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Research into Soil Resource Management Technologies in Context of Aggravating Exogenic Processes

Viktor Kaminskyi[1], Larysa Kolomiiets[1], Volodymyr Bulgakov[2], Jyri Olt[3], Valentyna Kaminska[1], Ivan Shevchenko[1], Yevhen Ihnatiev[3,4], Adolfs Rucins[5*]

[1] National Scientific Centre, Institute of Agriculture of NAAS of Ukraine, 2b, Mashinobudivnikiy Str, Chabany vil., Kyiv-Svyatoshin Distr., UA 08162, Kyiv Region, Ukraine

[2] National University of Life and Environmental Sciences of Ukraine, 15, Heroyiv Oborony Str., Kyiv, UA 03041, Ukraine

[3] Estonian University of Life Sciences, Institute of Technology, 56 Kreutzwaldi Str., Tartu, EE 51006, Estonia

[4] Dmytro Motornyi Tavria State Agrotechnological University, 66 Zhukovsky Str., UA 69600 Zaporizhzhia, Ukraine

[5] Latvia University of Life Sciences and Technologies, Institute of Engineering and Energetics, Faculty of Engineering and Information Technologies, Ulbroka Research Centre, 1 Instituta Street, Ulbroka, Ropazu Region, Stopinu Municipality, LV 2130, Latvia

* Corresponding author's e-mail: adolfs.rucins@lbtu.lv

ABSTRACT

The erosion of soil falls into the class of landscape destruction processes. It disturbs the balance in the geo-ecosystem to a significant extent, thus generating the whole spectrum of negative geo-ecological after-effects. The protection of soils against erosion and the improvement of fertility in sloped agricultural landscapes are part of the overall environmental concern that has notably aggravated lately. This has given rise to a number of topical issues for which scientific and practical solutions are urgently required. The paper describes the state of the art in the research into the issue of the protection of soils against erosion. It discusses the regional patterns in the progress of erosion processes. The integrated agro-ecological assessment of the effect that various components of the integrated erosion protection system have on the erosion resistance and properties of soils in agricultural landscapes was outlined for the development and implementation of conservation cropping systems. The study is based on the results of the long-term stationary and expeditionary field research that addressed the following issues: the natural conditions of the territory and the development of erosion processes as a result of snowmelt and rain water run-off, as well as artificial sprinkling. The research was carried out using a combination of geomorphological, cartographic and pedomorphological analysis methods and approaches. By modelling rainfalls on typical eroded chernozem soils in combination with different agricultural crop growing technologies, the quantitative characteristics for the resulting erosion losses were determined. These characteristics are needed to make long-term forecasts of the development of erosion processes in agricultural land areas in the context of intensifying exogenic processes. The tested soil-protecting agronomic technologies (subsurface blade tillage to a depth of 10–12 cm with simultaneous slitting to a depth of 40 cm, subsurface blade tillage to a depth of 20–22 cm) demonstrated their high erosion prevention efficiency. They reduced the surface run-off by a factor of 1.3–2.3, the soil loss by a factor of 1.9–12.7 in comparison to the traditional ploughing to a depth of 20–22 cm. Accordingly, the indices and conditions of the surface run-off water infiltration into the soil were also optimised with these techniques.

Keywords: agricultural landscape, geo-ecosystem, soil erosion, soil protection.

INTRODUCTION

The natural soil-building process and the erosion of soils are two inextricably related phenomena in nature. The immunity of soil to erosion processes implies its capacity to retain its main structural and functional parameters under the human-and-nature impact. The parameters include, first of all, the structure of the soil and its humus component, as they are responsible for the unique qualities of soil and its integrity. On the basis of long-term studies, considerable progress has been achieved in the development of the erosion control measures aimed at protecting soils in eroded agricultural landscapes [FAO, 2015].

To date, a whole set of organisational, hydraulic engineering, vegetative and forest reclamation measures has been developed [Lindwall and Sonntag, 2010; Lisetsky et al., 2012; Kuznetsov et al., 2019; Marandola et al., 2019; Larocque, 2020; Stepanjevic, 2021]. However, in many cases, the individual agronomic practices, forest plantings or water control structures arranged on eroded lands under the conditions of strained terrain with an aim of mitigating the erosion processes are implemented and developed without their mutual coordination and ignoring the specific physiographic conditions of the region [Pimentel and Kounang, 1998; Ma et al., 2019].

On the basis of long-term observations and calculations, various individual erosion-preventive have been evaluated in terms of their water retaining capacities. It has been revealed that their capacities to retain water are different and in the majority of cases not sufficient to guarantee the capture of the average annual run-off rate.

Considering the actual distribution of run-off rates with different probabilities, it is necessary to additionally retain surface water, apart from the water absorbed by the agricultural lands, at the following levels: in the autumn-ploughed fields with grey forest soils and podzolised chernozem soils – 25–30 mm (50%); with ordinary chernozem soils – 10–15 mm (30%); in the fields with plant cover – 40–60 mm [Boardman et al., 1994; Komissarov et al., 2011; Misir and Misir, 2012].

Therefore, the efficient protection of soils against erosion is impossible without implementing a complete package of erosion control measures in agricultural landscape systems. The systemic approach for protecting soils against erosion implies the development and implementation of a complete package of erosion control measures, designed on the basis of the actual landscape and including the arrangement of agronomic, forest management and hydraulic engineering measures. In recent years, a number of methodological studies were published [Kashtanov et al., 1997; Morgan, 2005; Glinski et al., 2013; Farooq and Siddique, 2014; Gonzalez-Sanches et al., 2015; Volnov and Boiko, 2015; Chalov, 2016; Stepanjevic, 2021], outlining the new methodical principles for the research into soil-erosion processes in agricultural landscapes and their environmental consequences, the development of the optimal system of measures for preventing the degradation of the soil cover and the contamination and silting of minor rivers as well as improving the productivity of cultivated lands. The new approach implies, first of all, research into the moisture rotation processes: precipitation, the variation of the land moisture content and water permeability, the overland slope run-off. Moisture, on the one hand, defines the energy resource potential of the agricultural landscape; on the other hand, it produces a most intricate set of environmental consequences in the territories reclaimed by agriculture [Hazarika and Honda, 2001; Kudryukova, 2020; Slyusar et al., 2020).

