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Soil loss tolerance for agricultural land of the Right-Bank Steppe of Ukraine

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Abstract

The aim of the study was to develop a method of determining the soil loss tolerance for chernozem of the Right-Bank Steppe of Ukraine. The most reliable method of determining the soil loss tolerance is based on the quantitative assessment of the probable change in the productivity of chernozem under the influence of erosion for a fixed period of time. Such admissible decrease of soil productivity will be later compensated by the progress in farming at the expense of more perfect technologies of crops cultivation, fuller realization of genetic potential of agricultural plants, strengthening of soil-forming process, etc. The most accurate quantitative assessment of soil productivity is a definite integral of the distribution function of the modernized fertility index of Pierce along the soil profile. The fertility index of chernozem of the Right-bank steppe of Ukraine depends on five indicators normalized from 0 to 1: humus content, soil solution pH, bulk density, content of mobile forms of phosphorus and potassium, and weight index. Soil loss tolerance calculated for the chernozem of varies from 0.4 to 9.1 t/ha for the control period of 50 years, from 0.2 to 4.5 t/ha for the control period of 100 years, and from 0.1 to 2.3 t/ha for the control period of 200 years depending on the planned loss of productivity (from 1% to 20% of the initial value).

1. Introduction

Soil erosion, as is known, is defined as the process of separation, movement, and deposition of soil or rocks by gravity, water, wind, or ice, and this is the most important environmental problem in the agro sphere (Svetlichniy et al., 2004; Pimentel, 2006).

As a result of anthropogenic activity (agriculture, irrigation, and grazing), an accelerated version of erosion now for exceeds the natural rates of denudation in the agrosphere. This accelerated erosion quickly reduces the content of humus and nutrients in the soil, worsens physical properties of the soil particularly the structure of the soil and reduces the effective depth of rooting, thereby reducing the productivity of the soil (Svetlichniy et al., 2004). Large-scale reduction in soil productivity can pose a direct threat to food security.

Effectively protecting of the soil against erosion and degradation of productivity is possible only through the use of the concept of soil loss tolerance (SLT). This procedure compares actual soil erosion rates with permissible values, set both for concrete soil conservation practices and for the long-term management of soil resources (Wishmeier and Smith, 1978).

The term «soil loss tolerance» arose in the 1930s and 1940s in the United States, almost contemporaneous with the commencement of work on the USLE. In the thirties, H. Bennett (1939) determined the SLT (or T-level) as the maximum annual erosion loss, which the fertility of the soil would remain indefinitely at an economically substantiated level. Wishmeier and Smith (1978) determined SLT as the maximum level of soil erosion, which would allow for a long, high-yielding, economically justified harvest. In his monograph «Erosion and Soil Protection», Morgan (2005) states that SLT should be understood as «the maximum allowable extent of erosion in which the soil fertility would be maintained for 20–25 years».

By analyzing various definitions of SLT it is possible to draw precisely two meanings (Verheijen et al., 2009). The first interpretation of this term stipulates maintaining a dynamic equilibrium in a specified amount of soil (weight or volume) in any place under any conditions. The second interpretation is functional: SLT is a way of realizing the production function of the soil, directed only at acquiring biomass. But when in the 2000s a comprehensive and holistic concept of the functions of soils was developed based on location, informational, production, engineering, and regulations (ecological in general), a new definition of SLT also arose. According to these authors, this term should be understood as «any average actual annual volume of soil erosion at which there is no deterioration or loss of one or more soil functions of soils» (Verheijen et al., 2009).

Analysis of publications (Stamey and Smith, 1964; Skidmore, 1982; Pierce et al., 1984; Alexander, 1988; Chornyy, 1999; Svetlichniy et al., 2004; Bhattacharyya et al., 2008; DSTU 4730:2007, 2008; Li et al., 2009; Duan et al., 2012; Duan et al., 2017; Chornyy and Polyashenko, 2017; Ostovar et al., 2020) shows that SLT can be defined according to various concepts:

- taking into account the properties of the root-containing soil layer;
- on the basis of the rates of soil formation;
- taking into account the probable change in soil productivity as a result of erosion.

As for determining SLT based on the properties of the root layer of soil, the best known is the methodology of the Natural Resources Conservation Service (USDA-NRCS). All US soils were previously divided into separate groups based on various properties for promoting crop cultivation (Li et al., 2009). As a result, five levels of permissible erosion rates were determined at 2.5, 5.0, 7.5, 10 and 12.5 ton per hectare per year. The minimum values of SLT were determined for soils with the worst properties of the root-containing layer, and the maximum for soils with the best conditions for the development of root systems of plants. Determination of the USDA-NRCS T-level, practically from the moment of its conception, has undergone devastating criticism because of weak scientific validity. Therefore, many authors turned to other concepts for the definition of SLT, in particular, taking into account the rate of soil formation (Alexander, 1988; Chornyy, 1999; Svetlichniy et al., 2004; Li et al., 2009, Alewell et al., 2015). It should be noted that “The European strategy for protection of soils” directly states that natural rates of soil formation can be used as a basis for the establishment of SLT. This document specifies that all soil losses of more than 1 ton per hectare per year irreversibly change properties of the soil during 50–100 years of operation (Verheijen et al., 2009).

