Theoretical research of the work of technological equipment for lifting large planting material with a soil clod

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Abstract. Large woody plants are a promising type of planting material for use in landscaping and forestry. The most labor-intensive technological operation in the process of growing them is lifting. To increase efficiency, this type of work must be performed using special equipment. The aim of the study is to study the process of plantlets lifting with a soil clod based on mathematical modeling methods to determine the optimal design parameters of lifting equipment developed by the authors. For a theoretical study of the equipment working process, a mathematical description of the interaction of the digging working tool with the soil-plant environment is carried out. The research work with the model consisted in the implementation of computer experiments to solve the compiled differential equation of the working tool motion around a fixed axis. Moreover, within the framework of changing the parameters of the working tool and the medium being processed, the dependences of the moments created by the driving forces and resistance forces are recorded. According to the results of the study, patterns of changes in the power characteristics of the digging process were established depending on the parameters of the working tool and the soil-plant environment.

1. Introduction

When greening and restoring forests, taking into account the increasing volumes of timber harvesting, large-scale forest fires of recent years and the active growth of urban space, intensive methods of producing high-quality planting material are required. At present, both traditional and advanced methods are used to grow seedlings and seedlings in forest nurseries and selection and seed-growing centers, for example, using biotechnologies or breeding to obtain plants with improved hereditary properties. However, its use does not fully ensure the accomplishment of the tasks of landscaping settlements and forest conservation due to low survival rate and subsequent preservation, slow growth rate, especially in the initial period of development, and limited agronomic planting periods [1].

An approach to solving the problem of increasing the efficiency of landscaping and creating seed plantations using high-quality planting material from the standpoint of environmental and resource conservation shows that at the present time, when performing these works, the use of large seedlings is promising - specially grown planting material in height from 2 to 3.5 meters with a developed crown, the excavation of which is advisable to produce, preserving the soil around its root system [2, 3]. It has certain advantages over seedlings and seedlings that are grown according to generally accepted technology: it has high survival rate and resistance to external negative influences, prolongs the season of planting work and reduces the volume of its implementation [4, 5].
However, in the general cycle of using this type of planting material, the process of lifting it most often remains not mechanized, which means that it is low-productivity. Experts note the importance of mechanization of the process of obtaining large plants with a soil clod, which is manifested in interest in conducting research in this direction [6]. Equipment manufactured by Holmac (Italy), Optimal Opitz (Germany), Dutchman (Canada), Pazzaglia (Italy), Vermeer (USA) and others is used for the preparation of standardized planting material in forest and decorative nurseries. At the same time, the lifting equipment should have a wide operational flexibility [6], since the quality of the harvested planting material and its subsequent survival at the place of growth largely depends on the efficiency of lifting.

Scientists have long considered the problems of transplanting large trees [7, 8]. The factors that determine the success of this operation are evaluated: the need to prune the root system of the tree and its crown, the presence of water stress, the timing of lifting, the size of the soil clod, which ensures minimal root loss, and others [9]. It is noted that larger plants are more difficult to survive the transplant and take root in a new place, so when lifting it is especially important not to damage their developed root system. At the same time, cutting and digging soils is an energy-intensive process, so when working with equipment, it is also necessary to reduce the energy intensity plants lifting of the large. To increase the functionality of equipment for lifting large-sized plants, scientists study the power and kinematic features of the developed lifting mechanisms.

In order to reduce the resistance and energy consumption when lifting soil by the working tool of the developed device, the authors of the work [10] compiled a mechanical model in accordance with its working conditions and analyzed the effort of a digging working tool. Thanks to numerical modeling, a new type of bionic shovel has been designed and the digging angle of the shovel has been optimized. Certain optimal design parameters allowed to reduce the resistance to the working process. Assessment of the maximum working forces acting on the cutting edge of the working tool during the operation of the designed equipment was carried out in article [11] based on the finite element method.

The analysis of the kinematic characteristics of the blade working tools with a hydraulic drive was performed in work [12]. Zhao D, Guo Y and Song W implemented dynamic modeling of angular velocity and angular acceleration of a hydraulic cylinder using Matlab and Adams software.

In the work [13], the process of lifting trees in the winter, when the soil is frozen, is studied. Glubokaya A and Danilov A developed attachments for transplanting large plants with a milling working tool, which makes it possible to extract a clod of cylindrical form together with a plant from frozen soil.