In the studies by several scientists [Van Oost et al., 2000; Li et al., 2001; Gareev and Habibullin, 2010; Kutzenko, 2012; Routchek et al., 2014; Shevchenko and Kolomiiets, 2014; Brycta and Janeček, 2019; Baboshkina et al., 2020] certain regularities have been revealed in the development of erosion processes. They provide the tools for designing the models of erosion-preventive systems on the basis of calculations. The erosion of soil as a result of the superficial snowmelt and rainwater run-off upsets the environmentally sound functioning of the water – soil – plant system. The methods of optimising all erosion components are generally the same in all cases: increasing the water retention and absorption capacity of the surface, improving the erosion-preventive strength of the soil with the use of the system of erosion-preventive measures. The erosion-preventive measures applied within a certain territory have to constitute a system that is adequate to the erosion danger level, irrespective of whether it is created by rainwater or snowmelt.

It is necessary to define the role and position of every component in the package of erosion-preventive measures. For that purpose, the quantitative assessment of the water control, erosion protection, agronomic and economic efficiency of the erosion prevention package has to be done [Kachmar et al., 2018). It is facilitated by the considerable information database about the intensity of soil wash-off on slopes, the properties of denuded soils, the efficiency of individual erosion control measures and their packages that has been collected by now [Ivanov, 2007; Belolyubcev, 2009; Gomes et al., 2019; Kust et al., 2019; Xie et al., 2019]. The research into the progress of erosion processes, in view of their specific nature, requires designing and implementing special methods. In this respect, the most efficient method is sprinkling or artificial rain irrigation. A significant factor in reducing water erosion of agricultural land is proper soil tillage, which necessitates the development of new machinery and tractor units, with their working parts designed considering the study of soil particle movement across the working elements [Bulgakov et al., 2017b; Ivanovs et al., 2020; Bulgakov et al., 2020].

It is necessary to develop physically justified models and experimental methods of research into soil erosion in order to explore erosion processes with a view to solving the respective applied problems. Only the proper understanding of the mechanism of these processes will provide for finding the ways to control them in actual practice [Achasov et al., 2019 and 2021; Zhidkin et al., 2019; Bulgakov et al., 2017a]. In order to provide the successful protection of soils against washing off and washing out, it is necessary to carry out research into the edaphic and climatic conditions that define the mechanism of erosion processes with an aim of determining their patterns in different regions [Krasnov et al., 2001; Kanatyeva et al., 2010; Kaminskyi et al., 2018 and 2021].

The aim of the research was to provide for the improvement of the erosion resistance and properties of soils by means of analysing the development of surface run-off in the agricultural landscapes susceptible to erosion.

MATERIALS AND METHODS

The elementary river basin featuring a complex structure and mutual dependence relations between its components and meeting all the requirements to be considered a geosystem was chosen as the main territory unit in the research, while the integral function of the run-off represents the development, functioning and condition of the geographical landscape, first of all, in terms of the impact produced by the physical factors.

The methods used in the research to evaluate the intensity of denudation processes included the stationary monitoring of run-off sites, the full-scale physical simulation of erosion processes (sprinkler irrigation), the experimental investigations of the soil washing-off and linear washout intensity, field route surveying, field and laboratory experiments, the statistical-economy and calculation-and-design landscape modelling method. The statistical confidence of the research results was assessed with the use of a PC and the Statistica 6.1 software.

The changing climatic conditions have a significant impact on the moisture exchange in agricultural landscapes. These changes bring about the development of erosion processes resulting in the degradation of the soils and also promote aridisation processes represented by the decline of the water table, as well as changes in the hydrological and biochemical conditions of the water bodies. Moreover, the surface and underground run-off flows are the agents that directly define the conditions for the development of the territory macro- and microrelief and the plant vegetation conditions, which have effect on the soil cover formation or degradation processes.

The presented research into the development of technologies for the management of soil resources in context of aggravating exogenic (erosion and accumulation) processes has been carried out in the natural-anthropogenic and anthropogenically modified landscapes of the minor river basins in the Right Bank Forest Steppe zone of Ukraine, Kyiv Oblast [Kaminskyi et al., 2021].

The research included investigations on the water-control, agro-ecological and soil-protection efficiency of the agricultural crop farming technologies within the framework of the long-term field experiment. This experiment was part of the model of the agricultural landscape situated under the landscape-geomorphological conditions of the Right Bank Forest Steppe Region of Ukraine (Fig. 1). The location of the field experiment was in a sloping agricultural landscape with a slope gradient of 5–6° in the south-east aspect within the system of contour and amelioratory territory organisation system (Fig. 2).

The development of erosion and accumulation processes was monitored during the long-term field experiment carried out in the run-off sites of the research base farm of the NAAS National Research Centre “Institute of Field Husbandry”. The land of the pilot farm unit is situated on the higher right bank of the Dnieper River in the Kyiv Oblast, the Right Bank Forest Steppe Region of Ukraine. This agricultural locality features the significant roughness of the relief, the low altitude of the erosion base level (the Dnieper River), the high agricultural development of the land and, as a consequence, the intensive development of water erosion processes. Taking into account the nature and climate conditions, paedogenesis

Figure 1. Run-off sites in long-term field study (gradient of 5–6°): 1 – spring barley field, 2 – winter wheat field

Figure 2. Run-off sites in long-term field study (gradient of 5–6°): 1 – spring barley field, 2 – winter wheat field

factors and geomorphological properties of the above-mentioned research territory as well as the type of its economic development and the level of progress of water erosion processes in it, it is reasonable to assume that the geographical landscape chosen for the research is representative of the anthropogenic landscapes in the Right Bank Forest Steppe Region. Thus, the area is appropriate for carrying out the scientific research into the problems of preserving the soil cover on cultivated lands under the conditions of the development of the exogenic processes unfavourable for agriculture. The soil in the field experiment location is described as follows: typical chernozem (black earth), severely eroded, weakly humous, silt, fine sand and light loam on loess. Its principal fertility indices are as follows: humus content in topsoil is equal to 1.65–1.70%, pH of salt extract – 6.5, hydrolytic acidity – 0.80–1.50 mg-eqv (100 g)$^{-1}$ of soil, cation absorption capacity – 23.6–24.6 mg-eqv (100 g^{-1}) of soil, alkali saturation rate of soil – 88.4–96.9%.