However, some other publications (Pierce et al., 1984; Alexander, 1988) declare two rates of soil formation, on the basis of which two T-levels (two SLTs) are calculated. The first is the rate of formation of the top, most valuable soil layer. It is obvious that a quality, well aggregated and aerated soil layer, occupying about 25–30 cm in the upper part of the soil profile, allows maintaining certain moisture content in the soil, thus providing the agricultural plants with nutrients. The second (and best, according to a number of authors, for example (Li at el, 2009) – is the rate of soil formation of the whole soil profile. However, it is considered that this rate is extremely difficult to determine, because soil formation within the profile has significant temporal and spatial variations associated with changes in the properties of the bedrock and microclimate. In addition, under anthropogenic conditions the rate of soil formation is influenced by a set of other factors, such as, for example, the duration of soil use as arable land, the structure of crop rotation, the features of soil tillage, the rates of fertilizers applied, the current rate of soil erosion, the application of soil protection measures, and so on. Numerous anthropogenic components of soil formation are poorly accounted for and therefore practically do not appear in methods for determining the SLT based on norms of soil formation, for which such approaches are fairly criticized by various authors. Our attempts to introduce SLT (based on the speed of anthropogenic soil formation) into the soil protection practices of Ukraine encountered resistance by land managers and farmers due to the very small permissible values of SLT, the realization of which demands considerable financial resources (Svetlichniy et al., 2004; DSTU 7081:2009, 2010).

As for the value of permissible fertility reduction under the influence of erosion, there is there is no consensus on this problem in the scientific literature. For example, Runge et al. (1986) believe that a 1% decrease in fertility over 100 years should not affect long-term soil productivity. Schertz (1983) suggested that a specific time interval of 500 or even 1,000 years would be more appropriate for maintaining production than using the concept of "over a long period of time" in establishing an allowable erosion rate. Benson et al. (1989) believe that the decrease in fertility over 100–500 years cannot be less than 5%, and that such a decrease will be compensated by advances in crop cultivation methods and the creation of new varieties and hybrids of agricultural plants. Morgan (1987) defined the "limit point" of erosion as the point at which crop yields fall below 75% of the maximum possible yield. In determining SLT based on the Pierce fertility index, fertility loss rates are calculated at 1%, 2%, 3%, 5% and 10% of the base value for a controlled period of 50, 100 and 200 years (Pierce et al., 1984; Duan at al., 2012; Chornyy and Polyashenko, 2017).

Landowners, state land control bodies need to be offered a set of SLT values that should be calculated for a wide range of soil control periods and allowable fertility losses. Thus, the goal of the study was to create an objective methodology for evaluating acceptable erosion indicators, which should be suitable for the steppe part of Right-Bank Ukraine with chernozem soils and to obtain a list of SLT values for different management periods and different probable fertility losses. For this, it was necessary to modify the SLT assessment method, which is determined using the Pierce index (Pierce et al., 1984; Duan et al., 2012; Chornyy, Polyashenko, 2017), taking into account temporal changes in the fertility index under the influence of erosion and the admissibility of such changes.

2. Materials and methods

2.1. Study area

The study area is located in the Steppe zone of Ukraine, in particular, on its right-bank part, relative to the Dnipro River. The surface of the Right-Bank Steppe of Ukraine is the loessial plain, with absolute altitudes from 0 to 240 m and gently sloping in the southern direction. Its largest (central and southern) part is the Black Sea lowland. In the north are spurs of the Dnipro and the Podolian Upland, which are separated by a network of gullies.

Loess is the main sediment from which the soils of the region were formed. Loess covers the entire interfluve and bordering watersheds, coastal Pliocene marine terraces and ancient river valley terraces. The climate of the Right-Bank Steppe of Ukraine can be characterized as moderately continental, arid, with large heat resources.

2.2. Soils

For soils of the Right-Bank Steppe of Ukraine the main type of soil formation is the steppe (sod) process, which created the main soil of the region–chernozem. Chernozem soil has a «chernic» horizon which is a thick well-structured black with base saturation; it has a high biological activity, moderate to high content of organic carbon.

A characteristic feature of the Right-Bank Steppe chernozem formed on carbonatic sediment (loess) is the presence of a calcic horizon or layer with protocalcic properties, which begins at a depth of 40–50 cm. Therefore, in most cases, soils were classified as Calcic Chernozems (IUSS Working Group WRB, 2015) (Table 1). In the southern part of the region, in conditions of decreasing rainfall, the soil forms an «argillic» horizon subsurface B soil horizon, which is determined by the illuvial accumulation of silicate clays. These soils were classified as Luvic Chornozems (Table 1).

Right-Bank Steppe chernozem often has a short humus horizon, because here, as a result of irrational structure of sown areas and complex terrain, water erosion is widespread.