The possibility of harvesting planting material directly under the forest canopy is considered in [14]. Rukomoinikov K notes that transplanting plants with a closed root system is more effective than transplanting undergrowth with an open root system. To work on the cutting area, he developed interchangeable lifting equipment placed on the base of the manipulator. This unit is able to dig out several plants with a soil clod from one working position.

A number of scientists are studying the features of the operation of equipment similar in technological process for extracting stumps from the ground in preparing areas for reforestation. In the work [15], quantitative values of the average and maximum forces required for vertical grubbing of the stumps of common spruce and birch by an aggregate based on an excavator were determined, as well as the influence of various types of soils and grubbing methods on the working process. In the work of Kärhä K. evaluation of the effectiveness of two devices for vertical grubbing of Norway spruce stumps. Calculations have shown that the cost of removing stumps is extremely high when their diameter is less than 20 cm [16]. The dependencies connecting the stump extraction force and its diameter, which can be used for rational selection of the stump grubber with a griper tool and determining the cost of grubbing, are considered in the work [17]. Previously, for the mechanization of the process of lifting and transplanting large planting material with a soil clod, the authors studied the available promising technical solutions in this matter and proposed a special design of lifting equipment [18].

The aim of the study is to research the process of lifting seedlings with a soil clod on the basis of mathematical modeling to determine the optimal design parameters of the lifting equipment that provide the minimum energy consumption of the working process.
2. Material and methods

2.1. Design and technological process of equipment for lifting large planting material with a soil clod

Digging is the most time-consuming operation to obtain large planting material, during which it is necessary to maintain such a volume of physiologically active roots, which in the future will ensure high establishment and active development of the plant herb.

To improve the establishment of planting material after transplantation, it is advisable to excavate plants with a root system closed by a soil clod, aged 3 to 7 years, when they have high root restoration efficiency.

Based on an analytical assessment of the known data on the features of the development of the root systems of the main forest-forming species in soil horizons, it was found that the root system of the plant must be dug up to a depth of 40 cm (parameter H). However, the larger the volume of soil clod to be recovered, the clod is heavier and larger, which complicates the subsequent lifting and movement of harvested plants to the planting site (figure 1).

![Figure 1. Lifting depth (H = 40 cm) of large planting material with a soil clod.](image1)

For lifting large planting material with a soil clod in forest nurseries, in Voronezh State University of Forestry and Technologies the authors have developed a special equipment (figure 2), the design of which contains a frame with load-bearing bars (1) and a device for attaching to the tractor (2), vertical posts (3) with a working tool fixed in it with blades in the form of two triangles (4), a half-bucket (5) in its rear part [18].

![Figure 2. A equipment for lifting large planting material with a soil clod: 1 – load-bearing bars, 2 – device for attaching to the tractor, 3 – vertical posts, 4 – knives of the working tool, 5 – half-bucket, 6 – hydraulic cylinders, 7 – hinges.](image2)
Two hydraulic cylinders (6) rotate the two shoulders of the lever formed by the vertical struts (3) and the working tool (4). Bearing bars (1), equipped with hinges (7) for fastening vertical racks, are made cantilevered with the presence on the lowered ends of supports placed under the hinges on the lower side of the bars. The working tool is made in the form of two triangles, the pointed peaks of which are directed towards the dugout seedling. This form of the working tool with an increased length of the cutting edge provides less energy-intensive oblique cutting of the processed medium, and therefore, smooth, jerky, entry into the soil.

The technological process of lifting large seedlings with a soil clod is as follows. An aggregated tractor with an attached equipment moves in the direction of the plant being dug. The equipment is raised, and the working tool is in its original position. The tractor stops when the limiter rests on the seedling trunk, while the equipment with the help of the hinged system is lowered until its supports come into contact with the soil. The working tool is partially embedded in the soil.

Then the operator sets the control cylinder of the rear tractor hitch in the neutral position and turns on the hydraulic cylinders (6). When the working fluid is supplied to the hydraulic cylinders (6), the working tool (4) is rotated to the final position, cutting out the root system of the seedling together with a soil clod. A half-bucket (5) of the working tool, made along a variable decreasing radius, during a rotation raises the soil clod, thereby facilitating its separation from the soil monolith. While lifting the rear hitch, the soil clod is completely detached from the soil surface. A cut seedling with a soil clod is transported to the place of planting or to a warehouse for temporary storage [18].