Depending on the developed agricultural technology, the research into the erosion processes and main properties of typical eroded chernozem was carried out in certain segments of the following soil-protecting crop rotation cycle: Medicago sativa of three-year utilisation – winter wheat + winter rape (in stubble) as green manure, barley with complementary Medicago sativa seeding.

The experiment design comprised the following primary soil cultivation systems:

1. Conventional – ploughing (reference) to a depth of 20–22 cm,
2. Soil protective – subsurface blade tillage to a depth of 20–22 cm,
3. Soil protective – subsurface blade tillage to a depth of 10–12 cm with simultaneous slitting to a depth of 35–40 cm.

The total area of an elementary research plot was equal to 850 m^2. The allocation of experiment alternatives was systematic. The number of plot replications is two. The experiment was located in three fields and equipped with run-off plots with areas of 850 m^2 for recording the water run-off and the soil wash-off. The run-off sites were allocated on a slope and aligned down the slope. Each site had a length of 100 m and a width of 8.5 m, accordingly, an area of 100×8.5 m = 850 m^2 (Fig. 3). The run-off sites were arranged by means of moulding down the slope 18–20 cm high earthen walls. The walls were moulded in autumn after seeding winter wheat and completing the under-winter primary tillage for spring crops, in spring – after seeding barley with the complementary seeding of Medicago sativa. The automatic run-off recording units were installed in the exit ranges of the run-off sites (Fig. 4)

The extent of the soil wash-off was determined using the method of recording the erosion in accordance with the metered volume of erosion rills. This method allows estimating the soil wash-off in any section of the run-off site against different agronomic backgrounds that has resulted from one or more rainstorms and also in the snow melting period. In all the specific spaces of the monitored slope, usually including the top, the middle and the bottom of the site, profiles were allocated at a right angle to the slope line. Within each profile, the volume of soil surface outwash was measured. The average outwash volume was referred to the total area of 850 m^2. In some specific cases, the wash-off was estimated also by the volume of the fine earth deposited at the foot range of the run-off site as well as by the volume of the detrital accumulation cones.

The number of run-off sites needed in the field experiment depends on the quantity of soil tillage and fertilisation alternatives, including the absolute reference case. The total number of run-off sites in the fields of the experiment was equal to 18. The study was carried out in the run-off sites of the pilot farm situated in the Kyiv Oblast in the Right Bank Forest Steppe Region of Ukraine.

In order to determine the aerometric properties of the 18 run-off sites in the long-term field experiment, the topographic mapping on a scale of 1:1000 was done using the international coordinate system (WGS– 84) and the Baltic height system with contour intervals of 1.0 m (Fig. 5).

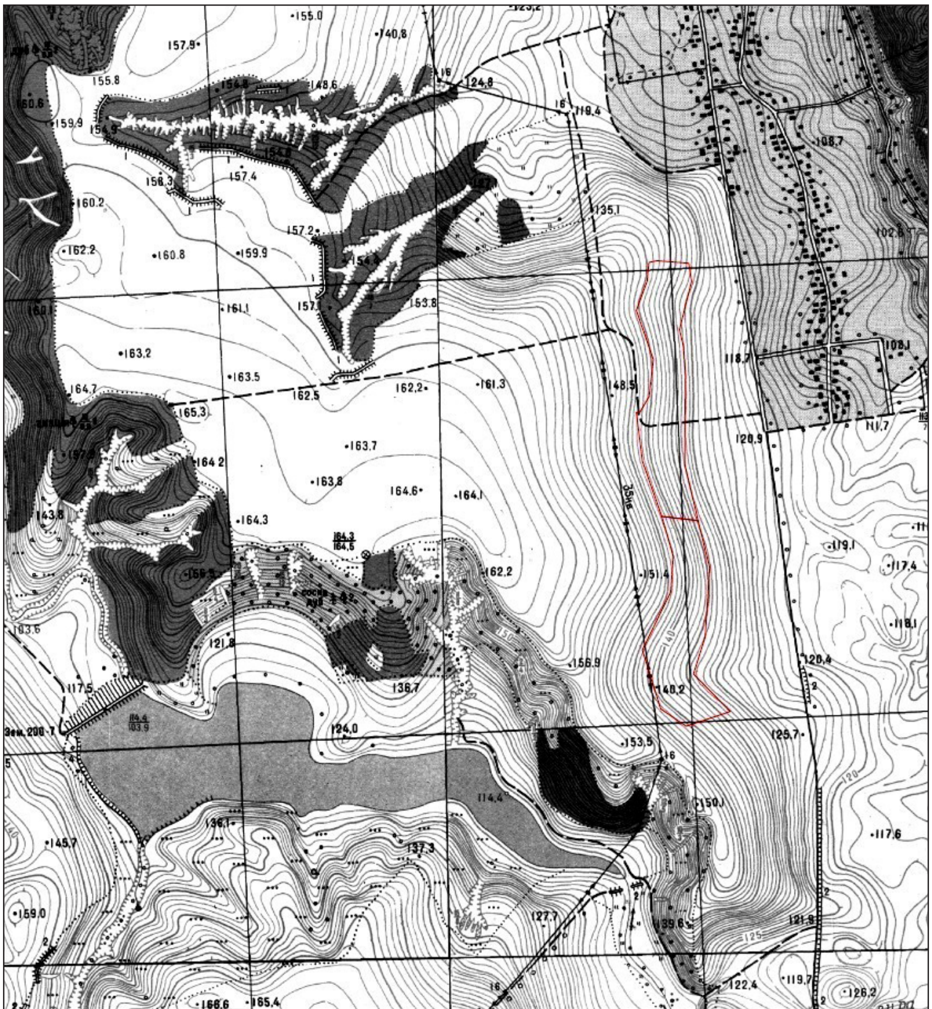
Figure 3. General appearance of run-off site in long-term field experiment (S – 850 m^2)

Figure 4. Automatic run-off recorder in run-off site of field experiment

In order to ensure the reliability of the results obtained during the field experiment investigations on the water erosion processes in typical severely eroded chernozem, the run-off sites with the field experiment alternatives located in them were protected from the ingress of surface run-off water from the adjacent water catchment areas.

