

THEORETICAL PRINCIPLES OF GROUNDING AND OPTIMIZATION OF THE PARAMETERS OF SOIL PROCESSING MACHINE UNITS

Andrii VYHOVSKYI, Candidate of Technical Sciences, Associate Professor

Maksym BILOUS, Candidate of Agricultural Sciences, Associate Professor

National University of Life and Environmental Sciences of Ukraine

ВИГОВСЬКИЙ Андрій Юрійович, кандидат технічних наук, доцент

БІЛОУС Максим Михайлович, кандидат сільськогосподарських наук, доцент

Національний університет біоресурсів і природокористування України

The publication highlights the theoretical principles of substantiation and optimization of the parameters of tillage machine-tractor units as one of the key factors in increasing the efficiency, productivity and energy performance of forestry production. The research is based on a systematic methodology that integrates the fundamental principles of theoretical mechanics, soil mechanics, traction theory and the general theory of machine-tractor units for the development and operation of high-performance aggregates. A comprehensive analysis of the main factors determining productivity, energy efficiency, reliability and quality of technological operations during primary tillage was carried out. Particular attention is paid to the complex interrelationships between the structural and technological parameters of tillage machines, the traction and energy characteristics of power units, soil properties and specific operating conditions.

Considerable attention is focused on the problem of reducing energy losses and improving the utilization of the traction capabilities of tractors. Modern approaches to mathematical modeling and optimization of operating parameters using traction-balance models, energy indicators and analysis of the time structure of technological operations are considered. The proposed methodology makes it possible to take into account actual operating conditions, changes in soil resistance, working speed, tractor wheel slip and the technical characteristics of the machines included in the unit.

The research results, including the developed algorithms for determining the optimal number of machines in the aggregate and rational working speeds while taking into account skidding indicators and energy limitations, can be used to improve technological processes in forestry. The implementation of the proposed approaches provides a scientifically substantiated basis for selecting the composition and operating modes of machine-tractor units, increasing productivity and economic efficiency, reducing specific fuel and resource consumption, and improving the overall energy efficiency of forestry operations.

Keywords: machine unit, basic tillage, traction balance, productivity, specific resistance of the soil, energy efficiency, productivity of units, modeling of technological processes, operational indicators.

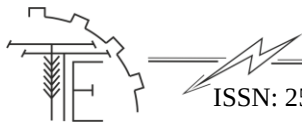
Eq. 34. Ref. 9.

1. Problem formulation

Tillage machines are the main technical means of implementing the technologies of the main and pre-sowing tillage in modern agriculture. The efficiency of their work is determined not only by the technical characteristics of individual machines, but also by the scientifically based selection of the rational composition of the unit and optimal modes of its operation. The theoretical justification of the parameters of tillage units is based on the fundamental provisions of theoretical mechanics, soil mechanics, the theory of traction and the theory of machine performance. The synthesis of these scientific directions allows to form a systematic methodology for the design and optimization of aggregates capable of providing the specified agrotechnical indicators with minimal energy and material costs.

The parameters of machine complexes for the main tillage are formed in accordance with the chosen system of mechanized technological processes of afforestation. The basis of this system is a set of defined technological operations that ensure the execution of the planned volumes of the main tillage works in the established agrotechnical terms. Engineering activity in the field of machine use is aimed at scientifically based determination of the composition of machine complexes (in particular, for basic tillage) and the development of methods for their effective application in specific natural and industrial conditions.





The organization of work becomes especially important in those periods when a significant number of technological operations of the main tillage are performed at the same time. The rational use of machine complexes for these tasks is extremely important, because the efficiency depends on the composition of the i -th machine unit used to perform the j -th technological operation. The arrangement of aggregates forms the composition of a complex of machines as a complex dynamic system, the performance indicators of which largely determine the effectiveness.

2. Analysis of recent research and publications

A significant contribution to the development of the theoretical foundations of optimizing the parameters of tillage units is highlighted in professional works. Some scientific publications [2, 5] reveal analytical dependencies for determining the optimal values of the grip width and the working speed of tillage units at a given power of the tractor engine and the linear nature of the dependence of skidding on traction force.

Other studies [1, 4] convincingly illustrate that the combination of technological operations is one of the defining directions of increasing productivity and an important vector of the development of the theory of aggregation.

