

Analysis of the State and Assessment of Possible Ways of Preservation of Soil Fertility During its Mechanical Treatment

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ABSTRACT

The issues of soil fertility preservation are relevant in all countries of the world. Concrete actions, technological and organisational solutions allowing to overcome this complex and continuous phenomenon by using exclusively agroengineering approaches are proposed. The preservation of the structure of agricultural soils requires urgent adoption of technological and organisational decisions in the following areas: maximum limitation of immobilisation of nitrogen in the soil after introduction of organic residues into the soil; development of technological methods and tools for the soil cultivation, aimed at loosening the surface layer of the soil with a minimum area of its contact with the airborne environment; improvement of the fundamentals of aggregation of agricultural machines, taking into account the maximum permissible slipping of wheeled energy facilities at the level of 15%, and a conceptual approach to their ballasting with respect to the requirements of the tire ecophilicity; application of a soil structure indicator when determining the ploughing frequency by means of ploughs with skimmers or their two-tier analogs; wide practical application of the controlled traffic farming system; adoption of a legislative document on specific conformity of the land users for the level of soil fertility for agricultural purposes.

Keywords: soil fertility, humus, destruction, soil structure, mechanical treatment.

INTRODUCTION

Investigations of the soil structure recovery processes, being one of the most important indicators of preservation of its fertility, are sometimes contradictory. The issues concerning preservation of soil fertility have been dealt with great interest in the research literature (Barwicki et al. 2012; Šimanský et al. 2019; Novakovska et al. 2016).

According to the classical definition of the famous soil scientist V. Williams, soil fertility is its

ability to provide the vital needs of plants in the simultaneous and joint presence of two factors of their existence – moisture and nutrients (Williams 2009). Such an ability is primarily determined by the structural condition of the soil environment. It is known that this condition may have two forms: lumpy (structural) and separately partial (structureless) (Nugis et al. 2016; Kaminski, 2011). The first of them is a more or less loose layer of lumps with a diameter of 0.25 to 10 mm, formed with the help of a special “cement”, which is humus.

In contrast, in a structureless condition individual soil particles, between which the correlation is weakened, lie in a continuous mass throughout the entire depth of the arable horizon. The humus content here becomes catastrophically small due to the active process of dehumification.

If the structure of the soil, formed by humus, is the determining factor of its fertility, then it should be recognized that the minimum task of agriculture is to preserve, and the maximum is to improve this structure. For detailed acquaintance with this, it is enough to refer to special publications by domestic scientists in the agronomic direction. In work (Balyuk et al. 2017) there is information about the loss of humus without a substantive analysis of the reasons for this process. If a certain consideration is given, then it is aimed at drawing attention to the need of solving the problem how to increase humus, rather than preserve it.

Recently, a negative or sceptical attitude to the basic soil tillage by the mouldboard plough has been expressed to a greater or lesser extent in many published scientific works. Scientists and producers in many countries of the world systematically assert that the technical and economic expediency and agrotechnical benefits of the mouldboard soil tillage using ploughs are minimal. In this case, the main emphasis falls on the correct choice of the processing system. (Kartamyshev et al. 2008) drew a conclusion that for the formation of a positive balance and expanded reproduction of humus, it is only necessary to replace the main mouldboard tillage of the soil by its local presowing loosening with the introduction of a full dose of mineral fertilisers.

At the same time, as practice shows, even a complete denial of moldboard tillage quite often does not stop the decline in the soil fertility as a result of constant loss of humus. This fact unambiguously indicates incomplete knowledge of the farmers regarding the ways and nature of the destruction of this organic matter.

The aim of the study was to analyse the possible agroengineering ways of stopping the rapid decline and further ensuring the conservation of humus in agricultural soils.