Before initiating the long-term stationary field experiment on the erosion-preventive and agroecological efficiency of the set of agronomic technology procedures (soil tillage, fertilisation, crop rotation), a system of hydraulic engineering structures, that is, water-retention earth mounds of various configurations were erected in the part of the researched slope agricultural landscape near the water divide. The mounds were set for containing and safely discharging the surface run-off into the water body (Fig. 6). The distance between the water-retention banks in the system of water control structures was equal to 50–100 m, depending on the slope gradient. The rise and development of erosion processes to a considerable extent depends on the water permeability of the soil, especially its tilled layer. The water absorption processes determine the influx of atmospheric precipitation into the soil stratum as well as the formation of surface run-off, which has a direct impact on the development of soil destruction processes. The latter eventually result in the loss of the fertile soil layer, the significant reduction of the soil fertility and a decline in the yield of agricultural crops.

Therefore, the water infiltration into the soil belongs to the most important indices used in the erosion science for the evaluation of the erosion prevention and run-off control agricultural crop cultivation practices applied in conservation farming. The research into the water permeability of the soil becomes an especially topical task under the conditions of slope landscapes, where, in case of heavy precipitation or during active snow melting



- Location of a long-term field experiment in a slope agricultural landscape

Figure 5. Topographical map of terrain relief in research territory

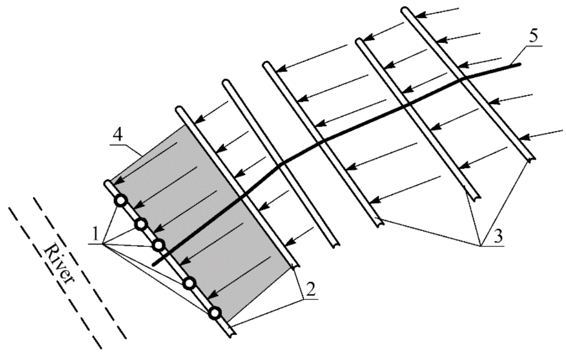


Figure 6. Schematic model of three-dimensional situation of experimental fields in agro-ecological testing ground within the contour and amelioration territory organisation system: 1 – run-off recording devices; 2 – plough-transfer mounds; 3 – water-retention mounds; 4 – run-off record sites; 5 – longitudinal profile of slope

in spring, significant part of the water has no time to infiltrate inside the soil profile, but instead runs off down the slope causing the outwash of the soil cover. According to the research results, typical chernozem soils in the Right Bank Forest Steppe Region feature high water permeability (113–131 mm (year)$^{-1}$) as well as a considerable content of agronomically valuable aggregates (63–78%), but their eroded varieties have a significantly worse infiltration capacity [Kaminskyi et al., 2021].

For that reason, one of the targets in the research was to determine the possibility of improving the infiltration capacity of highly-eroded typical chernozem soil by means of implementing a system of agricultural erosion control measures, among which the soil tillage methods and crops in rotation played the leading role.

RESULTS AND DISCUSSION

The results obtained during the research carried out in the form of a long-term field experiment in eroded typical chernozem prove the low water permeability of the soil, where winter rape is planted in the stubble, in the case of all the agronomic backgrounds used in the research. However, in the case of subsurface blade tillage to a depth of 20–22 cm, a greater infiltration capacity has been recorded. Its value is equal to 0.22 mm min^{-1} in the first hour of observation and 0.07 mm min^{-1} after two hours of experiment (Fig. 7a). In case of ploughing to a depth of 20–22 cm, these indices are equal to 0.17 and 0.05 mm min^{-1}, respectively. The advantages of the soil-protective crop cultivation technologies based on the subsurface blade soil tillage to a depth of 20–22 cm lie in the creation of proper pore space in the soil, as compared to ploughing, as well as the greater water resistance of the soil aggregates and their greater content in the upper soil layers.

The detailed analysis of the water permeability variation in time has proven the following. Its rate in the first five minutes of observation stays at a level of 1.00–1.12 mm (min)$^{-1}$. After 10 min, the absorption substantially decreases in the different alternatives – 0.35–0.38 mm min^{-1}. The process of water absorption by the soil lasts for about 20 min, then the water is filtered by the upper soil layers. At the same time, the rate of water infiltration in the soil is low and equal to: in case of subsurface blade soil tillage – 0.11 mm min^{-1}, in case of ploughing – 0.04–0.05 mm min^{-1}. Inevitably, at such a low infiltration rate and a medium intensity rainfall (over 0.3 mm min^{-1}), the fine earth

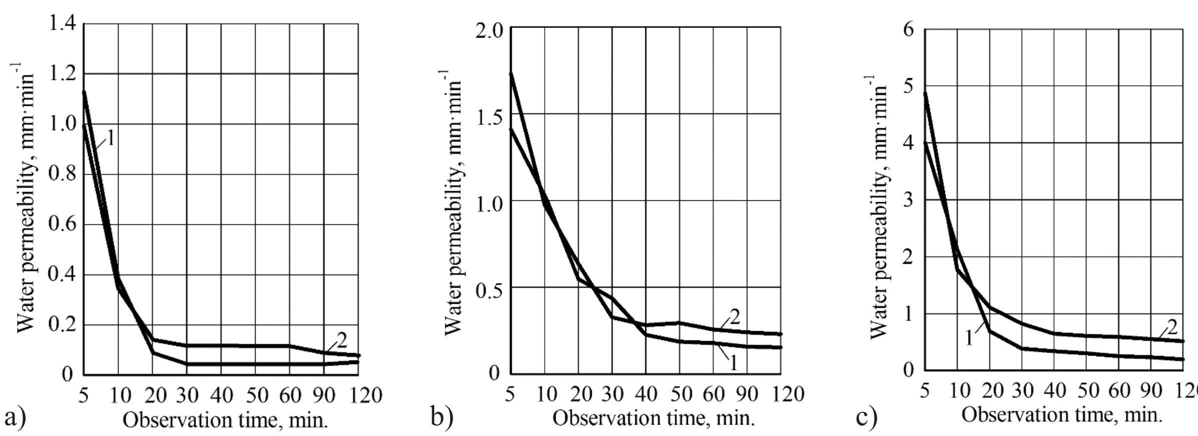


Figure 7. Water permeability of severely eroded chernozem in relation to soil tillage technique and crop in rotation: (a) winter rape; (b) Medicago sativa in 2nd year of use; (c) Medicago sativa in 3rd year of use; 1 – ploughing to depth of 20–22 cm; 2 – subsurface blade tillage to depth of 20–22 cm

wash-off in the tilled soil will be substantial. In terms of erosion prevention, the more rational way of using such lands is to plant perennial grasses, which firmly fix the soil with their roots as well as improve its water-air and nutrient status.