The problem of optimizing traction performance from the standpoint of minimizing energy costs occupies one of the main places in modern research. Traction force generated on the surface of the soil is a basic characteristic that determines the possibility of realizing certain parameters of the tillage unit. Research states that the generation of tractive effort in field conditions is an energy-intensive process that consumes about 50% of the total power required in mechanized systems, and from 20% to 55% of tractive energy can be lost at soil-tire and soil-tool contact [7, 9].

3. The purpose of the article

The purpose of the study is the theoretical justification and development of approaches to optimizing the parameters of tillage machinery units taking into account the natural and production conditions in order to increase their productivity and reduce resource costs.

4. Results and discussion

The composition of the machine unit and the corresponding indicators depends on a number of factors: natural and production conditions, the terms of operations, the volume of work at each stage, as well as the area of cultivation of forest crops. Since production is purely practical in nature, the best indicator of its efficiency is the establishment of total costs for the performance of mechanized work. The necessary labor costs for the implementation of a specific technological operation of the main tillage can be estimated by the relevant dependencies and methods.

$$R_j^0 = \frac{r_{ij} \cdot O_j}{W_{ij}}, \quad (1)$$

where R_j^0 – costs for the entire volume of work on the j -th operation; r_{ij} – hourly costs during the operation of the i th unit on the j th operation; W_{ij} – hourly productivity of the i th unit on the j th operation, ha; O_j – volume of work on the j th operation, ha.

The volume of work when performing the j th operation is equal to:

$$O_j = S_d k_j, \quad (2)$$

where S_d – area of the forest plot, ha; k_j – coefficient that takes into account the amount of work per unit area.

Coefficient k_j is defined as follows:

- for technological operations:

$$k_j = \gamma_j, \quad (3)$$

where γ_j – coefficient that takes into account the multiplicity of the j -th operation;

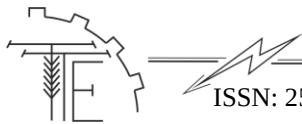
Knowing O_j you can determine the hourly volume of work:

$$\omega_j = \frac{S_d k_j}{T_j}, \quad (4)$$

where T_j – the time allocated for the j th operation.

Substituting dependency 2 into formula 1, we get:

$$R_j^0 = \frac{r_{ij} S_d k_j}{W_{ij}}. \quad (5)$$



Technical and economic indicators and operational properties of power tools, characteristics of tillage machines and tools, as well as natural and production conditions of their use determine the modes of operation of machine units in each specific operation. Taking into account the agrotechnically admissible speed mode of the soil cultivation operation, the specific resistance of the soil, the condition of the site, the parameters of the technical characteristics of the power tool, the tangential force of traction that the engine can provide is determined as follows:

$$P_d = \frac{3,6N_H \eta_T}{V_d}, \quad (6)$$

where P_d – tangential traction force, кН; N_H – rated engine power, кВт; η_T – transmission efficiency; V_d – permissible operating speed of the unit, km/h⁻¹.

In cases of aggregation of the traction-drive machine, the power of the engine, which is spent on traction N_T , is equal to:

$$N_T = N_H - N_{BBII}, \quad (7)$$

where N_{BBII} – the power used to drive the working bodies of the machine, kW.

The resulting value N_T for this energy source is substituted into formula 6 instead of N_H .

Due to the fact that the driving force is limited by the traction force of the driving apparatus with the ground, its value can be determined:

$$P_{3q} = G_{Tp} \gamma_{3q} \varphi g, \quad (8)$$

where P_{max} – the maximum traction force of the driving apparatus with the soil, кН; G_{mp} – the mass of energy means, т; γ_{3q} – coefficient, which takes into account the distribution of the mass of the energy vehicle on the driving apparatus; φ – coefficient of traction of the leading apparatus with the soil; g – acceleration of free fall, m (s²)⁻¹.

The coefficient of adhesion of the driving device to the soil depends both on the background of the site and on the class of soils on which the soil tillage unit functions, as well as on the type of driver. With a sufficient level of accuracy, this parameter can be determined by the following dependencies:

- for power vehicles with crawler drives:

$$\varphi = 0,9867 - 0,3289 \ln(\psi) + 0,02\rho, \quad (9)$$

- for power tools on pneumatic tires:

$$\varphi = 1,1428 - 0,2402 \ln(\psi) + 0,02\rho, \quad (10)$$

where ψ – the background of the site on which the machine unit works; ρ – class of soil according to specific resistance.