MATERIALS AND METHODS

When preparing the work, a wide analysis of literary sources was carried out and the results

of the authors' own theoretical and experimental studies were used in the following areas: mechanical and technological foundations of the ploughing process, as a special method for restoring the structure of the soil; determination of the maximum permissible slipping of the propellers of the wheeled tractors and their ballasting from the point of view of preserving the soil structure; creation of a family of wide-grip combined aggregates according to the "push-pull" scheme; development of technologies for growing crops using the "Controlled traffic farming" (CTF) system; bases of legislative responsibility of the land owners for their use.

The limiting structure of the soil was assessed by the relative amount of agronomically suitable aggregates, which include lumps of soil with a diameter of 0.25 to 10.0 mm:

$$K_c = \frac{\sum M_a}{\sum M_o} \quad (1)$$

where: K_c – the soil structure index; M_a – the mass of the soil particles with a diameter of 0.25–10.0 mm; M_o – the mass of the soil particles, the diameter of which is less than 0.25 mm and more than 10.0 mm.

The process of determining the K_c index using the "dry" method requires only three, one of which is solid (without holes), and the other two with holes of 0.25 and 10.0 mm in diameter (Hakansson 2005; Nugis et al. 2016). The decision on the need for ploughing is made when the value of the coefficient and the soil structure is less than 0.67.

At the same time the presence of a sieve with a hole diameter of 0.25 mm significantly complicates the process of sifting the soil and obtaining reliable laboratory data. The situation could be radically changed for the better by the creation of a modern electronic device, capable, in the "on-line" mode, at least in one plane, to estimate the quantity of the soil particles and aggregates, and their geometrical dimensions.

When determining the humus content in the soil, the basic provisions of the standard were used "Soils. Methods for laboratory determination of organic matter content" (Standard GOST 23740-79).

The standard of Ukraine «Agricultural mobile equipment. Standards for the impact of the running systems upon the soil» (Standard DSTU 4521: 2006) were employed to assess the impact of the running systems of tractors on the soil.

RESULTS AND DISCUSSION

Over the past 30 years, the humus content in many black soils (“chernozem”) of Ukraine (where intensive farming is carried out) has decreased by 30–35%. At the same time, the negative tendency towards a decrease in the humus content persists. Soil scientists should widely discuss this problem and make proposals for preserving soil fertility for future generations.

The study of the deterioration of soil fertility due to the loss of humus is a multifaceted problem that requires complex consideration. Currently, there are three main ways of the loss (destruction) of humus: 1) biological; 2) physical and chemical; 3) mechanical. For exact understanding of the problem and possible solutions, each of them will be analysed.

1. Normal plant nutrition requires decomposition of the soil organic matter by aerobic bacteria into oxidised mineral forms, which contain all the necessary elements. Thus, all the organic substances entering the zone of action of aerobes (including humus) are subject to systematic and immediate destruction. Since humus is synthesised mainly under anaerobic conditions, its destruction occurs under aerobic conditions on the surface of the soil lumps. The physical essence of this phenomenon is that humus loses its cementing and adhesive properties. Because of this, each lump of soil loses its strength, by slow, yet relentless disintegration into individual dust particles. In the course of their accumulation, they increasingly fill the gaps between the soil lumps and create conditions for which air and soil moisture become antagonists. As a result, the surface layer of the soil gradually loses its structure, and, consequently, its fertility. If the process of decay of humus by biological means is fundamentally impossible to stop, then it is probably possible to slow down the course of this process in a certain way. Thus, for example, simultaneously with the introduction of the plant residues into the soil, additional mineral (nitrogen) fertilizers should be applied at the rate of about 7–10 kg d. r. per ton. In this case, the fertilizers are needed not for plant nutrition but to ensure the functioning of aerobic bacteria when they process the plant residues, wrapped in the soil. If this is not done, then the process of nitrogen immobilisation in the soil environment, known to the scientists and practitioners, will take place with all the ensuing negative consequences. To preserve humus,

the procedure of returning the organic matter to the soil with the simultaneous application of mineral fertilisers should be carried out in two of their norms: the first – for the nutrition of the cultivated plants, and the second – for the nutrition of aerobic bacteria and other soil microorganisms. The more fully these norms take into account the specific zonal soil and climatic features, the better. Any other methods of inhibiting the loss of humus biologically should be known not only to the scientists but also be in service of those who are directly involved in the cultivation of agricultural crops.

