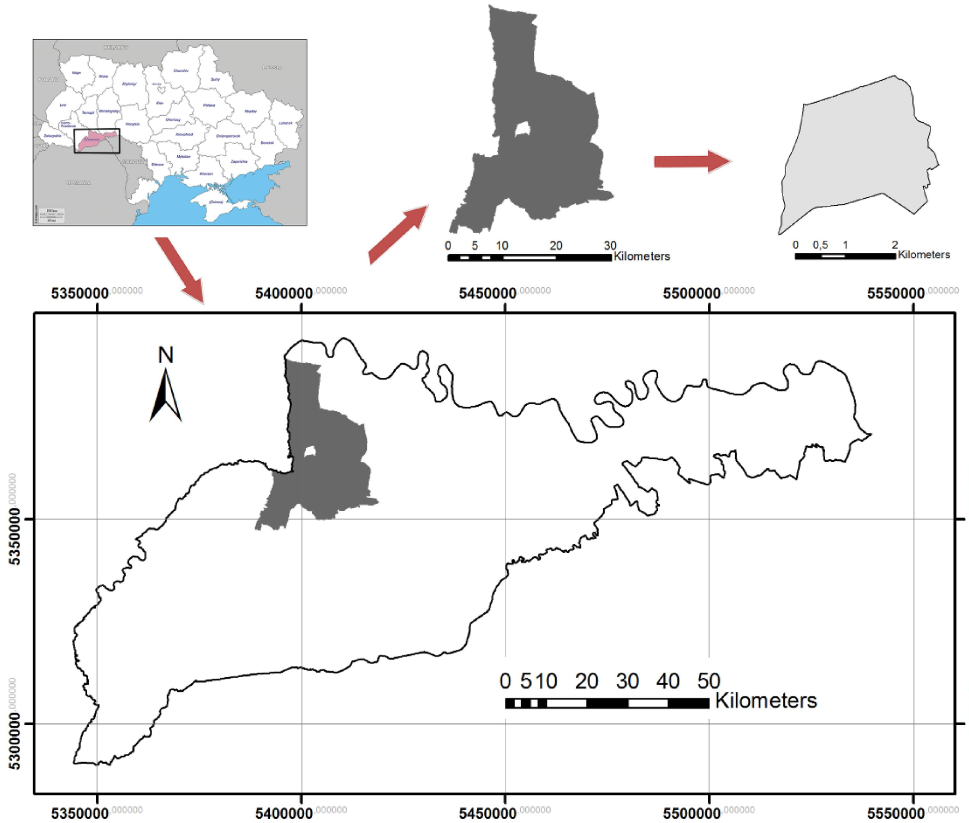
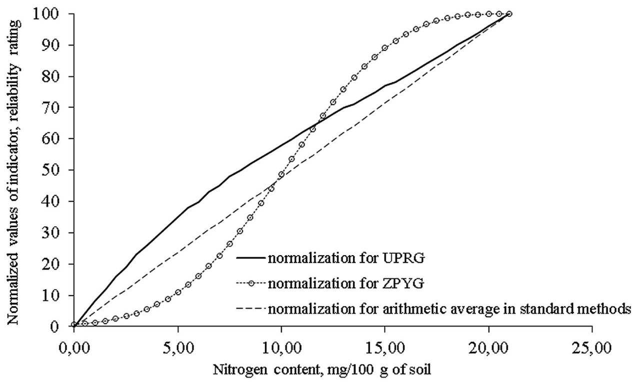


