Chapter 9
Determination of Soil-loss Tolerance for Chernozem of Right-Bank Ukraine

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Abstract Soil loss tolerance (*T*-value) is the maximum rate of soil erosion that may be tolerated and still allow high, sustainable crop yields. For modelling soil loss tolerance for *Chernozem* of the Right-Bank Steppe of Ukraine, a modified productivity index (MPI) is developed by summing productivity values of each 10 cm layer over the upper metre thickness of the soil. Productivity values depend on the content of humus, available phosphorus and potassium, bulk density, and pH. The equation is defined by the size of change in MPI over a given time and, also, the rate of decline of MPI in the topsoil caused by soil erosion. Calculations for eroded and not-eroded *Ordinary chernozem* and *Southern chernozem* under the condition of losing not more than 5% of soil fertility over 100 years indicate a soil loss tolerance of 5–7 t/ha/year.

Keywords Soil loss tolerance · Soil erosion · Productivity index · Chernozem

Introduction

For long-term management of soil resources and the design of erosion control measures, it is helpful to compare actual rates of soil erosion with a defined, tolerable value. The concept of soil loss tolerance (*T*-value, SLT) refers to the maximum level of soil erosion that still allows the land to sustain an economic level of crop productivity. SLT has been variously defined in the literature—for instance, the State Standards of Ukraine devoted to scientific soil erosion terminology (State Standard of Ukraine 2009) define it as follows: *the maximum soil loss from erosion which doesn't lead to degradation of the soil cover, and is established taking into account the existing or prospective soil control resources and/or rate of topsoil formation.* Definitions take one of the three approaches: first, conservation of

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important soil attributes such as the status and humus content of the topsoil or rooting layer (Wischmeier and Smith 1978; USDA 2014), secondly, rates of soil loss compared with the rate of soil formation (Alexander 1988; Chornyy 1999; Svetlichny et al. 2004), and thirdly, change of productivity caused by soil erosion (Pierce et al. 1984; Duan et al. 2012) where SLT (t/ha/year) is calculated as a function of a permissible value of reduced soil productivity taking account of initial soil fertility expressed as a productivity index (PI), soil density, and the planning horizon (years), as well as a function defining the relationship between changes of the soil productivity and the amount of potential erosion (Pierce et al. 1984). Arguably, the last method is most objective, whereas assessment taking into account the rate of soil formation, itself problematic, greatly underestimates SLT values.

Study Area

The Right-Bank Steppe of Ukraine is a plain rising from sea level northwards to 240 m above sea level and bordered to the north by the Dnieper and Podolsk uplands. The dominant soil parent material is loess which blankets interfluves, marine terraces, and ancient river terraces. The climate is continental with warm summers; drought is common. The main soils are *Ordinary chernozem* and *Southern chernozem*. *Ordinary chernozem* have a thick humus horizon (up to 1 m) with 6–8% humus in the plough layer, big reserves of nutrients (especially phosphorus and potassium), high base-saturation and near-neutral reaction, and a heavy texture that promotes a water-stable soil structure. With adequate rainfall, the potential productivity of these soils is almost unlimited. *Southern chenozem* have a thinner humus horizon (50–60 cm) with a lesser humus content, overlying a well-developed calcic horizon; commonly, these soils are saline. The Right-bank Steppe suffers from soil erosion driven by intense summer rains, sloping relief, and a large proportion of arable (more than 80%) and irrational land use; about half of the arable land is eroded, compared with one-third of the country a whole.

Field and Laboratory Methods

Definition of SLT, taking account of admissible reduction of productivity through soil erosion over a given period of time, provides a quantitative assessment of soil fertility by means of a productivity index (IP). To identify criteria, two profiles of *Southern chernozem* and four profiles of *Ordinary chernozem* were compared in 10-cm layers to a depth of 120 cm (Table 9.1). Dry bulk density was measured on undisturbed core samples (State Standard Ukraine 1998); particle-size distribution, $pH_{soil\ solution}$, content of organic matter, and available phosphorus and potassium were measured on disturbed samples (State Standard Ukraine 2002, 2004b, 2007a, b).