The developed equipment can also be used to prepare seats for planting large seedlings. An educated planting hole completely repeats the contours of a dug-up soil clod with a seedling, thereby reducing the amount of work when planting plants or landscaping.

2.2. Modeling the technological process of lifting seedlings with a soil clod by a plant lifter

For a theoretical analysis of the process of lifting plants with a soil clod, a mathematical model of the work of lifting equipment is developed.

The interaction of the working tool with the soil is accompanied by a complex process of its deformation and destruction of the structure. The model of the stress-strain state of the “working tool-soil environment” system should take into account the multiphase and complex structure of the soil, the features of its rheological behaviour, as well as the presence of inclusions of organic nature - the roots of seedlings. The modeling was carried out with the aim of increasing the efficiency of the technological process of the plant lifter by choosing the optimal geometric characteristics of its working tool (blade sharpening angle, cutting angle, bucket surface shape and others). On figure 3 presents the design parameters of the equipment, taken into account in the mathematical description of the interaction of the working tool of the plant lifter with soil and roots of seedlings.

![Figure 3. Design parameters of technological equipment.](image-url)
The model is based on the differential equation of motion of the main element of the plant lifter – its working tool in the form of a double-crank arm around a fixed axis OY

\[ I_{oy} \ddot{\phi} = M_{oy} (\ddot{P}_{hc}) + M_{oy} (G_P) - \tilde{M}_{oy} (P_{res}), \]

where \( I_{oy} \) – moment of inertia of the lever relative to the axis OY, \( \text{kg} \cdot \text{m}^2 \); \( \phi \) – angle of rotation, degree; \( \ddot{P}_{hc} \) – pressure force generated in hydraulic cylinders, \( \text{Pa} \); \( G_P \) – lever gravity, \( \text{N} \); \( \tilde{M}_{oy} (P_{res}) \) – total moment of resistance forces to the movement of the working tool relative to the axis OY, \( \text{N} \cdot \text{m} \).

In this case, the total value of the moment of the external forces of \( M_{OY} \) is determined by the formula

\[ \tilde{M}_{oy} = M_{d.f} - M_{res.f} \]

where \( M_{d.f} \) – moment of driving forces, \( \text{N} \cdot \text{m} \); \( M_{res.f} \) – moment of resistance forces to the working process, \( \text{N} \cdot \text{m} \).

The pressure force applied to the working tool from the side of the hydraulic cylinders has a line of action \( \tilde{OB} \) (figure 4). The moment of pressure force \( P_{hc} \) relative to the OY axis is

\[ M_{oy} (P_{hc}) = z_{\vec{B}} P_{hc} \cdot \sin \phi_{\vec{B}} + x_{\vec{B}} P_{hc} \cdot \cos \phi_{\vec{B}}, \]

where \( x_{\vec{B}} = O \tilde{B} \cos (\phi + \phi_{\vec{B}}) \); \( z_{\vec{B}} = O \tilde{B} \sin (\phi + \phi_{\vec{B}}) \), \( P_{hc} = |P_{hc}| \cdot \cos \phi_{hc}, P_{hcz} = |P_{hc}| \cdot \sin \phi_{hc} \).

**Figure 4.** Scheme for calculating the moment of pressure force \( P_{hc} \) relative to OY axis.

While analysing the distribution of forces of resistance to the movement of the digging mechanism of the equipment for the following consideration, the following elements of the working tool were identified:
- two cutting elements (blades) in the form of wedges;
- side walls of a half-bucket;
- working surfaces of the half-bucket.

The value of the moment of gravity relative to the axis OY is defined as

\[ M_{oy} (G_P) = m_{p} \cdot g \cdot \mathbf{O} \mathbf{C} \cos (\phi + \phi_{C}). \]

The total moment of resistance forces of the side surfaces of the half-bucket relative to the OY axis is

\[ M_{oy} (\tilde{P}_{ri}) = P_{ri} \cdot |OC| = f \sigma_{P2} S_{i} \cdot |OC|, \]

where \( \tilde{P}_{ri} \) – tangential component of the drag force of the side surfaces of the half-bucket; \( f \) – slip friction coefficient of the “soil-metal” pair; \( \sigma_{P2} \) – specific resistance to pressing a punch into the soil,
Pa; \( S_i \) – unit cell area, \( m^2 \); \( |OC_i| \) – distance from point \( O \) to the centre of parallel forces in the \( i \)-th cell – the point of application of force \( \vec{P}_{ri} \), m.