Fig. 4. *Location of the research area within Ukraine*

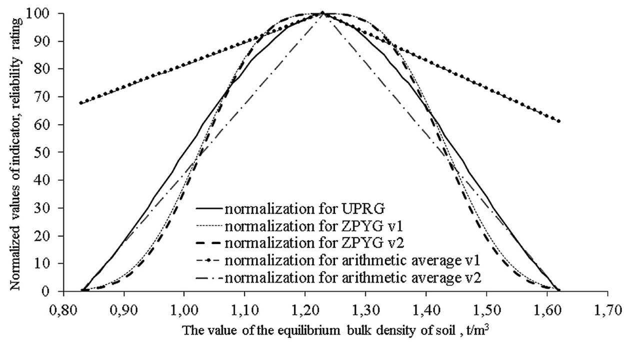
Results and discussion

The important point, which is of key importance in assessing the quality of soils, this is recalculation points for individual indicators in the scale of 0-100 points. In this case in the official method (Demidov et al. 2013), which is adopted in Ukraine, is used conversion method in which the values in a etalon of soil taken as 100 points, and in the estimated soil - proportional to it. Such way allows to get straight-proportional of assessment (Fig. 5a - normalization for the arithmetic mean), but the attempt to introduce in techniques additional indicators that change in ranges rather distant from scratch and have a direct impact on the productivity of crops and accordingly, the quality of the soil can cause serious errors. For example, recalculation in this way values of equilibrium bulk density in a points will be obtained obviously overstated results, because between of averaged optimum (1.23 t/m^3) and conditionally smallest and largest of its values, which can be found in soils (0.8 and 1.6 t/m^3) it is possible get estimate only in the range of 60-100 points (Fig. 5b – normalization for arithmetic average v1) while estimate of other indicators can varied within significantly wider range. The correctness of comparison in this case could put under some doubt, and accuracy based on their integrated assessment due to poor comparability of greatly reduced. The approaches proposed Kulakovskaya (1990), introduced into calculations the minimum (or maximum) value of indicator which allows to get its normalized value in the entire range 0-100 points (Fig. 5b – normalization for arithmetic average v2), but do not account for parabolic (or other) the nature of the curve that describes the conditions of growth and development, that usually takes place.

This to a certain extent accounted in normalization in case ZPYG (Grinchenko et al. 2008). The curve has *S*-shaped profile, the highest value reached in the theoretical optimum (100 points), smallest (0 points) at points of minimum and maximum values of indicator (Fig. 5a, b). But a detailed revision found that this curve is strictly symmetrical regarding the optimal point. This does not allow to consider asymmetry, which is very often occurs. This problem can be circumvented, by pointing to critical points separately for the left and right branches of the picture. Thus, we get two curves – normalization for ZPYG v1 and ZPYG v2 respectively (Fig. 5b). In this example, this asymmetry was not demonstrative, but it increases when considering such indicator, these differences will be very noticeable, as evidenced by the calculations. In this case left branch - normalization for ZPYG v1 - satisfactorily describes the porosity of the soil, giving a certain error for compacted conditions, and normalization for ZPYG v1 - conversely. But even such a possible way has certain features because a methodological problem turns out for this method of calculation: description of applied exponential function makes it impossible to set a fixed value of the nodes that correspond to points 100th, 80th, 50th and 0 scores, the importance of which is shown below. In practice, this means that for the same scores values of the normalized features, such as *pH* and equilibrium bulk density, their proportion will not be the same, as can be considered because crop tolerance to fluctuations of various parameters significantly different. With this approach, 50 scoring automatically assigned a mid-range between the minimum and maximum of possible values of the indicator. As can be seen in Fig. 5b, the *S*-shaped profile curve thus provides redundant scores for the approach of optimal values and minimizes them in the range of {50-0} scores. Obviously, this case will be received by averaging some error.



a) unilateral criteria



b) bilateral criteria

***Fig. 5.** Differences in values scores for various ways of normalization (on example winter wheat)*

To avoid the described problems Cherlinka (2001a, b), Smaga et al. (2007) suggested an approach that we describe in more detail. For normalization, we used scale of parameters suggested Medvedev et al. (1997). There are three gradations of indicators:

1) optimal – crop yield ranges from ≈20% of theoretically possible; 2) tolerable - crop yield is reduced by ≈30% from the previous; 3) unacceptable – productivity is reduced by more than ≈50% of the theoretically possible and tends to zero (Tab. 1).