Table 9.1 Location and description of investigated soils

No.	Soil species	Coordinates of control soil profile		MIP	*V*
1.	*Ordinary chernozem,* not eroded (BSOne)	N47°53′08,5″	E031°48′10,6″	0.7554	0.0009
2.	*Ordinary chernozem,* eroded (BSOe)	N47°53′06,1″	E031°48′26,0″	0.6885	0.0009
3.	*Southern chernozem,* eroded (BSSne)	N46°55′20,5″	E031°40′56,2″	0.7753	0.0008
4.	*Southern chernozem,* (BSSe)	N46°54′35,4″	E031°40′04,4″	0.4143	0.0006
5.	*Ordinary chernozem,* not eroded (BSOne-2)	N47°53′28,8″	E031°49′11,3″	0.7857	0.0009
6.	*Ordinary chernozem,* eroded (BSOe-2)	N47°53′03,1″	E031°49′17,0″	0.6509	0.0007

Modified IP Model

Change of *IP* over a given time is at the heart of definition of SLT. The original *IP* model, developed for *Mollisols* in the Midwest of the USA with respect to maize and soya bean cropping, concerned only so-called *irreplaceable* soil attributes (Pierce et al. 1983, 1984; Gantzer and McCarty 1987). The parameters were as follows: water-retention capacity (A_i), bulk density (C_i), $pH_{soil\ solution}$ (D_i), and a root weighting factor (WF) recording the proportion of root mass per unit mass of soil. Each parameter was normalized as a fraction of layer-by-layer values. The basic form is:

$$\mathrm{IP} = \sum_{i=1}^{n} (A_i \times C_i \times D_i \times \mathrm{WF}), \tag{9.1}$$

where *IP* is the productivity index, with $i = 1, 2, \ldots, n$ representing the different soil layers.

The so-called *irreplaceable* soil properties in Eq. (9.1) are actually regulated by fertilizers, irrigation, and tillage; consequently, various authors following the proposed structure of the index have inserted additional indicators of soil fertility—*e.g.* content of water-soluble salts (Larson and Stewart 1990; Mulengeraa and Payton 1999), adsorbed sodium (Doll and Wollenhaupt 1985), and water permeability (Burly et al. 1989).

For our own modified productivity index, we have taken account of extensive Ukrainian research on soil potential (*bonitat*) ratings. Medvedev and Plisko (2006), drawing on a wealth of earlier work on the relationship between soil quality and crop yields, propose 9 indicators of soil fertility: thickness of the root layer, content of humus, $pH_{soil\ solution}$, clay content, bulk density, content of mobile phosphorus and available potassium, depth to the gley horizon (impeded drainage), and specific

resistance of the soil (the work needed to implement cultivation procedures). In the droughty steppe, a very important factor of fertility is the range of available moisture (RAM)—the ability of the soil to provide crops with water. We would also modify the thickness of the root layer, accounted for in Eq. (9.1) through the WF index. Specific resistance and depth to a gley layer have no direct bearing on productivity; soil texture is homogenous and unchanging over a wide area (clay content lies within the range of 50–60%) so it makes no difference to the productivity index, either according to the degree of erosion or different subtypes of *chernozem*, and may be excluded from the list of indicators defining the productivity index; also RAM, which is defined by soil texture, does not change in our soils, neither between horizons nor on degree of erosion. In calculating the productivity index, we have also chosen to modify the interpretation of several indicators; the soil profile data show dispersion in respect of nutrients and maintenance of humus, especially in the plough layer, probably connected with different applications of manure and fertilizer.

We argue that it is not the multiple of the values of the individual indicators that integrates their influence on productivity but, rather, a more complicated averaging procedure—the geometric mean of these parameters. It is important to emphasize that the averaging procedure takes place without indicator WF. Thus, for a soil thickness of one metre, the modified soil productivity index (MIP) is calculated using the formula:

$$\mathrm{MIP} = \sum_{i=1}^{10} (h_i \times ph_i \times \gamma_i \times \rho_i \times \kappa_i)^{0,2} \times \mathrm{MWF}_i, \tag{9.2}$$

where i number of soil layer (i = 1, 2, 3, ..., 10); h_i, ph_i, γ_i, ρ_i, κ_i are, respectively, the impact on the value of the modified soil productivity index (MIP) in the ith layer of soil humus content, pH, bulk density, and the content of mobile phosphorus and mobile potassium, and MWF_i is the modified root weighting factor. Each of these parameters is a dimensionless quantity normalized to unit parts (0–1); the higher the value, the more suitable for crop growth.