2. The physico-chemical process of humus destruction is carried out as follows. According to Williams (2009), all the atmospheric precipitation that enters the soil includes ammonium salts, which are in a state of ionisation. A special place among these ions is occupied by the ammonium cation NH_4^+ . It is the ammonium cation which, in contact with the surface layer of the soil, inevitably displaces the calcium cation Ca^{++} , present in that humus, and takes its place. This cationic substitution leads to the fact that humus gradually loses its cementation and adhesive properties. As already mentioned above, because of this soil phenomenon, the structure of the soil is gradually deteriorating, which decomposes into dust-like particles. Eventually, it becomes incapable (at least almost incapable) of reaching the required level of supply of the plants with food and moisture, that is, it loses fertility. Like the biological way, it is also impossible, in principle, to stop the physico-chemical path of humus destruction. Apparently, only a certain slowdown of this process is possible. But how? A more or less exhaustive answer to this problematic question should be given by the soil scientists. In authors' opinion, a certain positive solution of this issue is provided by cultivation of agricultural crops using the “no-till” and “strip-till” technologies since the plant mulch, located on the soil in a certain way, limits the contact of NH_4^+ cations with the surface layer of the soil. One of the options for the solution of this problem may be a scientifically grounded systematic application of calcium-containing fertilisers, yet with obligatory consideration of the presence of boron. Only under such conditions assimilation of calcium by the soil-absorbing complex will be efficient (Sokolova & Trofimov 2009). Under real conditions, such a

measure is usually resorted to when it becomes necessary to reduce the acidity of the soil. In this case, the state of its structure remains without attention, which is currently an unacceptable fact. These methods of basic soil cultivation that allow for the given loosening of its lower (anaerobic) layer and minimum – of the upper (aerobic) one, are promising. In this case, the surface area of the latter is significantly reduced, which is directly exposed to the action of ammonium cations. The development of fundamentally new working bodies of the soil-cultivating tools for such a technological purpose should be one of the priority tasks of agricultural engineers. When applying ammonium fertilisers (ammonium sulfate $(\text{NH}_4)_2\text{SO}_4$, ammonium chloride (NH_4Cl) , etc.), not all cations are assimilated by the plants from the soil absorption complex. Part of these ions are converted to a nitrate form. In addition, it is quite probable that with excessive application of ammonium fertilisers, a certain part of the ammonium cations will have a destructive effect in relation to the humus of the soil. Having in mind this careful determination of the dose of such fertilisers, it was, is and will remain a very important aspect of the correct management of field cultivation. One of them should include the use of effective developments in algology (Roncero-Ramos et al. 2019): the use of soil algae of the “Nostoc commune” type to convert the atmospheric molecular nitrogen into a nitrate form, accessible to the plants. The same result can be achieved by applying non-moldboard tillage, in which soil algae are capable of developing their populations (especially in the autumn period).

3. The mechanical way of destruction of humus has an exclusively subjective nature, primarily due to the technogenic human activity in the agricultural sector. In principle, this problem has been thoroughly enough investigated by scientists (Hakansson 2005; Wojciechowski et al. 2020; Skrypchuk et al. 2020). In practice, in Ukraine, the requirements of the standard (Standard DSTU 4521: 2006) are rarely met due to the lack of a methodological basis for practical application. The latter, as it is known, for specific soil and climatic conditions limits the pressure of the movers of the means of energy upon the soil in kPa at a level that makes it impossible to deteriorate its structure and fertility. How can farmers take advantage

of these requirements in practice? After all, in their technical documentation the tractor manufacturers do not provide to the operators such extremely necessary information as the specific pressure of the movers upon the soil in kPa. This is typical for all tractor builders in the world. To a certain extent, they can be understood since the value of such an indicator depends not only on the operating weight of the means of energy but also on the air pressure in the tires, their width and diameter, and most importantly, on the hardness of the soil and its moisture content. That is, in each specific case the use of a particular tractor, the specific pressure of its movers upon the soil will be different. Finally, everything is complicated by the problematic nature of measuring this indicator under the field conditions (especially in terms of determining the area of the supporting surface of the tractor movers).