Tab. 1. *Agro-ecological requirements of winter wheat to the factors of productivity*

The indicators, measurement units	Estimation conditions	The numerical values
a) bilateral criteria		
1. pH(KCl)	optimal	6.1-7.5
	tolerable	5.6-6.0 : 7.6-8.0
	unacceptable	<5.6 : >8.0
2. The equilibrium bulk density, t/m^3	optimal	1.10-1.35
	tolerable	1.00-1.09 : 1.36-1.45
	unacceptable	<1.00 : >1.45
b) unilateral criteria		
3. The humus content, %	optimal	>3.5
	tolerable	2.0-3.5
	unacceptable	<2.0
4. Nitrogen content, mg/100 g soil	optimal	>16
	tolerable	8-16
	unacceptable	<8
5.The content of mobile phosphorus, mg/100 g soil	optimal	>20
	tolerable	8-15
	unacceptable	<8
6. The content of exchangeable potassium, mg/100 g soil	optimal	>17
	tolerable	8-17
	unacceptable	<8
7. Depth of horizon with humus content, cm	optimal	>65
	tolerable	35-65
	unacceptable	<35

Source: (Medvedev et al., 1997)

In this range, unfortunately, there are no gradations which indicate the size parameters under which the plants begin to die. Therefore, to formalize and accurate assessment of the full range of features in which the plant has "economic value" – yields of crops, the original scale has been slightly amended by introducing a point where the plant begins to fight for "survival". In the case of bilateral criteria (*pH*, equilibrium bulk density etc.) are available two points that indicate, respectively, the right and left limits of the critical conditions for plant growth and development. In the extended in this way version of the scale been established boundaries of tolerable, unacceptable and optimal parameters (Tab. 2).

The equilibrium bulk density for winter wheat illustrates this case. Point of theoretical optimum (TO) achieved the mark 100, in which possible maximum realization of adaptive capacity of crops occurs. The extreme limits of optimal interval obtained the score of 80, extreme points of the tolerable range reached the 50 of score, and unacceptable was the 0 score. In connection to the lack in initial scale data width unacceptable range, we have taken the following: on the width of the tolerable ranges can draw conclusions about plant tolerance to a particular factor. If they are narrow, it means that the plant does not tolerate a reduction in values of factors, and in the worst conditions she would react the same way. The same applies to wide tolerable ranges. Therefore in the calculation we acted as follows: if on the tolerable range the assessment index was reduced to 30 points with a proportional reduction of its numerical value, then reduction for 50-scores is on the unacceptable range and the corresponding values of the indicator (Tab. 2).

Tab. 2. *Extended variant the scale of equilibrium bulk density (dens) in a range of plant growth and development (an example of winter wheat)*

	Unacceptable (left unacceptable range)	Tolerable (left tolerable range)	Optimum			Tolerable (right tolerable range)	Unacceptable (right unacceptable range)
	left critical limit*	left tolerable limit	left optimal limit	theoretical optimum (TO)*	right optimal limit	right tolerable limit	right critical limit*
reliability rating	0	50	80	100	80	50	0
dens	0,83*	1	1,1	1,225*	1,35	1,45	1,62*

**obtained by own calculation*

Before the occurrence of experimental data of this kind, this variant of the solution of this problem is obviously the only one possible. Its undeniable advantage, in our view, is to obtain a fixed assessment of normalized attributes at points of theoretical optimums, transition from optimal values of indicators to tolerable, from tolerable to unacceptable and critical points that allows for correct comparison of the evaluated features of soils, which is due to their equal scoring in the mentioned points and in the range between them. The transition from discrete pairs "score – value of features" shown in the Tab. 2, to continuous (Fig. 5) ensured using spline functions (Webster and Oliver 2007), including higher order polynomials, by approximation which accurately reproduce the function in the nodes {100-80-50-0} scores and in the intervals between them. Such method calculation makes it possible to obtain asymmetrically line that takes into account the deviation in requirements plants to the conditions of growth and development from ideal parabola unlike the curves for normalization for ZPYG v1 and ZPYG v2 and even more so lines to the normalization for arithmetic average (Fig. 5a,b). For the left and right branches graph (in connection with their asymmetry) are ob-tained various expressions, although at a sufficiently high degree of polynomial may receive one expression, which will be satisfactory to describe this relationship for both branches.

We developed an equation for estimating bilateral features for winter wheat (Tab. 3a). Development of advanced version the scale for unilateral criteria (nutrient content, humus, etc.), which is a particular case of bilateral, based on the same provisions. Relevant equations for unilateral criteria are given in Tab. 3b.