2.3. Field and laboratory research

Determination of SLT by the method of a permissible reduction of soil productivity in a predetermined time frame provides for a quantitative assessment of soil fertility. In this publication, soil fertility will be quantitatively determined by means of modified index of productivity. To identify the index of productivity of the soil of the region, several soil profiles were created.

Table 1
Location and description of investigated soil profiles.

№	Landform, slope grade	Land use	Coordinates		Horizon sequence of soil profile	Name of the soil (IUSS Working Group WRB, 2015)
			Latitude (N)	Longitude (E)		
1	Watershed	Arable land	46°55’20.5”	31°40’56.2”	A (0–33 cm), AB (33–47 cm), Bk (47–65 cm), Ck 65–120 cm	Luvic Chernozem
2	Slope of the western exposition	Arable land	46°54’35.4”	31°40’04.4”	A (0–19 cm), AB (19–32 cm), Bk (32–52 cm), Ck 52–120 cm	Luvic Chernozem (eroded soil)
3	Watershed	Arable land	47°20’55.1”	32˚52’13.5”	A (0–27 cm), AB (27–43 cm), Bk (43–63 cm), Ck 63–113 cm	Calcic Chernozem (Clayic)
4	Slope of northwest exposure, 2–3°	Arable land	47°20’47.1”	32˚51’47.6”	A (0–27 cm), AB (27–49 cm), B_k (49–96 cm), Ck > 96 cm	Calcic Chernozem (Clayic)
5	Slope of northwest exposure 6–7°	Arable land	47°20’49.7”	32˚51’48.7”	A (0–20 cm), AB (27–40 cm), B_k (40–68 cm), Ck > 68 cm	Calcic Chernozem (Clayic) (eroded soil)
6	Watershed	Fallow	47°20’53.0”	32˚51’44.0”	A_1 (0–5), A_2(5-18 cm), AB (18–35 cm), Bk (35–54 cm), Ck > 54 cm	Calcic Chernozem (Clayic)
7	Watershed	Arable land	46°53’54.0”	31°40’55.9”	A (0–37 cm), AB (37–52 cm), B_{tk} (52–77 cm), Ck > 77 cm	Luvic Chernozem
8	Slope of the western exposition 4–5°	Arable land	46°53’41.7”	31°40’37.0”	A (0–28 cm), AB (28–45 cm), Btk (45–68 cm), Ck (68–120 cm)	Luvic Chernozem (eroded soil)
9.	Watershed	Arable land	46°56’10.7”	31°39’16.0”	A (0–34 cm), AB (34–47 cm), Btk (47–65 cm), Ck > 65 cm	Luvic Chernozem
10.	Watershed	Arable land	46°56’11.2”	31°39’31.3”	A (0–38 cm), AB (38–50 cm), Btk (50–68 cm), Ck > 68 cm	Luvic Chernozem
11.	Watershed	Arable land	47°14’30.5”	31°35’48.0”	A (0–45 cm), AB (45–55 cm), Bk (55–72 cm), Ck > 72 cm	Calcic Chernozem
12.	Watershed	Arable land	47°14’45.7”	31°35’37.2”	A (0–41 cm), AB (41–50 cm), B_k (50–73 cm), Ck > 73 cm	Calcic Chernozem
13.	Watershed	Arable land	48°02’44.0”	31°40’14.0”	A (0–55 cm), ABk (55–78 cm), Bk (78–100 cm), Ck > 100 cm.	Calcic Chernozem
14.	Slope of the western exposition, 2–3°	Arable land	48°02’37.1”	31°39’16.6”	A (0–33 cm), ABk (33–54 cm), Bk (54–96 cm), Ck > 96 cm.	Calcic Chernozem (eroded soil)
15.	Watershed	Arable land	47°53’28.8”	31°49’11.3”	A (0–40 cm), ABk (40–64 cm), Bk (64–87 cm), Ck > 87 cm.	Calcic Chernozem
16.	Slope of the western exposition, 2–4°	Arable land	47°53’03.1”	31°49’17.0”	A (0–28 cm), ABk (28–50 cm), Bk (50–75 cm), Ck (75–120 cm).	Calcic Chernozem (eroded soil)

Coordinates of these soil profiles and their characteristics are specified in table 1. Samples were taken every 10 cm to a depth of 100 or 120 cm to determine the physical and chemical properties of the soil, namely, the bulk density, texture indicators, humus content, pH of the soil solution, and the content of mobile phosphorus and potassium. Determination of the properties of soils was carried out according to Ukrainian state standards.

The bulk density was determined by the cutting-ring method (DSTU 11272:2001, 2002).

The soil texture was determined by the "pipette method" with pretreatment of the sample with 10% HCl solution to remove carbonates. For complete dispersion of the soil into elementary soil particles, NaOH followed by boiling the suspension was used (DSTU 4730:2007, 2008).