The driving force of the unit P_{pyu} is equal to:

- provided that if $P_r > P_{3q}$ then $P_{pyu} = P_{3q}$;

- provided that if $P_r < P_{3q}$ would consist $P_{pyu} = P_r$.

The hook traction force developed by the power tool is:

$$P_r = P_{pyu} - P_o, \quad (11)$$

In case of exceeding the maximum allowable hook force calculated for the given conditions, it is accepted:

$$P_r = P'_r, \quad (12)$$

where P'_r – permissible hook force of the power tool, кН.

The main forces of resistance to the movement of energy means are defined as follows:

$$P_o = G_{Tp} g \left(f \pm \frac{i}{100} \right), \quad (13)$$

where f – rolling resistance coefficient; i – the slope of the terrain, %.

Coefficient of rolling resistance of energy vehicles:

- with a crawler can be determined from the expression:

$$f = 0,0413 \exp(0,1832\psi) - 0,002\rho, \quad (14)$$

- for power vehicles with wheel drives:

$$f = 0,02273 \exp(0,2854\psi) - 0,002\rho. \quad (15)$$

Depending on the type of working bodies of the tillage machine/tool, the working resistance created during the technological operation can be determined:

- for plows:

$$R = K_1 b a n_k + G_m g c \lambda \left(f \pm \frac{i}{100} \right), \quad (16)$$

- for conventional traction machines:



$$R = K_2 B + G_m g c \lambda \left(f \pm \frac{i}{100} \right), \quad (17)$$

- for trailed vehicles in the absence of traction resistance:

$$R = G_m g \left(f \pm \frac{i}{100} \right), \quad (18)$$

where R – total machine resistance, kN; K_1 – specific resistance of plows, $\text{kN} \cdot (\text{m}^2)^{-1}$; K_2 – specific resistance of ordinary machines, $\text{kN} (\text{m}^2)^{-1}$; b – plow body grip width, m; a – depth of tillage, m; B – constructive width of capture of ordinary machines, m; G_m – mass of the car, i.e; λ – coefficient that takes into account the additional load of the energy vehicle.

The specific resistance of tillage machines-tools depends on the speed mode of operation and can be specified according to the following empirical dependencies:

- for plows, $\text{kN} (\text{m}^2)^{-1}$:

$$K_1 = k_0 [1 + 0,006(V_p^2 - V_o^2)], \quad (19)$$

- for other machines, $\text{kN} (\text{m}^2)^{-1}$:

$$K_2 = k [1 + t(V_p - V_o)], \quad (20)$$

where k_0 – specific resistance of plows at a speed of up to 5 km/h^{-1} , $\text{kN} \cdot (\text{m}^2)^{-1}$; V_p – operating speed of the unit, $\text{km} \cdot \text{h}^{-1}$; V_o – the speed at which the specific resistance of machines is determined in production conditions, $\text{km} \cdot \text{h}^{-1}$ ($5 \text{ km} \cdot \text{h}^{-1}$); k – specific resistance of ordinary cars at a speed of up to $5 \text{ km} \cdot \text{h}^{-1}$, $\text{kN} \cdot (\text{m}^2)^{-1}$; t – rate of increase in specific resistance for the corresponding machine.

Thus, having found the hook force of the power tool, as well as the total resistance of soil tillage machines-tools, it is possible to determine the required number of them in the unit.

For multi-machine units, it is necessary to first determine the possible width of the machine unit:

$$B_T = \frac{P_r}{R_\xi}, \quad (21)$$

where B_T – maximum theoretical width of capture of the unit, m; R_ξ – machine resistance of the ξ th type, kN.

Then the number of machines of each type in the unit will be:

$$Z = \int_{\xi=1}^{\Theta} \left(\frac{B_T}{B_\xi} \right), \quad (22)$$

where B_ξ – construction width of the grip of the ξ -th type machine, m.

The total resistance of the machines in the unit is determined by the expression:

$$R_a = \sum_{\xi=1}^Z Z_\xi R_\xi. \quad (23)$$

Provided that $R_a > P_r$ adjustment of traction indicators of energy vehicles is carried out in the high-speed mode $V'_d = V_d - \Delta V$ until the moment at which the inequality will be fair $P_r > R_a$, and the current speed value V_d will not go beyond the lower limits permissible for this unit according to agrotechnical requirements.