The methodical approach that was developed to calculate normalized values of soil parameters allows building soil fertility model in relative units. This allows for considering criteria such as soil quality index. The fertility of the soil based on real dataset was described in the following procedure. First, a correlation matrix defining the relationship between all known factors was constructed (bold marked notation to be used in Fig. 6): yields (**crop**, centner/ha), soil acidity (**pH**), organic matter (**humus**, %), nitrogen (**N**, mg/100 g), mobile phosphorus (**P**, mg/100 g), exchangeable potassium (**K**, mg/100 g), depth of horizon with humus content (**depth**, cm), equilibrium bulk density of soil (**dens**, t/m^3). Finally, a scatterplot matrix (Fig. 6) was generated from this dataset with the Performance Analytics package (Peterson et al. 2014) comprising histograms, kernel density overlays, absolute correlations, and significance asterisks (0.05, 0.01, 0.001). Each significance level is associated to a symbol: p-values (0.001, 0.01, 0.05) <=> symbols("***", "**", "*").

Tab. 3. *Polynomials for converting absolute values of the indicators to normalized (an example of winter wheat)*

The indicators, measurement units	Expression
a) bilateral criteria	
1. pH(KCl)	*y(left)** $= -15{,}34x^3 + 257{,}59x^2 - 1378x + 2382{,}6$ *y(right)** $= 1{,}5766x^4 - 36{,}8971x^3 + 273{,}372x^2 - 585{,}071x - 331{,}524$
2. The equilibrium bulk density, t/m^3	*y(left)* $= -1630{,}4x^3 + 4798{,}9x^2 - 4381x + 12$ *y(right)* $= 1630{,}4x^3 - 7184{,}6x^2 + 10226x - 4642{,}6$
b) unilateral criteria	
3. The humus content, %	*y(left)* $= 1{,}1111x^3 - 11{,}111x^2 + 55{,}278x - 25$
4. Nitrogen content, mg/100 g soil	*y(left)* $= 0{,}0084x^3 - 0{,}3568x^2 + 8{,}5696x + 2E\text{-}11$
5.The content of mobile phosphorus, mg/100 g soil	*y(left)* $= 0{,}0065x^3 - 0{,}2808x^2 + 8{,}0795x - 2E\text{-}11$
6. The content of exchangeable potassium, mg/100 g soil	*y(left)* $= 0{,}0075x^3 - 0{,}3581x^2 + 8{,}637x + 6E\text{-}13$
7. depth of horizon with humus content, cm	*y(left)* $= 8E\text{-}05x^3 - 0{,}0144x^2 + 1{,}8358x - 2E\text{-}12$

**y(left) and y(right) – expression for the left and right part of the scale respectively*

The productivity of soil is correlated with a high significance level with all the features of the soil and the biggest of them with the content of humus, nitrogen (N), phosphorus (P) and potassium (K) (0.79, 0.61, 0.69 and 0.79 respectively). Correlation between crop yield and equilibrium bulk density of soil is reversible, confirming the overall conclusion: on the soil with compaction to achieve high yields is not possible. Statistically insignificant connections between depth of horizon with humus content, pH and density of the soil is also quite logical. Analysing the relation between depth of horizon with the humus content and other observed parameters and analyse of kernel density directly indicates cultivation of winter wheat on fields with two different types of soil.