The content of humus was determined by determining the content of carbon by the oxidometric method, the value of which is then converted into the content of organic matter. The specified method involves measuring the optical density on a photoelectric photometer with a wavelength of 590 nm) (DSTU 4289:2004, 2004).

The pH in the extract was determined by potentiometric method. Hydrogen ions of free acids were extracted from the soil with distilled water at a soil to water ratio of 1:2.5 (DSTU 10390:2007, 2012).

The method for determining the content of mobile forms of potassium and phosphorus was based on the extraction of phosphorus and potassium compounds from the soil with 1% ammonium carbonate solution, at pH 9.0, at 25 ± 2°C. The soil/solution ratio is 1:20 (DSTU 4114:2002, 2003).

2.4. Determination method of SLT

2.4.1. Quantification of soil resource quality

As it is defined above, the method of determining SLT based on a predetermined value of the probable change in soil productivity through the process of erosion looks to be the most justified in comparison with other methods.

The authors established changes in the index of productivity (*IP*) due to erosion of a certain soil over a period of time on the basis of the following calculations (Pierce at al, 1983; 1984):

$$IP = \sum_{i=1}^{n} (A_i \cdot C_i \cdot D_i \cdot WF_i), \quad (1)$$

where A_i is the water-retaining capacity of the soil, C_i is the bulk density of the soil, D_i is the pH of the soil solution, WF_i is the weighting factor representing an idealized distribution of root systems, and *i* is the number of horizons in the depth of rooting (Pierce et al, 1983). Each indicator, normalized in fractions of a unit, ranges from 0 to 1. WF_i is the root weighting factor of the i-th soil layer and reflects that physical and chemical properties at different soil depths have different effects on soil productivity (Pierce et al, 1983):

$$WF_i = 0{,}35 - 0{,}152 \times lg\ (h + \sqrt{h^2 + 6{,}45}), \quad (2)$$

where *h* indicates the soil depth within the profile in cm (Pierce et al., 1983; 1984; Duan et al., 2011).

The model (1) was further improved with the introduction of new fertility indicators: the content of organic matter, the content of clay and/or muddy particles by texture analysis (Duan et al., 2012; Chornyy and Polyashenko, 2017; Duan et al., 2017), the content of nutrients (Chornyy and Polyashenko, 2017) etc. When using model (1), not only in the context of SLT, but as an index of the fertility of specific soils, those indicators reflecting particular regional fertility characteristics were used most often. The authors (Pierce et al., 1983; Duan et al., 2011; Duan et al., 2012; Chornyy and Polyashenko, 2017; Duan et al., 2017) recommend using samples taken every 10 cm in 1 meter of soil thickness for analysis. If the soil has less than a 1-meter thickness (for example, in soils with the dense bedrock), then it is recommended using the actual thickness of the soil.

At the same time, judging by the published research (Pierce et al., 1983; Duan et al., 2012; Chornyy and Polyashenko, 2017; Duan et al., 2017), there are certain shortcomings in the methodology based on formula (1).

At first, the fertility of the soil in a layer of 0–100 cm (or in another layer) is defined as a non-renewable resource. That is the decrease of fertility of the soil under the influence of erosion will be proportional only to the size of the soil layer lost to erosion and eventually it will be completely exhausted. But with other things being equal, under the process of erosion, which is a reduction of uppermost, most fertile layers of soil, the lower, less fertile layers of soil participate in. in providing nutrients to a harvest of crops. It is especially evident in those soils formed on friable bedrock, which always has some fertility, in particular, on the loess. It is apparent that the size of these layers will equal to the capacity of topsoil which was lost to erosion.

Secondly, the normed parameters of the soils defining their fertility in the mathematical formula (1) are equivalent to one another, which is a certain exaggeration. In particular, it is obvious that the *WF* function is not directly related to soil productivity, but actually only shows the weight of each layer of soil in generating the overall productivity of the soil under conditions of average humidity. It should be noted that function (1) in the original publication (Pierce et al., 1983) was developed only on the basis of data on the distribution of a root system of corn in soils of the State of Wisconsin in the USA and cannot be universal for all cases.

And therefore, another approach to the procedures of land use optimization on erosion- hazardous areas is possible. If there is a mathematical function of fertility index (*fi*) change by soil depth, then a defenide integral of this function within the soil layer to be controlled (*H*) can be an indicator of the fertility of the whole soil, a quantitative parameter of soil resource quality (*SQ*):

$$SQ = \int_0^H f(fi)dh. \quad (3)$$

2.4.2. Change of parameter of soil resource quality in time

It is apparent that in using soil resources under the influence of soil erosion during time *T*, a certain layer of soil, *Δh*, will be destroyed (Fig. 1). At the same time, the process of land use