Considering the evaluation of each component of the right-hand side of Eq. (9.2):

Estimation of the influence of humus as a source of nutrients and its beneficial influence on many physical, chemical, and biological properties of *chernozem* is described in many papers (Medvedev and Plisko 2006; Nosko 2006). However, humus-driven productivity is most apparent in soils of medium or low humus content; when the humus content is more than about 3.5%, greater humus content is not reflected in greater crop yields. And so

$$h_i = \begin{cases} h/3.5, & \text{if} \quad h \leq 3.5\% \\ 1, & \text{if} \quad h > 3.5\% \end{cases}, \tag{9.3}$$

where h humus content, %.

The effect of $pH_{soil\ solution}$ on the fertility of *chernozem* is also recorded in several publications (Gubareva 1991; Medvedev and Derevyanko 1991; Medvedev and Plisko 2006). Analysis of published data in the range of pH that has been investigated (6.0–8.5) yielded the following relationship, which has been used to calculate the modified productivity index:

$$pH_i = -0.067 \times (pH)^2 + 0.875 \times (pH) - 1.863, \tag{9.4}$$

where $pH = pH_{soil\ solution}$.

The effect of soil bulk density on the fertility of *chernozem* has been reported by Pierce et al. (1984), Medvedev et al. (2004), and Medvedev and Plisko (2006). From these data, we derived the following quadratic equation specifying the influence of bulk density on soil productivity:

$$\gamma_i = -5.414 \times \left(Y^2\right) + 12.959 \times (Y) - 6.806, \tag{9.5}$$

where Y bulk density, g/cm^3.

The role of available forms of phosphorus and potassium in the calculation of the modified productivity index (MPI) was determined by the following equations:

$$\rho_i = \begin{cases} \frac{P_2O_5}{45}, & \text{if} \quad P_2O_5 \leq 45 \\ 1, & \text{if} \quad P_2O_5 > 45 \end{cases} \tag{9.6}$$

and

$$\kappa_i = \begin{cases} \frac{K_2O}{300}, & \text{if} \quad K_2O \leq 300 \\ 1, & \text{if} \quad K_2O > 300 \end{cases} \tag{9.7}$$

where P_2O_5 and K_2O are contents of available phosphorus and potassium, mg/kg.

Equations (9.6) and (9.7) integrate data from Nosko (1990, 2006), Nosko et al. (1996), and Medvedev and Plisko (2006) and State Standard Ukraine (2004a), all showing that there is no further increase in crop yields where the content of mobile P_2O_5 exceeds 45 mg/kg and the content of available K_2O is greater than 300 mg/kg.

Finally, to indicate the share of roots in each layer, compilation of published data (in particular, Stankov 1964, and Pierce et al. 1984) showed that for the main arable region, this parameter can be calculated by:

$$WF_i = 0.5 \times e^{-0.05 \cdot \eta}, \tag{9.8}$$

where η depth of soil layer, cm.

Calculation of SLT

In general terms, SLT reflects the tolerated loss of soil fertility over a given period of time, say 50 or 100 years:

$$G = \theta \times \frac{\Delta P}{T} \tag{9.9}$$

where G SLT, t/h/year; θ dimensionless coefficient; ΔP tolerable change of fertility, dimensionless size; and T—planning horizon, years. If a change of fertility may be expressed in terms of transformation of the modified productivity index (MPI), then admissible change of soil fertility (ΔMPI) will be measured as a difference between an initial value of the productivity index ($\mathrm{MPI_{IN}}$) and its value at time T ($\mathrm{MPI_T}$):

$$\Delta P = \Delta\mathrm{MPI} = \mathrm{MPI_{IN}} - \mathrm{MPI_T}. \tag{9.10}$$