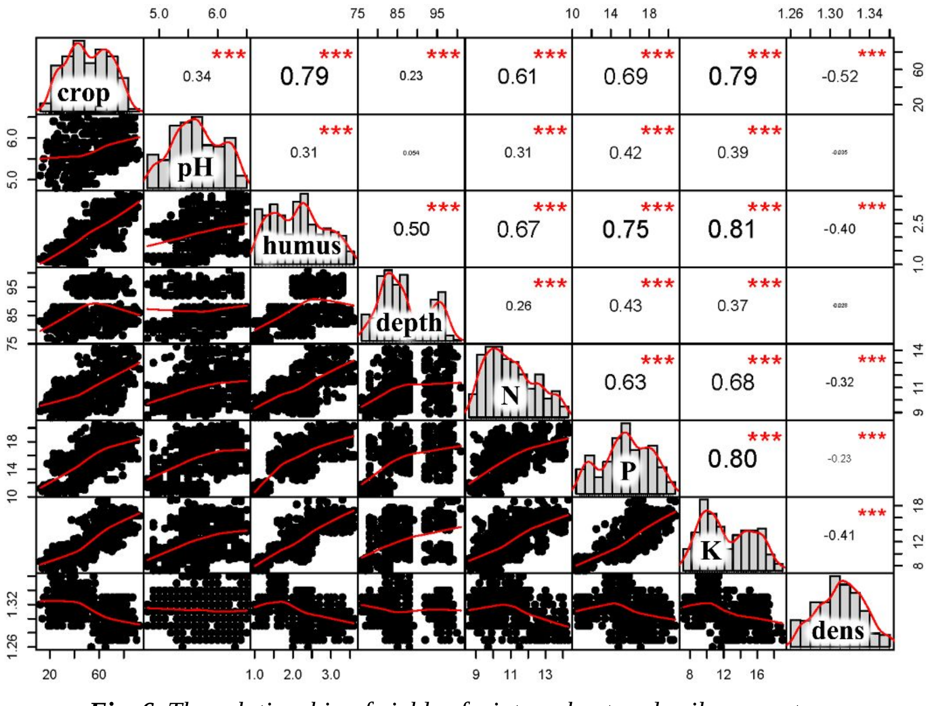


Fig. 6. *The relationship of yields of winter wheat and soil parameters;*
Note: The units of axes are explained in the text.

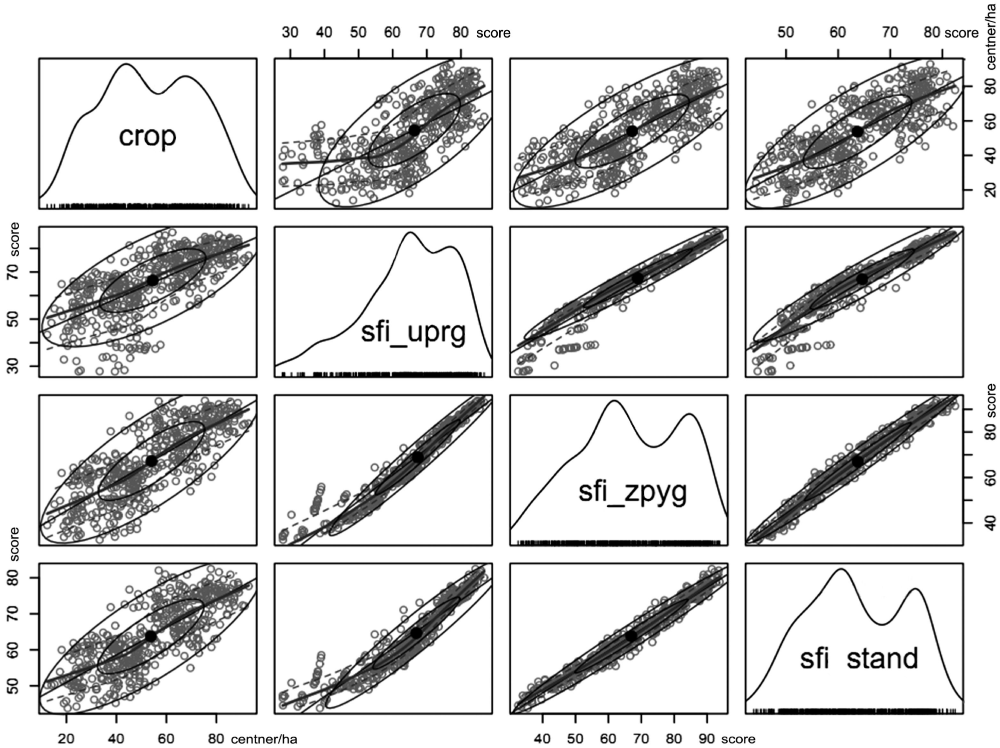


Fig. 7. *The relationship of productivity of yields of winter wheat and different integrated soil quality indexes*