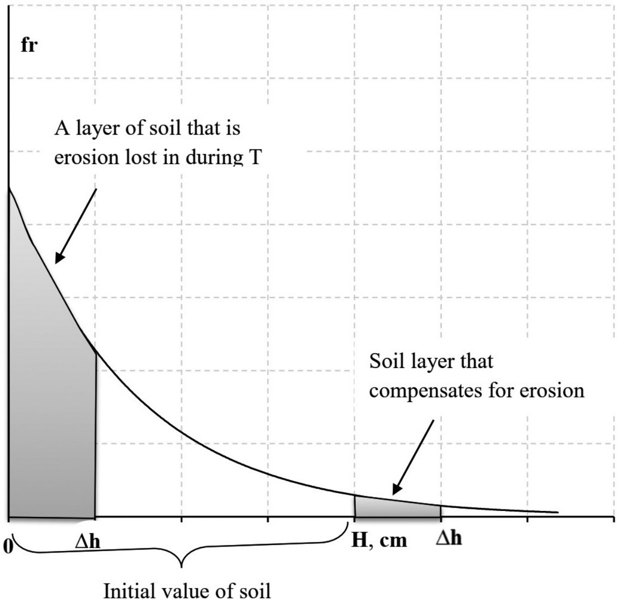

Fig. 1. Change of soil fertility under the influence of erosion

will gradually include a similar, but less fertile, soil layer that is deeper than the lower boundary of the controlled soil layer *(H+Δh)*. Therefore, during *T* the initial fertility of the soil will change as

$$\int_0^H f(fi)dh - \int_0^{\Delta h} f(fi)dh + \int_H^{H+\Delta h} f(fi)dh. \quad (4)$$

Such changes of soil fertility during time (*T*) should be smaller or equal to the acceptable norm of change of soil fertility, which is the difference between the initial fertility and its predetermined, planned loss, which is defined in fractions of a unit or a percentage of the initial parameter of soil resource quality (θ):

$$\int_0^H f(fi)dh - \theta \times \int_0^H f(fi)dh.$$

So final mathematical expression which defines the procedure of the management of the quality of soil's resources under conditions of erosive destruction on a separate land plot during time (*T*) has the following form:

$$\int_0^H f(fi)dh - \int_0^{\Delta h} f(fi)dh + \int_H^{H+\Delta h} f(fi)dh \leq$$
$$\leq \int_0^H f(fi)dh - \theta \times \int_0^H f(fi)dh, \quad (5)$$

where *f (fi)* is a function of distribution of the fertility index on a soil profile, within a layer of soil *0–H* cm; Δh is the value (cm) of a soil layer which will be lost as a result of an erosion over time (*T*); θ is a fraction of an initial parametr of soil quality which is planned to be lost during time *T* (in fractions of a unit).

Thus, the left side of inequality (4) shows the changes of soil resource quality parameter in the soil quality parameter under the influence of erosion over time (*T*), and the right side of the inequality determines the permissibility of such changes.

After reductions, inequality (5) can be written as follows:

$$\int_0^{\Delta h} f(fi)dh - \int_H^{H+\Delta h} f(fi)dh \leq \theta \times \int_0^H f(fi)dh. \quad (6)$$

Obviously, if inequality (6) is solved with respect to Δh (cm) and then the obtained value is divided by the time of land use control (*T*, years), then the value of $\Delta h/T$ (cm per year or tons/hectare per year) will be the soil loss tolerance (SLT) for any controlled soil layer with value *H* (cm).

2.4.3. Components of parameter of soil resource quality

It was determined above that the soil resource quality parameter (*SQ*) (3) and its changes under the influence of erosion (5) can be identified only in the presence of the mathematical function *f(fi),* which shows the changes in the soil fertility index fi along the soil depth. To construct the function *f(fi),* it is necessary to use approaches that are inherent to soil fertility modeling by means of *IP* index (1,2).

Analysis of literature data (Pierce et al., 1983; Duan et al., 2012; Chornyy and Polyashenko, 2017; Duan et al., 2017) and study of properties of chernozem's soils, showed that the optimal way to determine the fertility index $(fi)_h$ in each layer of the soil profile h is to multiply the geometric mean normalized (from 0 to 1) of some soil fertility indicators (*Pi*) and the weight factor WF, which shows the participation of each soil layer in the overall assessment:

$$fi_h = \left(\sqrt[n]{\prod_{i=1}^{n} P_i}\right)_h \times (WF)_h. \quad (7)$$

As for the list of fertility parameters that need to be used in the equation (7), it is necessary to use those parameters which are used in Ukraine for comparative characterization of soil quality in scores based on soil surveys.

In the most modern and detailed methodology for comparative characterization of soil quality Ukrainian soils, based on the existing correlations in the "soil-harvest" system, it is recommended to use 6 indicators that most fully characterize soil fertility in the Chernozem's zone of Ukraine (Medvedev and Plisko, 2006). These are the content of humus, pH of soil solution, the content of clay (soil particle content less than 0.01 mm by texture analysis), bulk density, and the contents of mobile phosphorus and potassium. But the analysis of the source data showed that, for all soil profiles of the soil of the Right-Bank Steppe of Ukraine, the soil texture is quite uniform: the content of clay is in the range of 55–60 %. And therefore this indicator has no decisive influence on studied soil's fertility.