The total moment of resistance forces of the surface of the considered blade relative to the axis \( OY \) is calculated by summing all the components

\[
M_{oy}(\vec{P}_{pi}) = \sum_{i=1}^{N_p} M_{oy}(\vec{P}_{pi})
\]

where \( \vec{P}_{pi} \) – normal component of resistance to cutting; \( x_i, z_i \) – force point coordinates \( \vec{P}_{pi} \); \( \vec{n} \) – vector of the normal to the plane of the blade.

To simulate an inhomogeneous and non-stationary field of resistance forces to soil and root cutting, a calculation algorithm was used that takes into account a randomly set arrangement of elements of the seedlings root system.

Let the rectangle \( A'B'C'D' \) (figure 5 – top view) limit the area where excavation occurs along with the plant. The sides of this rectangle \( |B'C'| = |A'D'| = S \), where \( S \) – the bucket width, \( |A'B'| = |C'D'| = L \), the value \( L = 2 \sqrt{R^2 - H^2} \).

**Figure 5.** Scheme of the soil with the seedling root system and the cut-off zone of the root system.

For certainty, it was assumed that the roots of the seedling are located mainly in the zone \( A_1B_1C_1D_1 \). We will distinguish three subdomains within this zone, each of which is dominated by roots with an average diameter of \( d_1, d_2, d_3 \). In this case, in zone (3) – \( A_3B_3C_3D_3 \), as a rule, there are roots of a larger diameter \( d_3 \), in zone (2) – of a smaller diameter \( d_2 \), in zone (1) - small roots of diameter \( d_1 \).

The moment of root cutting occurs or continues when the following condition is met

\[
\sqrt{(\bar{x}_k - x_{M_j})^2 + (\bar{y}_k - y_{M_j})^2} \leq d_k / 2, \tag{7}
\]

\[
\sqrt{(x_k - x_{L_j})^2 + (y_k - y_{L_j})^2} \leq d_k / 2. \tag{8}
\]

where \( (\bar{x}_k, \bar{y}_k) \) – the coordinate of the center of the root cross section with the number \( K; (x_{M_j}, y_{M_j}) \)
the current coordinates of the center of the plot with number \( j \) located on the tip of the cutting edge \( QM \) obtained by dividing the \( QM \) segment by points \( M_0, M_1, ..., M_j, ..., M_j \), \( j = 0, ... J \); the current coordinates of the center of the plot with number \( i \) located on the tip of the cutting edge \( QT \) obtained by dividing the \( QT \) segment by points \( L_0, L_1, ..., L_i, ..., L_i \), \( i = 0, ... I \).

The research work with a model in the form of computer experiments to solve the compiled differential equation was carried out using a special computer program in the programming environment Borland Delphi.

The experiment consists in simulating the process of lifting a seedling with a soil clod by the working tool of a plant lifter, which moves in a semicircle at a constant speed in the soil environment with the presence of root inclusions. Part of the blade elements in this case carry out a cut of the seedling root, and the other part is involved in the process of cutting the soil. In this case, the dependences of the moments created by various forces are fixed, as well as the value of the total moment value of all external \( M_{oy} \) forces acting on the working body relative to \( OY \) axis.

All input parameters of the research process model can be divided into the following groups:
- design parameters of lifting equipment (distance from the axis of rotation of the working tool to the surface \( H \), the initial angle of entry into the soil \( \varphi_0 \), the moment of inertia of the working tool relative to the axis \( OY I_{oy} \), the height of the working tool profile \( H_0 \), and others);
- geometric parameters of the digging working tool (width of the half-bucket \( S_{hb} \), thickness of the knives \( \delta_{ks} \), blade apex angles \( \alpha_1 \) and \( \alpha_2 \), sharpening angle \( \beta \), length of the cutting edge \( QM \) and \( QT \), length of the side walls arc of the half-bucket \( L_K \) and others);
- parameters of the roots of seedlings (number of roots in zones \( A, B \) and \( C \), root diameter \( d \), specific cutting resistance \( \sigma_{Pr,o} \));
- soil parameters (soil density \( \rho \), specific resistance to cutting \( \sigma_{Pso} \), specific resistance to the movement of the half-bucket \( \sigma_{K} \), coefficient of friction of steel on soil \( f \));
- technological parameters (pressure in hydraulic cylinders \( \bar{p}_{hc} \)).