Comparison of methods, such as standardized method of calculating the agrochemical and ecological and agrochemical scores points (Demidov et al. 2013) – **sfi_stand** (bold marked notation to be used in figure), method of calculation aggregate metrics of soil quality (ZPYG) proposed Grinchenko et al. (2008) – **sfi_zpyg** and generalized indicator of soil fertility – **sfi_uprg** taking into account normalization methods parameters showed that they are well describe the level of fertility of the soil in the our experiment (Fig. 7). The correlation coefficients are 0.69-0.79, which respectively indicate that these indicators include only 46-60% yield variability. Accordingly, 54-40% of the variability depends on factors that are not covered in our study. They can be divided into 2 parts: organizational and economic (which are generally difficult to account in such models) and climatic. As indicated by number of studies, our research confirmed the addition of climate parameters may help to improve the quality of integrated indicators of soil fertility (Alexandrov and Hoogenboom 2000, Barabas 2006, Lobell and Field 2007, Barabas 2007, Lobell and Burke 2010). Summarizing the arguments, we can infer that implementing this kind of calculations by using the average for most crops parameters (i.e. etalon), as used in the case a standard soils, provides, in our opinion, more opportunities to obtain correct estimates of soil quality about the possible range of values of attributes. The proposed model of soil fertility can be used not only to assess the quality of the soil, but also as an indicator of monitoring of changes soil fertility, in systems of precision agriculture and more.

Conclusions

Analysis of the published literature focusing on the use of soil fertility models as an indicator of soil quality showed that they have schematic character. In this paper, we aimed to develop a more complex model of soil fertility with finite number of parameters. This is important in adapting the model for the use in different countries and access to various data sets of soil parameters in them. It was indicated that the model must include agro-environmental requirements of individual crops to growth factors and basic laws of agriculture (law of limiting factor, law of minimum, optimum and maximum, law of combined effect of factors of Mitcherlih-Bowle, law of the critical periods) because all of the factors have a direct impact on the growth of crops and their response.

We proposed a method of creating a soil fertility model, which can be termed as a model of the state of fertility. In particular, the model is based on generalized indicator of soil fertility.

The formula of calculations complies with law of combined effect of factors and law of limiting factor. Compliance with other laws of agriculture and agro-environmental requirements of crops are providing a right choice of weighty parameters of soil and the most importantly – the specific way of their normalization. This is a very important moment, which is of key importance in assessing the quality of soils by means recalculation for individual indicators in the scale of 0-100 points. For normalization, we used next scale of parameters: optimal, tolerable and unacceptable. The point of theoretical optimum received assessment 100 – in her appears possible maximum realization of adaptive capacity of crops. The extreme limits of optimal interval obtained score 80, extreme points of the tolerable range – 50 score, and unacceptable – 0 score. The transition from discrete pairs "score – value of features" to continuous intervals ensured using spline functions including higher order polynomials. This approximation accurately reproduces the function in the nodes {100-80-50-0} scores and in the intervals between them.

We have developed an equation for estimate unilateral and bilateral features for winter wheat. The methodical approach that we developed to calculating normalized values of soil parameters allows further build soil fertility model in relative units. This makes it possible to offer such criteria as soil quality index.

Comparison of methods, such as standardized method of calculating the agrochemical and ecological scores points (used in Ukraine), method of calculation aggregate metrics of soil quality (ZPYG) and generalized indicator of soil fertility (UPRG) taking into account normalization methods parameters showed that they well describe the level of fertility of the soil in the our experiment. We made sure of its ability to describe the fertility of the soil on real facts. In this case was used next dataset: yields of winter wheat, pH, organic matter, nitrogen, mobile phosphorus, exchangeable potassium, depth of horizon with humus content, equilibrium bulk density of soil. It was shown that productivity of winter wheat is correlated with high significance level with all the features of the soil.

The correlation coefficients between crop and soil quality index are 0.69-0.79, which respectively indicate that these indicators include only 46-60% yield variability. Accordingly, 54-40% of the variability depends on factors that are not covered in our study. They can be divided into two parts: organizational and economic (which are generally difficult to account in such models) and climatic. Therefore, future research will focus on the combination of soil parameters of investigated models and climatic factors.