Consequently, formula (7) will have the following form:

$$fi_h = \sqrt[5]{g_h \cdot ph_h \cdot \gamma_h \cdot \rho_h \cdot k_h} \times (WF)_h, \quad (8)$$

where fi_h is the fertility in soil layer *h*; g_h, ph_h, γ_h, ρ_h, k_h are the following values (normalized from 0 to 1): the humus content, pH of soil solution, bulk density, contents of mobile phosphorus and potassium in soil's layer *h*; WF_h is the value of the weighting factor in soil layer *h*.

In formula (8), all factors are considered equal, which is obviously a certain exaggeration. But various authors (Pierce et al., 1984; Duan at al., 2012; Chornyy, Polyashenko, 2017), who used Pierce's model in its original or modified form to determine SLT, considered the possible inequality of fertility parameters insignificant, which does not affect the final result.

Quantitative analysis of the fertility factors of chernozem soils of Ukraine, based on a large number of data from field experiments, given in the monograph (Medvedev and Plisko, 2006), did not show a decisive influence on soil fertility of one or more parameters. The system of comparative soil quality characteristics of Ukrainian soils developed by the authors, based on existing ratios in the "soil-crop" system, is based precisely on the equivalence of individual fertility parameters.

Other important factors of fertility, including water retention capacity of soil and the amount of nitrogen, for Chernozem's soils of Ukraine, are considerably dependent on the already determined parameters. In particular, water retention capacity of soil is fully dependent on the particle size distribution and humus content, and the total amount of nitrogen in soil is determined by the humus content.

2.4.5. Normalization of fertility parametres

Numerous publications (e.g., DSTU 4362:2004, 2005; Medvedev and Plisko, 2006 etc.) evaluate the impact of humus as a source of nutrients and as a substance beneficial to the physical, chemical and biological properties of Ukrainian chernozem. However, the high role of humus in the formation of soil productivity is clearly observed only in soil with low or medium humus content. A tangible effect on the productivity of crops is not present at a humus content of more than 3.5% (Medvedev and Plisko, 2006). Therefore the normalization of the effect of the humus content (g_h) on fertility must be carried out as follows:

$$g_h = \begin{cases} h/3.5, & if \;\; h \le 3.5\% \\ 1 & if \quad h > 3.5\% \end{cases} \quad , \tag{9}$$

where h is the humus content as a percentage.

The influence of pH soil solution on the fertility of soils in Ukraine is presented in a number of papers (DSTU 4362:2004, 2005; Medvedev and Plisko, 2006). For most crops in the region, the best value of pH is 6.1–7.2. Increasing or decreasing the pH relative to this range decreases yield.

Generalizing from the publication data presented above shows that for the range of the pH value appearing in the soil of the Right-Bank Steppe of Ukraine (pH = 6.0–8.5), the following quadratic dependence can be used in equation (8):

$$ph_h = -0.062 \cdot (pH)^2 + 0.554 \cdot pH - 0.056, \tag{10}$$

where pH is the reaction of the soil solution.

The influence of bulk density on the fertility of Ukrainian soils is given in the following publications (DSTU 4362:2004, 2005; Medvedev et al., 2004; Medvedev and Plisko, 2006). For most crops grown in the soil of the Right-Bank Steppe of Ukraine, the optimum density values are 1.15–1.25 g·cm^{-3}. The monograph (Medvedev et al., 2004) for soil of the Right-Bank Steppe of Ukraine gives the following equation, which shows the influence of bulk density on crop yield:

$$\gamma_h = 1 - 5.00 \times (Y - 1.20)^2, \tag{11}$$

where Y is the bulk density, g·cm^{-3}.

Phosphorus and potassium are important in the formation of crop yields. Generalizations on this issue for Ukrainian soils are explained in publications (Nosko at al, 1996, Nosko, 1990; Medvedev and Plisko, 2006) and also in the state standard(DSTU 4362:2004, 2006). Based these publications, the normalized value of phosphorus and potassium content can be calculated as

$$\rho_h = \begin{cases} \frac{P}{45}, & if \;\; P \le 45 \\ 1, & if \;\; P > 45 \end{cases}, \tag{12}$$

$$k_h = \begin{cases} \frac{K}{300}, & if \;\; K \le 300 \\ 1, & if \;\; K > 300 \end{cases} \quad , \tag{13}$$

where P and K are the contents of the mobile forms of phosphorus and potassium, respectively, in mg·kg^{-1}.

2.4.6. Weighting factor (WF)

As mentioned above, the WF index is an indicator of the influence of a particular soil layer on its overall productivity. The current realization of this function (2) cannot be used for the soil of the Right-Bank Steppe of Ukraine because it does not take into account the specific list of crops in this region.

A generalization of the in-soil distribution of root systems of the main crops of the world's natural temperate zone is provided in the publication (Fan et al., 2016). The database that was the basis for the initial model was compiled from journals and book sections by searching for information in Scopus and Google Scholar.