Regardless of what was said above, there are ways of practical use of standard requirements (Standard DSTU 4521: 2006) concerning the prevention of the soil overcompaction. First of all, when choosing a strategy for ballasting the energy resources. Now, at practically all the exhibitional arrangements, one can see a line of modern tractors the frontally mounted mechanisms of which are equipped with metal ballasts. Among the scientists, there is an incorrect, in authors' opinion, belief that, in principle, the source of energy can be additionally loaded with ballast, equal to its operating mass (Janulevičius & Giedra 2005). According to the proposed conditions for the ecophilicity of a tractor tire, the level or amount of ballasting (Mb) of a wheeled source of energy should be determined taking into account two restrictions (Bulgakov et al. 2019). The first of them is determined by the requirements of standard (Standard DSTU 4521: 2006) regarding the maximum permissible pressure (Q_p) of the tractor movers upon the soil under specific soil and climatic conditions. The second limitation represents the maximum carrying capacity of the tire P_w , taking into account the vertical load N_{ek} , which falls on its supporting area F_s (Fig. 1).

As studies showed, when taking into account certain synergy of these restrictions under specific soil conditions, ballasting of a wheeled tractor, not only with single but also with double tires, can be limited and even impossible (!).

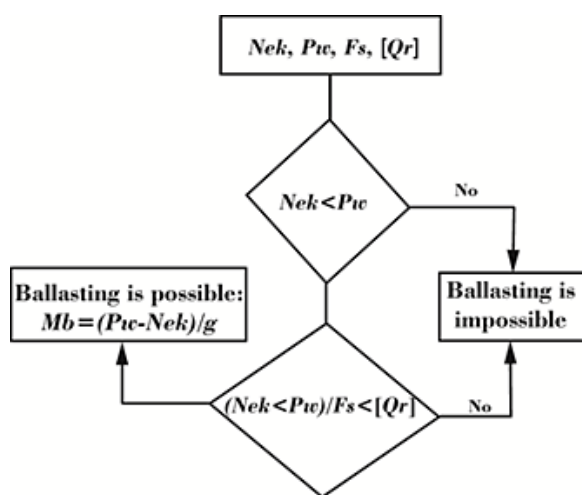


Figure 1. A block diagram for the determination of the possibility of ballasting the tractor, taking into account the condition the tire ecophilicity

Another direction of using standard (Standard DSTU 4521: 2006) is associated with slipping (skidding) of the sources of energy, First of all, of the wheeled ones. The fact is that the highest traction indicators are achieved by such sources of energy when the movers slip at the level of 22–24% (Guskov et al., 2008). From the point of view of the impact upon the structure of the soil, such a level of slipping of tractors is generally unacceptable; this is quite understandable and beyond any doubt. At the same time a question arises: what a more or less reasonable value of this indicator is the maximum permissible?

In order to find an answer to this important question, a methodological approach was introduced, the essence of which is as follows: it does not matter for the destruction of the soil structure in which direction – whether vertical or horizontal – excessive deformation or shearing of its layers is carried out. In addition, the pressure of the tractor movers upon the soil in the horizontal plane was considered as the ratio of the maximum tangential wheel traction force to the area of the side surface of the wheel lugs. the value of the aforementioned parameter $[Q_r]$, defined by the standard for use in the vertical plane (Nadykto et al. 2015) was taken as the limiting factor.