The working speed of the unit, taking into account the skidding of the engines, is determined by the dependence:

$$V_p = V'_d \left(1 - \frac{\delta}{100} \right), \quad (24)$$

where V_p – operating speed of the unit, $\text{km} \cdot \text{h}^{-1}$; δ – skidding of engines, %.

The skidding of the engines of power vehicles is determined by the total resistance of the towed part of the machine unit and the maximum force of traction of the driving apparatus with the ground. In order to determine the amount of skidding, the concept of the relative traction force indicator was introduced:

$$\rho_T = \frac{R}{F_{\max}}. \quad (25)$$

Knowing the meaning ρ_T , the amount of slippage is determined by the following equations [Ошибка! Источник ссылки не найден.]:

- for wheeled tractors:

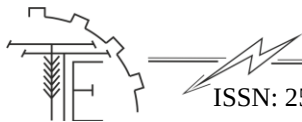
$$\delta_K = 2,75 + 12,5\rho_T + 100(\rho_T - 0,1)^6, \quad (26)$$

- for crawler tractors:

$$\delta_K = 0,15 + 4,0\rho_T + 100(\rho_T - 0,15)^6. \quad (27)$$

Productivity is one of the most important indicators of the use of machinery units, the accuracy of which largely depends on the assessment of the efficiency of the tillage machine complexes. For technological machine units, it is determined by a typical formula:

$$W_{\text{год}} = 0,1 B \beta V_p K_T, \quad (28)$$



where $W_{\text{год}}$ – unit productivity per hour, $\text{ha} \cdot \text{h}^{-1}$; B – construction width of the aggregate, m; β – bandwidth usage factor; V_p – operating speed of the unit, $\text{km} \cdot \text{h}^{-1}$; K_T – utilization rate of shift working time.

The productivity of the tillage unit is an integral indicator formed under the influence of two fundamentally different groups of factors. The first group is technical and design parameters of the unit (engine power, grip width, kinematics of working bodies), which are relatively stable and can be controlled during the assembly process of the unit. The second group is natural and production conditions (type and mechanical composition of the soil, its moisture and density, relief, dimensions and configuration of the site), which are objective, variable in space and time characteristics of the unit's working environment.

The interaction of these two groups of factors determines the real productivity of the unit in specific production conditions, which, as practice shows, can significantly differ from the calculated one. Therefore, understanding the mechanisms of the influence of natural and production conditions on the productivity of the unit is a necessary condition for the correct selection of the composition of the unit and the rational organization of its work.

With the introduction of the principles of the soil-protective, contour-agro-ecological farming system, which is a zonal modification of landscape farming, into the everyday production practice of farms, the need to take into account the complexity of the topography of forest areas has become ripe [5-8]. A special feature is the need to move the tillage unit in a direction that takes into account the landscape of the land allocation, the presence of perennial plantations, objects of man-made and natural activity, reclamation structures, etc.

It should be noted that the coefficient of use of working time of the shift from formula 28 does not fully take into account the quantitative relationships between productivity and the corresponding natural and productive factors. It is known that the utilization ratio of the working time of the shift is equal to [3].

$$K_T = \frac{T_o}{T_{3M}}. \quad (29)$$

In forestry, the elemental method of labor regulation is adopted, according to which the entire labor process is divided into the simplest constituent elements, followed by the study of each individual one. The shift time balance characterizes the distribution of the total shift time by the duration of individual components. The complete balance of shift time during the operation of tillage machinery includes the duration of all individual elements of the work process from the beginning to the end of the shift. According to the above considerations, the balance of the time of change during the operation of machine units can be presented in the form of a sum:

$$T_{3M} = T_{\text{III.TO}} + T_{\text{o.H.}} + T_{\text{i.p.}} + T_{\text{x.x.}} + T_{\text{T.L.O.}} + T_{\text{y.B.}} + T_{\text{i.II.}} + T_{\text{oc.II.}} + T_{\text{II}} + T_o, \quad (30)$$

where $T_{\text{III.TO}}$ – duration of shift maintenance of machine units, hours; $T_{\text{o.H.}}$ – loss of time to receive an outfit; $T_{\text{i.p.}}$ – the time of moving machine units to the place of work and back; $T_{\text{x.x.}}$ – idle time of the unit; $T_{\text{T.L.O.}}$ – technological service time; $T_{\text{y.B.}}$ – technological service time; $T_{\text{i.II.}}$ – loss of time associated with moving from one site to another; $T_{\text{oc.II.}}$ – time for rest and personal needs; T_{II} – loss of time due to meteorological and other organizational reasons; T_o – the duration of the main (net) work.