In the field prepared for winter rape, the process of water absorption by the soil had lasted for about 20 min, then the water was filtered by the upper soil layers. At the same time, the rate of water infiltration in the soil was low and equal to: in case of subsurface blade soil tillage – 0.11 mm min^{-1}, in case of ploughing – 0.04–0.05 mm min^{-1}. Inevitably, at such a low infiltration rate and a medium intensity rainfall (over 0.3 mm min^{-1}), the fine earth wash-off in the tilled soil will be substantial. In terms of erosion prevention, the more rational way of using such slope lands is to plant perennial grasses, which improve the water-air and nutrient status of the soil and significantly enhance its erosion resistance.

The results of monitoring the water permeability of eroded chernozem in the plantings of Medicago sativa in the 2nd year of use show its partial substantial increase in comparison with the winter rape agrocenosis. On the average for 2 hours of observation, the water infiltration in the case of subsurface blade soil tillage to a depth of 20–22 cm was equal to 0.32 mm min^{-1}, in the case of ploughing – 0.26 mm min^{-1} (Fig. 7b). That can be explained by the physiological features of the leguminous crop, the conditions of its growth and, finally, its impact on the improvement of the water-air and aggregate-structure status of the soil. However, in general, the said water permeability level is rated as low.

The cultivation of Medicago sativa for the third successive year in the same field resulted in an increase in the water permeability level of the highly-eroded chernozem soil. At the same time, the highest infiltration capacity was observed against the background of subsurface blade soil tillage to a depth of 20–22 cm where it was equal to 0.85 mm min^{-1} on the average for 2 hours of observation (Fig. 7c).

When ploughing to a depth 20–22 cm had been applied, the index was equal to 0.51 mm min^{-1}, while in case of shallow subsurface blade tillage – 0.38 mm min^{-1}. It has been established that the scientifically grounded cultivation of perennial grasses in crop rotation promotes the improvement of the water permeability level in highly-eroded chernozem soil and results in the reduced surface run-off as well as soil wash-off.

Overall, the monitoring of the eroded typical chernozem soil water permeability in the long-term field experiment has proven that, under the conditions of slope agricultural landscape, the infiltration capacity of the soil cover and, as a consequence, its erosion resistance is improved by the soil tillage without overturning furrow slices as well as the cultivation of perennial leguminous grasses for two or three years in sequence within the crop rotation system.

The soil-protective efficiency of agricultural technologies is considerably enhanced by the presence of a protective cover on the soil formed by plants, after-harvesting and post-cut residues, which protect the soil surface from the destruction by raindrops and superficial run-off water currents. The reliability of above-mentioned statements is supported by the results of the experiment [Larionov et al., 2017], in which the properties of chernozem soils were examined in terms of their effect on the storm water surface run-off infiltration rate in the absence of projective cover on the run-off site. One of the significant properties is the water permeability of the soil: the breaking of inter-aggregate bonds at some depth will start after the wetting front penetrates to that depth, while the rate of its penetration to a significant extent depends on the soil density. Although the relation between the inter-aggregate bond breaking rate and the water infiltration rate has been proven to be exponential, not linear, but it has a high coefficient of correlation. On these grounds, the soil infiltration capacity can be recommended as an indicator of the erosion resistance of soil.

As the soil infiltration capacity is subject to seasonal variation, it can be used for forecasting the annual dynamics of the soil erosion characteristics. The erosion-preventive soil tillage is of especial importance in terms of soil protection in the period, when plant cover is absent in the fields, because soil tillage (crop farming) technologies are exactly what contributes to improving the agrophysical indices of the soil and increasing its erosion resistance, while obtaining the maximum yield of produce per area unit. It has been established that under all the very diverse edaphic and climatic conditions found in Ukraine the non-mouldboard (subsurface blade) tillage of the soil on slope lands delivers a significantly greater soil protection effect, than conventional ploughing.

The research into the erosion-preventive effect of various components of agricultural crop raising technologies was carried out with the use of full-scale field experiments within the framework of a long-term stationary experiment. The specific problems that required more detailed research into the development of water erosion processes in relation to the slope gradients and the soil wash-off rates were investigated by arranging model experiments with the use of artificial sprinkling. The model run-off plots (with areas of 3×1 m = 3 m^2) (Fig. 8) equipped with artificial sprinkling were placed within the stationary run-off sites of the field experiment for each alternative of the long-term stationary experiment (ploughing, subsurface blade tillage). Hence, the conditions, under which the erosion processes took place, were identical both for the full-scale field studies and the modelling experiments with artificial sprinkling.

At the same time, the main soil erosion development indices obtained in the case of atmospheric precipitation and in the case of its simulation with the use of sprinkling system were compared to each other. When applying the artificial sprinkling method, one of the prerequisites for obtaining a wide range of indices related to the erosion resistance of the soil is to carry out the experiment directly under field conditions. The development of water erosion was modelled by means of simulating natural rainfall with the use of the sprinkling machine engineered in the Lugansk Institute of Agricultural Industry. The sprinkling machine ensured the uniform distribution of raindrops over the model run-off plot [Berezhnyak et al., 2018]. The use of artificial sprinkling methods in experimental research enables investigating within a short time the primary indicators of the water erosion process – the soil wash-off and the surface run-off – under different conditions depending on the geomorphological, agricultural process and soil factors as well as the applied set of land use arrangements and processes.

In the experimental research into the soil-protective effectiveness of different soil tillage systems as parts of crop raising technologies, the authors used the method of the artificial sprinkling of model run-off plots under field conditions, the model run-off plots being arranged in the stationary field experiment sites. In this method, a model of natural rain was simulated with the use of a special sprinkling machine. In the modelling field experiments with artificial sprinkling, the area of a model run-off plot was equal to 1×3 m = 3 m^2.