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Modely úrodnosti ako nástroj určovania kvality pôdy

Vasyl CHERLINKA

Zhrnutie: *Analýza publikácií zameraných na využitie modelov úrodnosti pôdy ako nástroja na hodnotenie jej kvality poukázala na prílišnú schematickosť využívaných modelov. Cieľom tohto príspevku preto bolo navrhnúť komplexnejší model úrodnosti a demonštrovať jeho aplikáciu pri hodnotení kvality pôdy. Model, ktorý sme navrhli rešpektuje poľnohospodársko-environmentálne požiadavky jednotlivých plodín z pohľadu rastových faktorov ako aj princípov poľnohospodárstva, ktoré majú priamy vplyv na rast konkrétnych plodín, pričom pri výbere vstupných ukazovateľov sme brali ohľad na variabilitu dostupnosti údajov o pôde v rôznych krajinách. Tieto faktory a princípy boli zároveň základom pre váženie hodnôt vstupných parametrov modelu a najmä ich normalizáciu na škále 0-100, a to v stupňoch optimálny (80 – 100 %), prijateľný (50 – 80 %) a neprijateľný (pod 50 % ideálneho výnosu z plodiny). Model sme aplikovali na odhad jednostrannej a dvojstrannej funkcie na príklade pšenice ozimnej.*

Navrhnutý metodický postup na výpočet normalizovaných hodnôt parametrov úrodnosti pôdy umožňuje jeho využitie aj ako indexu kvality pôdy. Vstupnými hodnotami testovania boli výnosy pšenice ozimnej, pH pôdy, organické látky, dusík, fosfor, draslík, hĺbka pôdneho horizontu s obsahom humusu a rovnovážna objemová hmotnosť pôdy. Preukázali sme významnú štatistickú koreláciu všetkých uvedených ukazovateľov vlastností pôdy s výnosmi pšenice ozimnej. Komparáciou s metódami, ako štandardizovanej metódy na výpočet agrochemického a ekologického bodového skóre (využívané na Ukrajine), metóda výpočtu agregátov kvality pôdy (ZPYG) a generalizovaného ukazovateľa úrodnosti pôdy (UPRG), sme preukázali relevanciu nášho modelu na odhad úrodnosti pôdy.

Hodnoty koeficientu korelácie medzi výnosom plodín a kvalitou pôdy sa pohybujú v rozmedzí 0,69 – 0,79, čo znamená, že uvažované ukazovatele vysvetľujú 46 – 60 % variability výnosnosti. Z toho vyplýva, že 40 – 54 % variability závisí od faktorov, ktoré v našom modeli nie sú zahrnuté. Tie možno rozdeliť do dvoch kategórií: organizačných a ekonomických (ktorých zapracovanie do takéhoto modelu je vo všeobecnosti veľmi zložité) a klimatické. Preto považujeme za vhodné smerovať ďalší výskum na zachytenie vzťahu parametrov kvality pôdy a klimatických faktorov.

Tab. 1. *Poľnohospodárske a ekologické požiadavky pšenice ozimnej na faktory produktivity*
Tab. 2. *Rozšírený variant rozsahu rovnovážnej objemovej hmotnosti pre rast a vývoj, príklad pšenice ozimnej*
Tab. 3. *Polynómy na konverziu absolútnych hodnôt uvažovaných ukazovateľov na normalizované (príklad pšenice ozimnej)*

Obr. 1. *Parabolický prístup: reakcia plodín ako funkcia dostupnosti minerálnych živín*
Obr. 2. *Variabilita integrovaného hodnotenia pôd v prípade použitia rôznych priemerov v porovnaní s pravidlom kombinovaného účinku faktorov podľa Mitcherliha a Bowleho*
Obr. 3. *Vplyv faktorov toxicity na produktivitu plodín*
Obr. 4. *Poloha územia prípadovej štúdie*
Obr. 5. *Rozdiely v hodnotách skóre pre rôzne spôsoby normalizácie (príklad pšenice ozimnej)*
Obr. 6. *Vzťah výnosov pšenice ozimnej a parametrov pôdy*
Obr. 7. *Vzťah produktivity reprezentovanej výnosmi pšenice ozimnej s rôznymi komplexnými ukazovateľmi kvality pôdy*

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