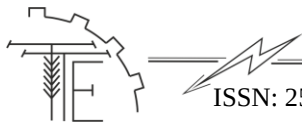
In accordance with the above considerations, the numerical value of productivity will be determined more precisely if we take into account the complexity of the conditions of use of the tillage machinery unit. It is known that there is a concept of typical conditions for the use of machine units for each class of race length, this section is rectangular in shape, the relief is up to 1°, there are no obstacles, the average humidity is 20-22%, the soil is not rocky, the height above sea level is up to 500 meters [3, 4]. However, in connection with the complexity of the conditions of use of machine units, to take into account the influence of factors other than typical ones, it is proposed to introduce a coefficient that characterizes the complexity of the use of machine units. That is, when determining the productivity of a machine unit that works in more complex natural and production conditions than typical, it is necessary to take into account the value of corrections, which determines the difference between real and typical conditions and has a gradation according to the complexity of the configuration of land allocations, the unevenness of the relief, the rockiness and moisture of the soil, the presence of obstacles and the height above sea level.

In a formalized form, the coefficient that characterizes the complexity of the conditions of use of machine units will be:

$$K_{\text{CK}} = k_{3B} \cdot k_{\text{III.}} \cdot k_{\text{KT.}} \cdot k_{\text{IIp.}} \cdot k_{\text{B.II.}} \cdot k_{\text{BC.}}, \quad (31)$$

where k_{CK} – factor of complexity of conditions; k_{3B} – coefficient of land allocation configuration; $k_{\text{III.}}$ – landscape coefficient of the land allocation; $k_{\text{KT.}}$ – coefficient of stony soil; $k_{\text{IIp.}}$ – coefficient of presence of obstacles; $k_{\text{B.II.}}$ – soil moisture coefficient; $k_{\text{BC.}}$ – height factor above sea level.

Taking into account the influence of natural and production factors on the working conditions of machine aggregates of the main tillage, it was established that the coefficient of the complexity of the conditions will have the following values: favorable conditions – 1.0; normal – 0.94; average – 0.88; medium-complex – 0.82; complex – 0.75; very complex – 0.7; extremely difficult – 0.62; almost impossible – 0.58; dangerous – 0.52.



Then the refined expression 28 takes the form $ha \cdot h^{-1}$:

$$W_{\text{год}} = 0,1B\beta V_p K_T K_{\text{ск}} . \quad (32)$$

Knowing the hourly volumes of work and the productivity of machine units, it is possible to determine the necessary integer number of machine units to perform each tillage operation:

$$N_{ij} = \int \frac{\omega_j}{W_{ij}} + 1 . \quad (33)$$

In this case, the costs for the total amount of work will be equal:

$$R_j^o = \sum_{j=1}^n \frac{r_{ij} T_j \int \frac{\omega_j}{W_{ij}} + 1}{S_{\text{н}}} . \quad (34)$$

Increasing the amount of tillage $S_o = S_{\text{н}} + \Delta S_o$, it is possible to reach the state of the system, when the efficiency criterion will not significantly change its value (or changes within insignificant limits) when the area increases. The area found in this way will be optimal for the operation of the machine unit, and the quantitative and qualitative types of power tools and tillage machines that are part of the machine units represent the initial set of machines for the main tillage, which will ensure the fulfillment of the planned volume.

5. Conclusion

As a result of the conducted research, the theoretical principles of substantiation and optimization of the parameters of tillage machine units based on the integration of the provisions of theoretical mechanics, soil mechanics and traction theory were summarized. The developed system methodology, based on the use of interconnected mathematical models of the traction balance, force interactions in the "soil-machine" system, the load of the energy means and the structure of the changeover time, provides a comprehensive approach to the design and assembly of aggregates.

The developed algorithm for determining the optimal composition of the machine-tractor unit makes it possible to reasonably set the rational number of machines and their modes of operation, taking into account engine power, transmission efficiency, conditions of traction of engines with the soil and resistance of tillage implements. This ensures coordination of energy and technological parameters of the unit in specific natural and production conditions.

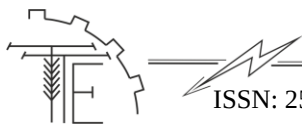
It is proved that the productivity of the unit is an integral indicator, which is determined by the combined action of technical-constructive and natural-production factors. The introduction of the factor of complexity of conditions allows to increase the accuracy of calculations and provides a differentiated approach to the standardization and planning of mechanized works.