In the absence of rainfall producing water run-off, simulation modelling provides for obtaining similar, very dependable results within a sufficiently short period of time, that is, 2–3 years, which is the reason of the wide application of the sprinkling method in erosion research. The erosional potential of the rain to a considerable extent depends on its intensity. The selection of intensity levels for modelling was based on the typical storm rain indices of the place of research, that is, Right Bank Forest Steppe Region. The typical rain intensity in the area is 3 mm·(min)$^{-1}$. Each observation had been carried out for 30 min

Figure 8. Model run-off plot with artificial sprinkling equipped with automatic run-off recording unit in exit range

under the conditions of monodispersed rain with an intensity of 3 mm/min (± 20%). The artificial sprinkling of the agronomic background was applied to the following soil tillage alternatives of the long-term field experiment: ploughing to a depth of 20–22 cm; subsurface blade tillage to a depth of 20–22 cm; subsurface blade tillage to a depth of 10–12 cm together with slitting to a depth of 40 cm. The sprinkling of model run-off plots (S = 3 m^2) was done after harvesting the preceding crop (the second cutting of Medicago sativa for green material) and primary soil tillage, in the period of the field preparation for winter wheat sowing. The artificial sprinkling experiments by the authors have proven that the conditions when the soil surface is most exposed to the destruction by raindrops and to the fine earth wash-off by the slope run-offs generated by autumn rainstorms arise exactly at this stage. The sprinkling of the soil was done on the slope with a gradient of 5–6°.

For the purpose of estimating the soil wash-off intensity, samples were taken directly from the flowing stream, also average samples were taken from the run-off collecting tank. The depth of precipitation was determined with the use of rain gauges, the rainfall intensity – with the use of computational methods. The completed experimental investigations had proved that the surface water run-off against the background of ploughing to a depth of 20–22 cm had been the greatest of all and equal to 125.6 m^3·ha^{-1} (Table 1).

It was established that the soil wash-off rate was accordingly substantial – 9.88 t·ha^{-1}. The concentration of suspended materials in the run-off water was equal to 78.6 g·l^{-1}. These facts prove that, in the period of the openness of the soil and the absence of its proper fixation by roots combined with heavy rainstorm precipitation, the soil wash-off consequences will be rather severe. Taking into account the fact that the soil under research has low water permeability, moderate density and high openness of the slope surface, rainstorm precipitation can become the primary cause of not only sheet washing, but even certain linear washouts.

In the case of sprinkling the soil surface that has been subsurface blade tilled to a depth of 10–12 cm and slit to a depth of 40 cm, the liquid run-off started almost at the same time as in the

Table 1. Results of sprinkling eroded chernozem after applying different soil tillage systems

Sprinkling parameters	Soil tillage		
	Ploughing to a depth of 20–22 cm	Subsurface blade tillage to a depth of 20–22 cm	Subsurface blade tillage to a depth of 10–12 cm with slitting to a depth of 40 cm
Gradient of slope, deg	6	6	6
Rainfall intensity, mm min^{-1}	3.0	3.0	3.0
Duration of sprinkling, min	30	30	30
Time between start of sprinkling and start of run-off, min	5	9	6
Water absorption before start of run-off, mm	11.5	30.5	16.0
Water absorption intensity before start of run-off, mm min^{-1}	2.30	3.39	2.67
Water absorption by soil during run-off, mm	40.0	26.8	36.2
Water absorption intensity during run-off, mm min^{-1}	1.60	1.52	1.51
Total amount of water absorbed by soil, mm	51.5	57.3	52.2
Total amount of filtrate water per record plot, ml	2010	920	1640
Total amount of liquid run-off per record plot, ml	1935	910	1590
Mass of washed-off fine earth per record plot, g	158	12.5	83.5
Run-off intensity, mm min^{-1}	0.52	0.27	0.43
Run-off rate, mm	13.1	5.67	10.3
Suspended material concentration in run-off, g l^{-1}	78.6	13.6	50.9
Water run-off, m^3 ha^{-1}	125.6	57.5	102.5
Soil wash-off loss, t ha^{-1}	9.88	0.78	5.21
Openness of background, %	92	20	45

case of the ploughing background – in 6 minutes, and only after the surface layer had become sufficiently saturated with moisture, the wash-off of the soil itself together with the water started, the suspended material concentration in the run-off was equal then to 50.9 g·l^{-1}. The total amount of water run-off in the case of shallow tillage with slitting was equal to 102.5 m^3·ha^{-1}, the soil wash-off – 5.21 t·ha^{-1}, which was 1.9 times lower, than in the case of ploughing. After subsurface blade tillage to a depth of 20–22 cm, the soil conservation effect was even more notable: the soil wash-off amounted to mere 0.78 t·ha^{-1}, the surface run-off – 57.5 m^3·ha^{-1}. The statistical validity of the research results has been assessed in terms of their variation range $\left(\overline{X} \pm S\overline{x}\right)$, standard deviation ($S$) and coefficient of variation (V [%]) with the use of the PC and the Statistica 6.1 software.

The mathematical assessment of the rates of superficial water run-off and soil wash-off by means of statistical analysis has proven that the water run-off on the average for the experiment was within the range $\left(\overline{X} \pm S\overline{x}\right)$ of 95.2 ± 20 m^3·ha^{-1} at a standard deviation (S) of 34.6, while the average soil wash-off was within the range of 5.29 ± 2.63 t·ha^{-1} at a standard deviation of 4.55. The statistical analysis of the rates of water run-off and soil wash-off has proven that each of them had certain variation range and coefficient of variation. They featured significant variability, as indicated by the respective coefficients of variation V – 36.4% and 86.0% (Table 2). It is also to be taken into account that the erosional effect of rainstorm precipitation depends not only on the properties of the rain, but also on the state of the cultivated vegetation on the soil (its soil protective capacity) at the time of the rainfall [Kanatyeva et al., 2010].