This methodological technique allowed establishing such a maximum permissible value of slipping of the movers of a wheeled tractor (δ_{max}) at which the cut of soil layers by its wheels is excluded altogether, and the deformation of the landslide is limited by the permissible value of the parameter $[Q_r]$. According to the results of analytical studies,

it was found that the value of δ_{max} in this case should not exceed 15%. As the results of the experimental studies (Fig. 2) show, the value of the soil structure index $k_c = 0.51$ is higher than the minimum permissible value (0.4).

Further, we emphasize that modern wheeled tractors for the most part have active wheel drive of the front and rear axles, as well as high adhesion properties of their tires. If the requirement $\delta_{max} < 15\%$ is added to this, then a circumstance is obtained, according to which the dependence of the slipping of the tractor movers (δ) upon its tractive effort (P_{kr}) will be of a linear nature:

$$\delta = a \cdot P_{kr} + b \quad (2)$$

where a and b are definite constants.

In a practical sense, this means that in order to assemble efficient machine and tractor aggregates, the operators must have new, traction and dynamic characteristics of the wheeled tractors they use. To achieve such a result, scientists must convince the manufacturers or dealers of the means of energy who sell foreign samples to carry out a special cycle of field tests with them. The obtained traction and dynamic characteristics of tractors in this case should represent the modes of their operation, provided that the movers slip not more than 15% of their correct ballasting and reasonable traction operations performed on the double tires.

The machine-tractor aggregates, assembled with this in mind, will be characterised by at least a reduced impact upon the structure and fertility of the soil. This effect can be significantly

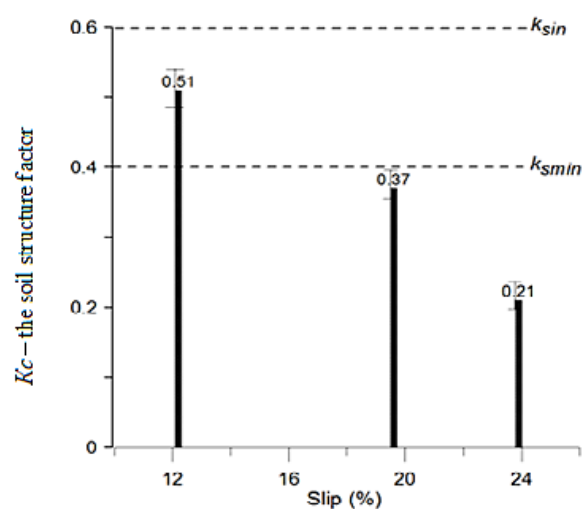


Figure 2. Dependence of the soil structure coefficient on slipping of a wheeled tractor

enhanced, if combined machine-tractor aggregates are used instead of the traditional ones. According to the method of aggregation, the combined machine-tractor aggregates are divided into three groups: 1) aggregates in which the single-purpose machines/ implements are connected in series with each other using couplings; 2) aggregates in which the means of energy is aggregated with a machine that has a single frame on which permanent or replaceable working bodies can be fixed; 3) aggregates according to the “push-pull” scheme, composed of several single-purpose machines/tools, some of which are hung on the frontal, and the others – on the rear mounted mechanisms of the means of energy. The main advantage of the first method of assembling a combined machine-tractor aggregate is that the latter is completed from a serial single-purpose machines, available on the farm without their rebuilding or with minor changes. Such combined machine-tractor aggregates, as a rule, are cumbersome and metal-consuming. The single-pupose serial machines that are part of these aggregates are usually designed to work independently with tractors at their optimum load. Therefore, they often do not have the same working width and optimal working speed, which makes it difficult to choose the optimal parameters of the composite combined aggregate. The advantage of the combined aggregates of the second scheme is greater compactness and lower metal consumption, which allows some of the machines/tools to be made mounted or semi-mounted. In addition, it is possible to use the working bodies and sections of serial machines/

implements in the required combination. The disadvantages of such combined machine-tractor aggregates are a more complex frame design, concentration of the working bodies on it, which often complicates the maintenance of the machine, increases the tendency of clogging the working bodies with soil and plant residues, and reduces operational reliability in comparison with the single-purpose machines/tools.