It was established that taking into account the full structure of the shift time balance in accordance with the elemental method of labor rationing makes it possible to more objectively assess the coefficient of use of working time and the actual productivity of units, as well as to identify reserves for improving the efficiency of their operation.

The practical implementation of the proposed approaches contributes to increasing the energy and economic efficiency of soil cultivation, reducing the specific consumption of resources and provides scientifically based planning of mechanized work in forestry production, taking into account the specifics of natural and production conditions.

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ТЕОРЕТИЧНІ ЗАСАДИ ОБҐРУНТУВАННЯ ТА ОПТИМІЗАЦІЇ ПАРАМЕТРІВ ҐРУНТООБРОБНИХ МАШИНИХ АГРЕГАТІВ

У публікації висвітлено теоретичні засади обґрунтування та оптимізації параметрів ґрунтообробних машинно-тракторних агрегатів як одного з ключових чинників підвищення ефективності, продуктивності та енергетичної результативності лісгосподарського виробництва. Дослідження базується на системній методології, що інтегрує фундаментальні положення теоретичної механіки, механіки ґрунтів, теорії тяги та загальної теорії машинно-тракторних агрегатів для формування високопродуктивних і енергоефективних технологічних комплексів. Здійснено ґрунтовний аналіз сукупності факторів, що визначають продуктивність, енергетичну ефективність, надійність і якість виконання технологічних операцій під час основного обробітку ґрунту. Обґрунтовано складні взаємозв'язки між конструктивними та технологічними параметрами машин, тягово-енергетичними характеристиками енергетичних засобів, властивостями ґрунту та специфічними умовами експлуатації.

Акцентовано увагу на проблемі зниження енергетичних втрат і підвищення ефективності використання тягових можливостей тракторів. Розглянуто сучасні підходи до математичного моделювання та оптимізації робочих параметрів із використанням моделей тягового балансу, енергетичних показників і аналізу структури часу виконання технологічних операцій. Запропонована методика дає змогу враховувати реальні умови експлуатації, зміну опору ґрунту, робочу швидкість, буксування рушіїв та технічні характеристики машин.

Результати дослідження, включаючи розроблені алгоритми визначення оптимальної кількості машин в агрегаті та раціональних робочих швидкостей з урахуванням показників буксування й енергетичних обмежень, можуть бути використані для вдосконалення технологічних процесів у лісовому господарстві. Впровадження запропонованих підходів забезпечить науково обґрунтований вибір складу та режимів роботи машинно-тракторних агрегатів, підвищення продуктивності й економічної ефективності виробництва, зниження питомих витрат пального, ресурсів та загальної енергоємності технологічних процесів.

Ключові слова: машинний агрегат, основний обробіток ґрунту, тяговий баланс, продуктивність, питомий опір ґрунту, енергетична ефективність, продуктивність агрегатів, моделювання технологічних процесів, експлуатаційні показники.

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INFORMATION ABOUT THE AUTHORS

Andrii VYHOVSKIY – Candidate of Technical Sciences, Associate Professor at the National University of Life and Environmental Sciences of Ukraine (15 Heroiv Oborony St., Kyiv, Ukraine, 03041; e-mail: vygovsjkyj@ukr.net; <https://orcid.org/0000-0001-6545-0430>)

Maksym BILOUS – Candidate of Agricultural Sciences, Associate Professor at the National University of Life and Environmental Sciences of Ukraine (15 Heroiv Oborony St., Kyiv, Ukraine, 03041; e-mail: mbelous@nubip.edu.ua; <https://orcid.org/0009-0002-8372-6802>)

ВИГОВСЬКИЙ Андрій Юрійович – кандидат технічних наук, доцент Національного університету біоресурсів і природокористування України (вул. Героїв Оборони, 15, м. Київ, Україна, 03041; e-mail: vygovsjkyj@ukr.net; <https://orcid.org/0000-0001-6545-0430>)

БІЛОУС Максим Михайлович – кандидат сільськогосподарських наук, доцент Національного університету біоресурсів і природокористування України (вул. Героїв Оборони, 15, м. Київ, Україна, 03041; e-mail: mbelous@nubip.edu.ua; <https://orcid.org/0009-0002-8372-6802>)