A total of 96 root profiles for 11 crops were included in the database. The aggregate was carried out through the creation of a cumulative curve of the distribution of the mass of root systems in the soil, by means of the equation of a logistic curve «dose effect»:

$$Y_i(h) = \frac{1}{1 + \left(\frac{h}{d_a}\right)^c} + \left[1 - \frac{1}{1 + \left(\frac{d_{max}}{d_a}\right)^c}\right] \cdot \frac{h}{d_{max}} \quad , \tag{14}$$

where $Y_i(h)$ is the root distribution for the soil profile at depth h (cm); d_a, and c are parameters of the logistic curve; d_{max} is the maximum length of the roots of a particular crop (cm).

The values of these parameters for the main crops of the temperate belt of the World are given in the article (Fan et al., 2016). To obtain the average values of the indicator $Y_i(h)$, which depend only on the parameters h, the values of d_c, c, d_{max} were calculated as arithmetic averages weighted by the areas of the main crops of the region (Table 2). Information from the website of the State Statistics Service of Ukraine (site 1) was used

Table 2
Estimated indexes for structure of sown areas for Steppe of Ukraine.

Agricultural culture	Percentage in percent	Indexes		
		d_a	c	d_{max}
Wheat	28.1	17.2	–1.286	150.4
Maize	6.9	14.9	–1.151	118.3
Barley	18.2	11.8	–1.06	146.1
Legumes crops (soybean, pea)	1.8	16.2	–1.115	104.8
Oilseed crops (sunflower, rape)	35.1	10	–0.671	133
Grasses	0.9	20.7	–1.032	176.8
Others	9.0	15	–1.117	141.9
Weighted average		13,364	–0.99945	139.876

to determine the structure of sown areas of agricultural crops in the Odessa, Mykolayv, and Kherson regions. It is evident that the WF_h value in every soil layer h in equation (8) equals the difference:

$$(WF)_h = Y(h)_j - Y(h)_i, \quad (15)$$

where $Y(h)_j$ is the value of the function (14) on the upper boundary of soil layer h, and $Y(h)_i$ is the value of the function (14) on the lower boundary of soil layer h.

2.4.7. The function of the distribution of the fertility index on a soil's profile

The function of fertility index distribution over the profile of the soil of the Right-bank steppe of Ukraine was obtained by the above method. For this purpose, the fertility index (f_{ih}) was calculated in accordance with (8) for each soil layer (Table 1) taking into account formulas (9–13, 15).

As a result of generalization on 16 soil profiles of the soil of the Right-Bank Steppe of Ukraine the following equation (R^2=0.92) was obtained (Fig. 2):

$$fi_h = 0.45 \cdot exp(-0.064 \cdot h), \quad (16)$$

where h is depth of soil layer in cm.

The curve fi_h=$f(h)$ looks like an exponent for two reasons. First, the upper part of the soil profile of the soil of the Right-Bank Steppe of Ukraine contains the greatest amount of organic matter and nutrients compared with the lower horizons, and this part is also the least dense part of the soil profile. The exception is the pH of the soil solution, which does not have optimal values in the humus layer of the soil. That is, most of the components of the fertility index have the highest values in the upper part of the soil profile. And, secondly, the *WFh* function, for obvious reasons, will take the highest values in the upper soil layer, and the lowest ones in the lower layers.

In other words, the equation (16) shows that the fertility of the the soil of the Right-Bank Steppe of Ukraine is largely determined by the upper layers, and the soil layers at a depth of more than 40 cm do not play a significant role in the formation of total soil productivity, although they do participate.

Approximation of the function fi_h=$f(h)$ in the form of (16) allows us to obtain the final mathematical model describing the intensity of changes in the soil of the Right-Bank Steppe of Ukraine fertility under the influence of erosion for the time T (the left part of inequality (6)) and the allowable losses of this soil resource for the time T (the right part of inequality (6)). The solution of this equation relative to the parameter Δh and divid-

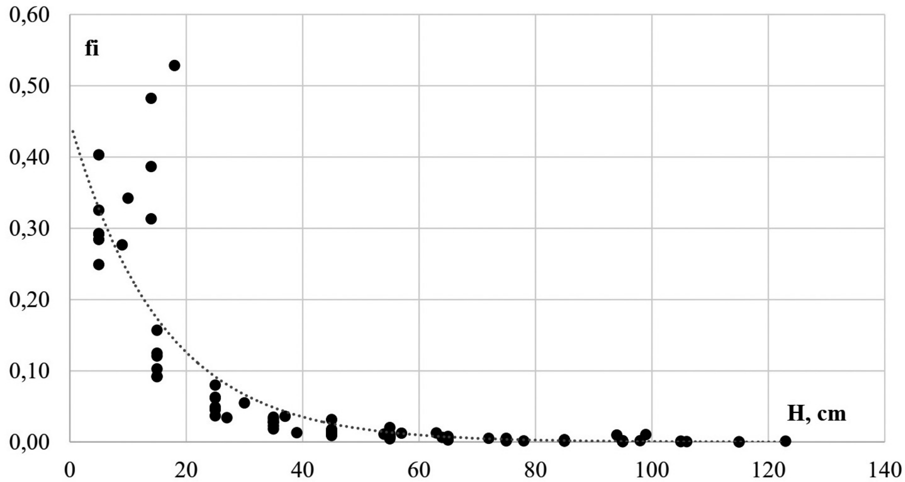

Fig. 2. Fertility index (fi) versus soil depth (H) (R^2=0.92).

ing its value by the time T ($\Delta h/T$ in centimeters per year or in tons per hectare per year) will be the soil loss tolerance (SLT) when using the soil layer of size H (cm).