Recalculation of changes in fertility in terms of millimetres of soil loss is accomplished using the index V, determined by dividing the amount of change in value MPI in the soil profile at a certain depth; it shows the rate of change of soil fertility resulting from soil erosion. Pierce et al. (1984) consider that V should be calculated for the top 500-mm layer. However, analysis of natural and economic conditions in the Right Bank Steppe and calculation using an adequate mathematical model of soil erosion (Svetlichny et al. 2004) show that even with the current land use, soil erosion will not exceed 15–25 t/ha/year. So, even with worsening erosion in future, not more than 250 mm of soil will be washed away over the planning period of 100 years. Therefore, for indicator V, it is necessary to count changes of MPI over a maximum of the topmost 30 cm. In the study of the distribution of MPI on all six profiles, calculations showed that the value of the indicator V varies between 0.0006 and 0.0009 (Table 9.1).

Thus, the change of soil fertility for a particular period of time in millimetres per layer is equal to:

$$\Delta P = \frac{(\mathrm{MPI_{IN}} - \mathrm{MPI_T})}{V}$$

Given the above and turning to the definition of SLT with the recalculation of the soil loss tolerance in tons per hectare per year, we get the following equation:

$$G = \frac{[10 \times (\mathrm{MPI_{IN}} - \mathrm{MPI_T}) \times \gamma]}{(V \times T)}, \tag{11}$$

where G SLT, t/ha/year; γ bulk density of topsoil, g/cm^3; V the rate of change in erosion process of the MPI 300-mm top layer, mm^{-1}; and T the planned time period, years (50 or 100). The remaining symbols are the same.

Results and Discussion

From Eq. (11), the degree of soil loss tolerance depends on the change in the modified productivity index (MPI) and an indicator of its rate of change through erosion of the topsoil (*V*). In turn, various values of *V* depend on features of distribution of MPI in the uppermost part of the soil profile. Figure 9.1 depicts the distribution of MPI in a metre layer of eroded and not-eroded *Ordinary chernozem* and *Southern chernozem*. The analysis shows that not-eroded *Ordinary chernozem* (BSOne) has a rather bigger MPI value than eroded profile (BSOe) in practically every layer. This is because the not-eroded soil contains more humus and mobile P