The third scheme for assembling the combined machine-tractor aggregates is the most promising. The advantages of such aggregates are that the mass and traction resistance of the frontally mounted sections of the machines or implements increase the vertical load upon the front traction wheels of the means of energy, increase their adhesion to the soil and reduce towing. As a result, the conditions for using the power of the means of energy improve due to the redistribution of loads across its bridges, labour productivity increases, and specific fuel costs are reduced. In many cases, the metal consumption and the kinematic length of the aggregate are reduced, which leads to a decrease in the width of the headland and the non-productive losses of time during the movement of the combined machine-tractor aggregate on it. However, to assemble combined machine-tractor aggregates according to such a scheme, an energy device with a frontal hitch is required. It is quite desirable that it also have a front PTO shaft, a reversible control post or reversible transmission, an engine with two power levels, etc. On the basis of experimental tractors, a number of schemes of the new promising combined machine-tractor aggregates were developed (Fig. 3).



Fig. 3. Experimental combined machine-tractor aggregates; a) ploughing-crushing, b) disk-chisel, c) ploughing-fertilising, d) reaper-peeler

The schemes, parameters and modes of their operation are substantiated on the basis of analysis of many results of theoretical and experimental studies of prototypes (Ivanovs et al. 2018). The results obtained indicate the prospects of using the new combined machine-tractor aggregates, operating according to the “push-pull” scheme when solving the problem of reducing soil compaction, increasing the technological versatility of the wheeled means of energy due to efficient application of their frontally mounted mechanisms. It should be emphasised that in most foreign wheeled tractors, their frontal attachments are equipped with metal ballast weights instead of attachments/ implements.

At the same time, regardless of the used machine-tractor aggregate – traditional or combined – a significant part of the cultivated area of the field is compacted. Quite often, it is 2–4 times less than that which falls on the total area of the tracks from the passage through the field of the means of energy as a part of a machine-tractor or combined machine-tractor aggregate. A principal way out of this situation is the distribution of the field area into technological and the transport areas. The first area is designed for the cultivation of agricultural crops, and therefore it is not at all influenced by the used movers of the means of energy. The second part of the field area, on the contrary, is intended exclusively for moving the running systems of tractors. Since it is not sown with cultivated plants, it essentially drops out of technological circulation. Yet, this is fully compensated by the fact that, due to the absence of the soil compaction by the means of energy, the soil fertility of the technological zone of the field increases. In the long term, this compensation is complemented by real economic benefits.

In the world practice, this technology, known as CTF (Controlled Traffic Farming), is quite efficiently implemented (Bulgakov et al. 2021). The technologies for growing row crops and grain crops, were developed using CTF. The obtained results indicate that in this case the process of compaction of the agricultural background is under full technological control. In general, this clearly contributes to the improvement of soil fertility and, as a result, leads to an increase in crop yields. On the whole, this unambiguously contributes to the improvement of the soil fertility and, as a result, leads to an increase in the agricultural crop yields.

On the basis of what was said above, it is difficult to deny that under the synergistic influence of the above-mentioned biological, physico-chemical and especially mechanical factors, the structure of the surface layer of the soil (in fact, it is 8–10 cm) gradually deteriorates over time. The dust-like (destructured) particles after the first sediments are cemented in high-density macroaggregates. Loosening of the surface layer of the soil, applied in this case in practice, does not solve the problem.