When visually inspecting the condition of the soil surface tilled with non-mouldboard implements, the high roughness of it had been noted, which was due to the presence of plant residues from the preceding crop, that is, Medicago sativa. The after-harvesting residues, the main part of which remains, in the case of subsurface blade tillage, on the surface of the field, were, probably, the main cause of the better water infiltration into the soil. They dispersed the raindrops near the soil surface, reduced their sizes and, accordingly, decreased the soil wash-off as compared to the ploughing alternative. As it is obvious from the results of the rainfall model sprinkling carried out on run-off sites in the field, the subsurface blade tillage has clear advantages, because with this technique a sufficient protective shield is made from the plant residues left in the field after harvesting the preceding crop. In the case of ploughing, chaff and other post-harvesting residues are ploughed into the soil to a depth of 15–25 cm, where they become a source of enriching the soil with organic matter and are actively used by the microorganisms. However, in terms of erosion control, the soil surface remains in this case greatly exposed to the hitting by raindrops and the surface run-off.

The modelling of the progress of erosion processes in the form of simulation sprinkling under field conditions was aimed at obtaining the unbiased characteristics of the erosion process with

Table 2. Results of sprinkling eroded chernozem after applying different soil tillage systems

Soil tillage	Sprinkling parameters							
	Water absorption by soil during run-off, mm	Water absorption intensity during run-off, mm min^{-1}	Run-off intensity, mm min^{-1}	Run-off rate, mm	Suspended material concentration in run-off, g l^{-1}	Water run-off, m^3 ha^{-1}	Soil wash-off loss, t ha^{-1}	Openness of soil, %
Ploughing, 20–22 cm	40	1.6	0.52	13.1	78.6	125.6	9.88	92
Subsurface blade tillage, 20–22 cm	26.8	1.52	0.27	5.67	13.6	57.5	0.78	20
Subsurface blade tillage, 10–12 cm, with slitting, 40 cm	36.2	1.51	0.43	10.3	50.9	102.5	5.21	45
$\overline{O} \pm S\overline{x}$	34.3± 3.92	1.54± 0.03	0.41± 0.07	9.69± 2.17	47.7± 18.8	95.2± 20.0	5.29± 2.63	52.3+ 12.2
V, %	19.8	3.20	31.1	38.7	68.4	36.4	86.0	69.9
S	6.80	0.05	0.13	3.75	32.6	34.6	4.55	36.6

due account for a sufficiently large number of the parameters, including those of the water flow infiltration process, that more or less fairly describe the progress of water erosion processes.

With the use of the sprinkling of model run-off plots, the quantitative water run-off, soil wash-off and water absorption indices that are characteristic for the researched edaphic and climatic zone in the case of intensive precipitation have been obtained. The soil wash-off (y_1 [t·ha^{-1}]), the surface run-off (y_2 [m^3·ha^{-1}]) and the water absorption by the soil (infiltration) before the washing-off (y_3 [mm]) had been designated as the effective parameters of correlations in the full-scale field investigations and model sprinkling experiments carried out by the authors.

The results of the completed field experiments, where the run-off sites with different agronomic backgrounds in highly-eroded chernozem soils were sprinkled, provided a possibility of correlating the obtained empiric parameters of the rainfall, the properties of the soil, the soil surface condition and the erosion characteristics: the water run-off, the soil wash-off and the water permeability of the agronomic backgrounds in relation to the researched agricultural technology methods of crop cultivation in agricultural landscapes. The results of the empirical data analysis were used for establishing the multivariable correlation between the main indices analysed during the model field experiments. Further, the regression equation was generated and, on its basis, the mathematical statistical model was developed for the analysis of the soil loss and the surface run-off during the rainstorm precipitation typical of the research location [Berezhnyak et al., 2016]. The obtained mathematical statistical model of the analysed system contains equations, in which, besides the above-listed factorial characteristics, also X_a – hyperbolic tangent of the slope gradient in degrees is included. The following parameters (factorial correlation criteria) have been used for developing the mathematical model of the system under consideration:

- X_e – erosional (after run-off) energy in artificial-rain water drops, kJ m^{-2};
- X_a – gradient of slope, deg;
- X_c – clay-silt fraction (< 0.01 mm) content in ploughing horizon of soil, %;
- X_h – humus content in ploughing horizon of soil, %;
- X_{of} – openness of soil surface, %;
- d – weighted mean diameter of soil particle moving in water erosion stream, m;
- I – artificial rain intensity, mm min^{-1};
- K_f – mean coefficient of gravity-feed (before run-off) water permeability of soil, mm min^{-1};
- K_{fc} – mean coefficient of water permeability of soil during run-off, mm min^{-1};
- O_p – total porosity of ploughing horizon of soil prior to sprinkling, % of soil volume;
- P_{aer} – gravity-ventilation porosity of ploughing horizon of soil prior to sprinkling, % of soil volume.

The initial research data are presented in Tables 3 and 4. Knowing the duration and average intensity of the artificial sprinkling as well as other important characteristics of the experiment alternatives, it is possible to calculate the total amount of water absorbed by the soil in mm or m^3 ha^{-1} with the use of the three effective parameters of the model (y_1, y_2 and y_3).

For the research into the statistical relationship between the effective parameters of water erosion processes (y_1, y_2 and y_3) and the factors that determine the said processes, the authors have taken into account the results obtained with the use of other existing mathematical statistical models for the calculation of the soil and water loss [Berezhnyak et al., 2016 and 2018; Ran et al., 2020]. As a result of the correlation analysis, it has been revealed that there is no relation between the soil loss due to its wash-off, on the one

Table 3. Factorial characteristics of soil used in mathematical statistical relations that describe development of erosion processes (under sprinkling)

Agronomic background	X_e	X_a	X_c, %	X_h, %	X_{of}, %
Eroded typical chernozem					
Without fertilisation (reference)					
Ploughing to a depth of 20–22 cm	1.50	6	19	1.70	92
Subsurface blade tillage to a depth of 20–22 cm	1.50	6	24	1.64	20
Subsurface blade tillage to a depth of 10–12 cm with slitting to a depth of 40 cm	1.50	6	22	1.64	45

Table 4. Factorial characteristics of soil used in mathematical statistical relations that describe development of erosion processes (under sprinkling)