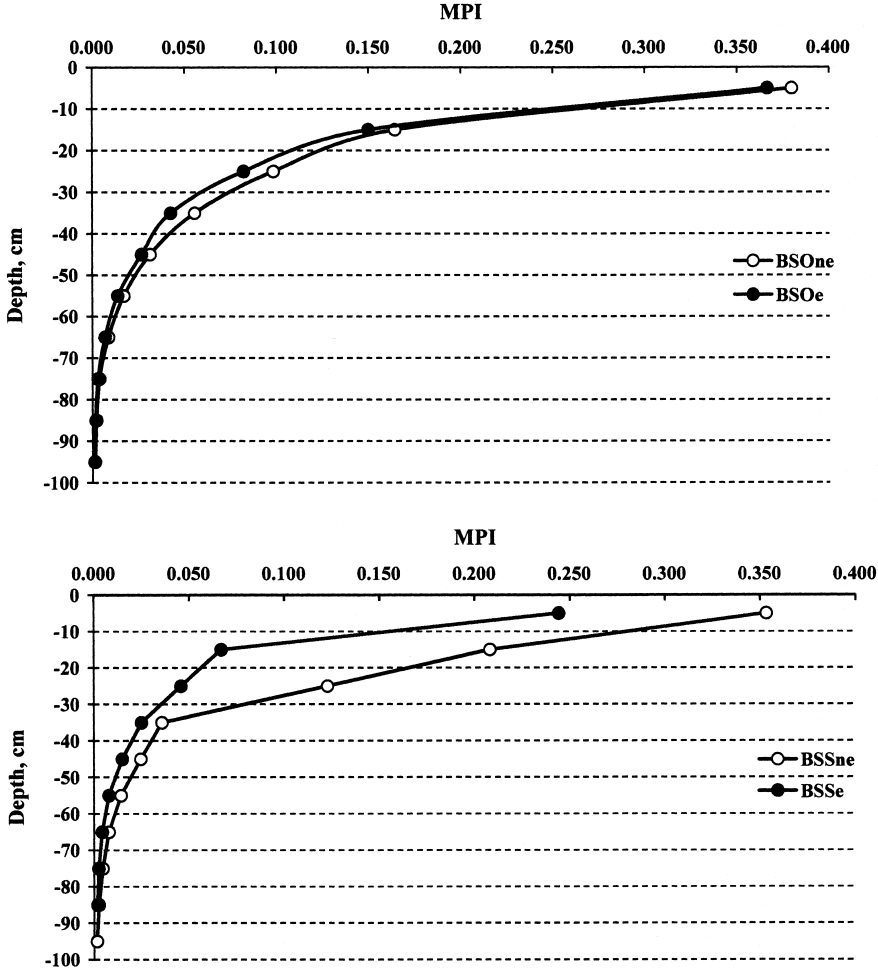

Fig. 9.1 Modified productivity index (MPI) distributions for 100 cm soil depth

Table 9.2 Attributes of *Ordinary chernozem* profiles standardized to 0–1

Layer (cm)	Humus content		Mobile phosphorus content		Mobile potassium content		Bulk density		pH	
	BSOne	BSOe	BSOne	BSOe	BSOne	BSOe	BSOne	BSOe	BSOne	BSOe
0–10	1.000	1.000	1.000	0.838	1.000	1.000	0.937	0.937	0.942	0.942
10–20	1.000	1.000	0.280	0.216	0.872	0.610	0.693	0.843	0.964	0.928
20–30	1.000	1.000	0.209	0.152	0.883	0.539	0.857	0.902	0.964	0.842
30–40	1.000	1.000	0.147	0.081	0.915	0.462	0.857	0.911	0.928	0.821
40–50	1.000	1.000	0.166	0.134	0.819	0.384	0.693	0.812	0.799	0.799
50–60	0.903	0.880	0.137	0.117	0.736	0.323	0.592	0.592	0.821	0.750
60–70	0.851	0.471	0.094	0.118	0.750	0.300	0.441	0.441	0.695	0.750
70–80	0.697	0.429	0.125	0.109	0.659	0.328	0.100	0.100	0.666	0.695
80–90	0.589	0.406	0.104	0.099	0.691	0.362	0.100	0.100	0.666	0.695
90–100	0.571	0.331	0.123	0.143	0.619	0.384	0.100	0.100	0.666	0.666

and K in practically all layers. Other parameters of fertility considered in the calculation of MPI (bulk density and pH) hardly change under the influence of erosion (Table 9.2). Such situation has an essential influence on the total value of MPI. Its value on not-eroded soil is equal 0.7554, whereas eroded soil only 0.6885 (Table 9.1).

Change in MPI in the upper 300-mm layer occurs almost simultaneously in not-eroded and eroded soils (Fig. 9.1); the value of *V* for these soils is the same at 0.0009. The second profiles of *Ordinary chernozem* (BSOne-2 and BSOe-2) give some different results: the value MPI for not-eroded soil (0.7857) is, again, more than that for eroded soil (0.6509), and for the same reason—there is higher maintenance of humus and available nutrients. However, an indicator of rate of change in MPI in the erosion process of top 300-mm layer is significantly different: in the first case of *V* is 0.0009 and in the second is only 0.0007.

The values of MPI for *Southern chernozem* are radically different from those in *Ordinary chernozem* (Fig. 9.1): MPI of not-eroded soils in the topmost 30-cm layer is much greater than values for eroded soils. This is because, in eroded *Southern chernozem*, the maintenance of humus and nutrients (especially phosphorus) decreases substantially; also, the eroded soil has high bulk density (Table 9.3). Therefore, the modified efficiency index on not-eroded soil is 0.7753 but on eroded soil, only 0.4143.

The rate of change in MPI in the top 300-mm layer for eroded soils is less than in not-eroded soil—approximately 0.20 units (0.23 for not-eroded soils)—resulting in lower values of the *V* indicator—0.0006 on eroded soil compared with 0.0008 for the not-eroded analogue.