The thing is that the soil porosity, significantly reduced because of compaction (less than 50%), can be restored only by vital activity of the soil microorganisms. However, this requires appropriate conditions and time. Ignorance of this prompts the developers of agricultural machines and implements to equip them with unnecessary mechanisms for loosening the compacted soil along the track of the tractor movers. In this case, there is no useful result, and, accordingly, there is an undesirable complication and rise in the cost of the machine. To restore the strength of the structure of the upper soil layer, it must be isolated from the impact of the droplet-rare atmospheric water and air by moving into anaerobic conditions to the place of the lower – structural one. The use of soil mulching can help solve this problem, yet in part, because it requires creating a thick layer of mulch. This is not always possible in practice. The only tool that is capable of interchanging two layers of soil without mixing them (which is fundamentally unacceptable!) is a plough. As it is known, this arable tool turnover the soil layer in two steps. First, the skimmer (or the plough trashboard) throws the clods of the soil, broken along the surfaces of the least resistance, to the bottom of the furrow, and then the main body of the plough covers these clods from above with a lumpy (prestructured) mass. Since the loss of the soil structure by the upper layer and its restoration by the lower layer does not occur in a year, there really is no need for annual ploughing. However, a question arises how to determine the time of this technological operation. A claim was put forward (Adamchuk et al. 2016) that the arable horizon of the soil can be exploited without rotation until its top layer (8–10 cm) reaches the required limiting structure. It was underlined above that the interchange of two layers of the soil by means of a plough should exclude their mixing. Otherwise, the destructured soil layer will gradually dilute the lower structured one. in the course of time,

such a systematically carried out process will lead to an unsatisfactory structure (and hence fertility) of the entire arable (20–22 cm) horizon.

The authors are deeply convinced that reducing the width of the skimmer is harmful, in general. On the contrary, it is possible (and even desirable) to use an equivalent working body instead. In practice, the design of such a tool is known as a double-deck plough. Experimental studies of the operation of these arable implements over the years have revealed a number of technological advantages. First of all, this concerns the completeness of embedding of the plant residues of the agrotechnical background – for a two-tier plough, it is almost 100%. The use of these arable implements allows the tractor to be aggregated with the right-side wheels into the furrow floor, thereby reducing the specific fuel consumption of the machine-tractor aggregate. If the currently indicated advantages of two-tier plows are little known to industrialists, then this is a direct flaw on the part of agricultural engineers.

In the end, regardless of the technological methods of humus preservation, without appropriate social and legal support they will not give a proper return. This includes the absence of a clear, unambiguous and specific mechanism of responsibility of the land user for the deterioration of the soil structure and its fertility. For example, it can be as follows: each land area that is either leased or owned by a land user must be certified for the level of humus content in it as a potential indicator of the soil fertility.

The quantitative characteristic of this indicator (CI) may be presented in the form of a confidence interval (%):

$$CI = CZ \pm GZ \quad (3)$$

where: CZ – the average value of the humus level on a certain land area; GZ – the limiting error of the CZ value.

If, after a certain time of using this land area, it turns out that the actual level of humus is within the certified CI , then the land user carries out the normal practice of its operation. If the actual level of humus exceeds the certified one, the land user must necessarily receive a substantial financial reward from the state – as an indicator of an excellent and highly desirable attitude towards national wealth. If such or a similar specific mechanism for monitoring the state of use of agricultural land is absent, the level of their fertility can only worsen. However, the presence of such a control

mechanism will make it possible for the entity to carry out a thorough and absolutely reasoned analysis of possible risks before making a decision on acquiring economic rights on the land.

CONCLUSIONS

The process of preserving the structure of agricultural soils requires urgent adoption of technological and organizational decisions in the direction of:

- maximum limitation of immobilisation of the soil nitrogen after embedding the organic residues into it;
- systematic control of the supply of the soil-absorption complex with calcium and the corresponding microelements;
- development of technological methods and tools for the soil cultivation, aimed at loosening the surface layer of the soil with a minimum area of its contact with the airborne environment;
- improvement of the fundamentals of aggregation of agricultural machines/implements, taking into account the maximum permissible slipping of the wheeled of the means of energy at the level of 15% and a conceptual approach to their ballasting in accordance with the requirements of ecological tires;
- the use of the soil structure index in determining the ploughing frequency with ploughs with skimmers or their two-tier analogs;
- wide practical application of the controlled traffic farming system;
- adoption of a legislative document on the specific conformity of the land users concerning the soil fertility for agricultural purposes.

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