It is the calculations according to (6) that can be put into the system of recommendations for landowners, which will allow them to determine the planned level of soil erosion degradation for a certain period of time taking into account farm specialization, market conditions of agricultural products, cost of erosion control measures and the like.

3. Results and discussion

The methodology for determining the soil loss tolerance based on inequality (6) suggests that the soil of the Right-ank Steppe of Ukraine formed on loose loess rocks is, in fact, an inexhaustible resource. This is evidenced by the parameters of equation (16), which demonstrates the nonzero value of this function in the deep soil layers outside the humus layer That is, even at erosion of already highly eroded soils, there will always be partial compensation of lost fertility at the expense of bedrock. On the other hand, equation (16) shows the determining value of the upper 40 cm layer on the total fertility of the soil of the Right-Bank Steppe of Ukraine and on the value of *SQ*.

The specific structure of the left part of the inequality (6) and the parameters of the curve (16), leads to the fact that with almost any values of erosion loss of fertility (Δh) there is, on the one hand, an obvious decrease in absolute values of *SQ,* and on the other hand, relative values of *SQ* depend little on the size of the soil layer, which is controlled in the process of land use. For example, for the probable loss of the top 10 cm of soil when controlling the 0–30 cm soil layer and when controlling the 0–50, 0–70, and 0–100 cm soil layer, the relative losses at different absolute values (3.16, 3.56, 3.67, and 3.7, respectively) are 52.73% of the original value (Table 3). It follows that in the process of calculating the allowable erosion rate, which begins with determining the value of Δh as the normative value of soil losses with erosion on the left side of inequality (6), we can neglect the size of the soil layer, which is managed during land use.

Table 3 shows SLT values for five levels of planned erosion losses—1% ($\theta=0.01$), 2% ($\theta=0.02$), 5% ($\theta=0.05$), 10% ($\theta=0.1$), and 20% ($\theta=0.2$) of the baseline value over 50, 100, and 200 years of fertility control of soil. The for the soil of the Right-Bank Steppe of Ukraine SLT varies from 0.4 to 9.1 t/ha for the control period at 50 years, from 0.2 to 4.5 t/ha for the control period at 100 years, and from 0.1 to 2.3 t/ha for the control period at 200 years, depending on the planned loss of productivity (from 1% to 20% of the control value).

Prospects of the proposed methodology for determining permissible erosion rates are related to expansion of soil nomenclature, specification of the list of soil fertility parameters involved in obtaining equation (16). Special studies on the distribution of root mass of the main agricultural plants on the profile of different soils are also needed.

4. Conclusions

A method for determining the soil loss tolerance (SLT) for chernozem's soils of the Right-Bank Steppe of Ukraine was developed on the basis of the modified Pierce productivity index. It is based on a quantitative assessment of the likely change in soil productivity under the influence of erosion over a fixed period of time. Such a permissible decrease in soil productivity in the future will be compensated by the progress of agriculture as a result of more advanced technologies for growing agricultural crops, the most complete realization of the genetic potential of agricultural plants, strengthening of the soil-forming process, etc.

Calculations showed that the value of SLT depends on the period of time during which it is planned to control the use of land resources. If we take 50 years as the reference period, the value of SLT ranges from 0.4 to 9.1 t/ha. The first value corresponds to 1% loss of fertility, the second – 20% loss of fertility from the initial value. If the controlled period is 100 years, then the SLT, accordingly, varies from 0.2 to 4.5 t/ha. With a controlled period of 200 years, SLT varies from 0.1 to 2.3 t/ha, respectively.

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Table 3
Soil loss tolerance for the soil of the Right-Bank Steppe of Ukraine

Rate of fertility loss, % of initial value of *SQ*	Δh, mm in the equation (6), cm	Soil loss tolerance, mm per year (numerator) and t/ha per year (at a bulk density of 1.3 g cm^{-3}) (denominator) at different control periods		
		50 years	100 years	200 years
1	0.155	0.031/0.403	0.015/0.201	0.008/0.101
2	0.312	0.062/0.811	0.031/0.406	0.016/0.203
5	0.796	0.159/2.068	0.080/1.034	0.040/0.517
10	1.643	0.329/4.272	0.164/2.136	0.082/1.068
20	3.496	0.699/9.088	0.350/4.544	0.175/2.272

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