The above features of the modified productivity index and the index rate of change through erosion of the MPI 300-mm top layer of soil (*V*) are reflected in the

Table 9.3 Attributes of *Southern chernozem* profiles standardized to 0–1

Layer cm	Humus content		Mobile phosphorus content		Mobile potassium content		Bulk density		pH	
	BSOne	BSOe	BSOne	BSOe	BSOne	BSOe	BSOne	BSOe	BSOne	BSOe
0–10	1.000	0.829	1.000	0.347	1.000	1.000	0.619	0.337	0.993	1.000
10–20	1.000	0.643	1.000	0.287	1.000	1.000	0.535	0.100	0.993	0.996
20–30	1.000	0.600	1.000	0.103	0.926	0.553	0.504	0.100	0.988	0.964
30–40	0.866	0.511	0.057	0.077	0.654	0.516	0.373	0.100	0.981	0.973
40–50	0.606	0.446	0.220	0.080	0.565	0.540	0.301	0.100	0.981	0.942
50–60	0.586	0.434	0.267	0.083	0.521	0.265	0.224	0.100	0.964	0.953
60–70	0.586	0.226	0.287	0.097	0.480	0.258	0.143	0.100	0.973	0.973
70–80	0.457	0.091	0.310	0.190	0.487	0.241	0.143	0.100	0.964	0.953
80–90	0.400	0.091	0.377	0.303	0.441	0.485	0.100	0.100	0.973	0.953
90–100	0.329	0.051	0.420	0.357	0.465	0.474	0.100	0.100	0.964	0.942

Table 9.4 Soil loss tolerance, t/ha/year, depending on acceptable decrease of productivity and planning period: 50/100 years

No.	Soil species	1%	2%	3%	4%	5%
1.	*Ordinary chernozem*, not eroded (BSOne)	2.1/1.1	4.2/2.1	6.3/3.2	8.4/4.2	10.5/5.3
2.	*Ordinary chernozem*, eroded (BSOe)	2.0/1.0	4.0/2.0	6.0/3.0	8.0/4.0	9.9/5.0
3.	*Southern chernozem*, eroded (BSSne)	2.7/1.3	5.3/2.7	8.0/4.0	10.7/5.3	13.3/6.7
4.	*Southern chernozem*, eroded (BSSe)	1.9/0.9	3.8/1.9	5.7/2.8	7.5/3.8	9.4/4.7
5.	*Ordinary chernozem*, not eroded (BSOne-2)	2.3/1.1	4.5/2.3	6.8/3.4	9.1/4.5	11.3/5.7
6.	*Ordinary chernozem*, eroded (BSOe-2)	2.5/1.2	4.9/2.5	7.4/3.7	9.8/4.9	12.3/6.1

calculations of SLT according to Eq. (9.11) at five levels of decreased soil productivity (1, 2, 3, 4, 5%) and two planning periods (50 and 100 years) (Table 9.4). As seen, SLT depends mainly on the value of the modified productivity index; the higher the value, the higher the SLT obtained so, at all levels of decrease in efficiency, values for not-eroded *chernozem* will be higher than for eroded soils. However, if there is a big difference in V values and little in MPI values, as in a case with the BSOne-2 and BSOe-2 profiles, then SLT on eroded soils can be larger, than on not-eroded.

The received SLT values for the conditions of the Right-Bank Steppe of Ukraine may be recommended for using erosion control in this region. They are of the same order as SLT values computed for analogous *chernozem* soils in Northeast China (Duan et al. 2012) and the USA (Pierce et al. 1984).

Conclusions

1. The fertility of *chernozem* of the Right-Bank Steppe of Ukraine is assessed by means of the modified productivity index (MPI), which is defined as the sum of values of productivity of each 10-cm layer for the topmost metre depth of the soil. The value for the productivity of each layer is defined by the geometric average of the following parameters: humus content, content of available phosphorus and potassium, bulk density, and pH, each normalized from 0 to 1. The modified root weighting factor (MWF) is not averaged.
2. The final version of mathematical model of definition of SLT depends on change in MPI during the planning period (T), the bulk density of the top layer of the soil, and an index of the rate of reduction of MPI through soil erosion.
3. For *chernozem* soils of the Right-Bank Steppe of Ukraine, SLT depends on the value of the modified productivity index (MPI) and the parameter that determines the speed of change in MPI in the top layers of the soil (V). SLT values are generally greater for not-eroded *chernozem,* compared with eroded analogues. However, where there is only a small difference in fertility between eroded and not-eroded soils, then the index of speed of change in MPI in the erosion process (V) will be significant.

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