Agronomic background	d, m	I, mm min^{-1}	K_f, mm min^{-1}	K_{fc}, mm min^{-1}	O_p, %	P_{aer}, %
Eroded typical chernozem						
Without fertilisation (reference)						
Ploughing to a depth of 20–22 cm	0.6×10^{-3}	3.0	2.30	1.60	50.2	32.5
Subsurface blade tillage to a depth of 20–22 cm	0.8×10^{-3}	3.0	3.39	1.52	48.7	27.2
Subsurface blade tillage to a depth of 10–12 cm with slitting to a depth of 40 cm	0.7×10^{-3}	3.0	2.67	1.61	47.5	28.2

Table 5. Indices of soil wash-off (y_1, t ha^{-1}), surface run-off (y_2, m^3 ha^{-1}) and water absorption before run-off (y_3, mm) in the case of sprinkling against different agronomic backgrounds obtained from experiments and calculated on the basis of models

Agronomic background	Soil wash-off (y_1) [t ha^{-1}]		Surface run-off (y_2) [m^3 ha^{-1}]		Water absorption by soil before run-off (y_3) [mm]	
	E*	C*	E	C	E	C
Eroded typical chernozem						
Without fertilisation (reference)						
Ploughing to a depth of 20–22 cm	9.88	10.9	126	115	11.5	12.7
Subsurface blade tillage to a depth of 20–22 cm	0.78	1.11	58	53	30.5	27.5
Subsurface blade tillage to a depth of 10–12 cm with slitting to a depth of 40 cm	5.21	3.78	102	92	16.0	17.4

Note: *E – experimental; *C – calculated value of effective parameter.

hand, and the erosional energy of the model rain or the morphometric properties of the run-off site, on the other hand. Also, the correlation between the soil wash-off indices and the degree of projective cover with plant residues is statistically not significant. The linear correlation between the soil wash-off, the amount of plant residues and the slope gradient has been found statistically significant. The correlation between the soil loss data obtained from experiments and the data calculated basing on the model is specified by the following parameters (Table 5): r = 0.938; r_2 = 0.880; Sr = 0.100 t_f = 9.38; if n^{-1} = 12 t_{05} = 2.18; t_{01} = 3.06; t_{001} = 4.32. This correlation is significant at all significance levels.

It has also been proven by the long-term monitoring in field conditions of run-off sites in the experimental field with severely eroded chernozem that under the action of variable-depth subsurface blade tillage and slitting the more erosion-resistant topsoil is formed. This soil layer mitigates the destructive effect of snowmelt and storm water. As a result, the soil wash-off is reduced as compared to the conventional soil cultivation. It has been established that the mean annual erosion soil loss in the case of ploughing is equal to 4.8–5.9 t·ha^{-1}, in the case of subsurface blade tillage – 0.02–0.01 t·ha^{-1}.

From the ecological point of view, it should be noted that simultaneously with the loss of fine earth in the washed-off soil, also a large amount of energy concentrated for the mostly in humus substances is lost, while this energy could be used for supporting the life of the flora and fauna in the landscape [Kaminskyi et al., 2021]. According to the results of the long-term observations carried out in the erosion-endangered agricultural landscapes of the Right Bank Forest Steppe Region, where the research territory is located, together with the washed-off soil (severely eroded chernozem) 2,484 MJ·ha^{-1} are lost in the case of ploughing to a depth of 20–22 cm. In the case of subsurface blade tillage of the soil to a depth of 10–12 cm together with its slitting to a depth of 40 cm, the energy loss is lower by almost a half – 1,288 MJ·ha^{-1}, finally, an almost negligible energy loss occurs in the case of subsurface blade tillage to a depth of 20–22 cm–196 MJ·ha^{-1} (Table 6).

The loss of energy due to erosion has been rather notable in typical slightly eroded

Table 6. Loss of energy in humus substances as result of fine earth wash-off from chernozem soils under different soil cultivation systems

Cultivation method	Mean humus content, %	Energy content in soil depending on humus content, kJ kg^{-1}	Soil wash-off, t ha^{-1}	Humus loss, kg ha^{-1}	Energy loss in humus compounds, MJ ha^{-1}
Eroded typical chernozem					
Ploughing to a depth of 20–22 cm	1.66	251.4	9.88	164	2,484
Subsurface blade tillage to a depth of 20–22 cm	1.66	251.4	0.78	12.9	196
Subsurface blade tillage to a depth of 10–12 cm with slitting to a depth of 40 cm	1.63	247.2	5.21	84.9	1,288

chernozem because of its higher humus content. It has been recorded at the following levels: in the case of ploughing – 2,415 MJ·ha^{-1}, against the subsurface blade tillage background – 1,497 and 2,069 MJ·ha^{-1}, respectively.

CONCLUSIONS

The soil and water protection capacities of different agronomic engineering measures applied to the eroded chernozem soils of the Right Bank Forest Steppe Region were determined. The trends in the management of the erosion resistance of the soils, the methods of improving individual elements in the agricultural technologies with an aim of reducing the erosion, increasing the water availability and obtaining the sustainable yield of agricultural crops were defined and theoretically justified.

It was established that the water permeability of the soil, that is, the ability of this natural body to absorb and conduct precipitation water as well as snowmelt is a factor that has high impact on the water erosion processes. Its magnitude depends on the structural and aggregative state, the water fastness of soil aggregates, the density, the presence of pore space, its size and configuration, the projective cover from plant residues of the cultivated crop. The higher the water permeability of the soil is, the smaller the surface run-off and the soil wash-off are. It was found that the water permeability of eroded chernozem planted with winter rape is low. In the case of such a level of water infiltration through the soil, the development of water erosion is quite probable.

The two-year cultivation of perennial grasses in crop rotation was found to promote a rise in the water absorption by the soil, especially in the case of deep subsurface blade tillage. Hence, it is advisable to implement soil cultivation without overturning furrow slices in sloped agricultural landscapes for the purpose of improving the water permeability of eroded chernozem soils.

As a result of the completed mathematical calculations, a direct correlation was established between the results of the physical modelling of erosion processes under field conditions and the main soil parameters that have effect on the erosion resistance of the soil, which can be described by a regression relation. The coefficient of correlation between the obtained experimental data and the calculated ones for the surface run-off is equal to $k = 0.897 \pm 0.142$, for the soil wash-off – $k = 0.938 \pm 0.100$.

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