Initially, a computer experiment was carried out with the most typical values of all input parameters
- \( p_{hc} = 4000 \) kPa; \( H = 0.65 \) m; \( H_0 = 0.3 \) m; \( \varphi_0 = 160^\circ \); \( L_K = 0.49 \) m; \( S_{hb} = 0.36 \) m; \( \delta_{ks} = 0.004 \) m; \( QM = 0.071 \) m; \( QT = 0.1215 \) m; \( \beta = 30^\circ \); zone \( A = 25 \); zone \( B = 15 \); zone \( C = 10 \); \( d_x = 0.005 \) m; \( d_y = 0.008 \) m; \( dc = 0.012 \) m; \( \sigma_{Pr,o} = 33342.6 \) kPa (corresponds to cutting pine roots); \( \sigma_K = 210 \) kPa, \( \sigma_{Pso} = 180 \) kPa, \( \rho = 1300 \) kg/m\(^3\) (corresponds to cutting wet medium loamy soils); \( f = 0.55 \).

Further research consisted in changing various input parameters of the model near the base values to observe changes in the simulation results compared to the base experiment.

The studied parameters \( F_i \) varied in a certain interval \([F_{i, min}, F_{i, max}]\) with a step \( \Delta F_i \), the remaining design and technological characteristics taken into account in the model remained unchanged. A separate calculation was performed for each resulting set of parameters. Each of the parameters was varied by at least five levels to establish the type of the resulting dependence, which allowed us to obtain patterns of changes in the output characteristics of the digging process, primarily the total moment of all external forces relative to the \( OY \) axis \( M_{oy} \).

The computer calculations were performed with the possibility of assessing the impact on the output characteristics within the framework of a series of experiments of the main parameters of the working tool of the plant lifter, the roots of seedlings and soil.

3. Results and discussion
Initially, computer experiments made it possible to study the effect of the distance from the axis of rotation of the working body to the soil surface \( H \) at the moment of all forces relative to \( OY \) axis, as an important characteristic of the actuator affecting the design and dimensions of the unit under study (this parameter varied at levels of 0.5–0.7 m).

It was found that with increasing distance from the axis of rotation of the working tool to the soil
surface, the total moment of all external forces relative to the $OY$ axis decreases (figure 6).

![Figure 6](image.png)

**Figure 6.** The dependence of the total moment of all external forces relative to the axis $OY$ on the distance from the axis of rotation of the working tool of the plant lifter.

A separate series of experiments was aimed at determining the influence of the thickness of the blade of the working tool of lifting equipment on the process of lifting seedlings with soil clod. An increase in the thickness of the blade of the excavating working body leads to a sharp increase in the cutting force and work, and, as a result, in the moments of resistance to the working process (figure 7), therefore, the total moment of external forces decreases linearly.

![Figure 7](image.png)

**Figure 7.** The dependence of the total moment of all external forces relative to the axis of $OY$ on the thickness of the blade of the knives of the working tool.

The inclination of the cutting edge with respect to the object being cut increases with an increase in the sharpening angle of the blade of the working tool. With this in mind, the value of the total moment of external forces decreases due to an increase in the resistance of cutting the soil and cutting of the roots of seedlings and, therefore, the moments from these forces of resistance to the process of lifting plants. Computational experiments have shown that the maximum values of the total moment of all external forces relative to the $OY$ axis, and therefore the minimum resistance to the cutting process of the medium being processed, are observed at a sharpening angle of the blade of the cutting element –
30-40° (figure 8).

![Figure 8](image_url)

**Figure 8.** The dependence of the total moment of all external forces relative to the $OY$ axis on the angle of sharpening the knife blade.

With an increase in the length of the cutting edge of the blade $QM$ and $QT$ of the knives of the working tool, a decrease in the value of the total moment of all external forces is observed (figure 9). This is due to an increase in the area of the upper chamber of the knife and, as a consequence, an increase in the amount of friction on the material being cut.

![Figure 9](image_url)

(a) (b)

**Figure 9.** The dependence of the total moment of all external forces relative to the axis of $OY$ on the length of the cutting edge of the blade $QM$ (a) and $QT$ (b).

Using the model, the influence of the thickness of the cut roots of woody plants on the value of the resistance forces to the working process is studied. It was found that with an increase in the diameter, the forces of resistance to cutting the root wood increase linearly, thereby decreasing the value of the total moment of all external forces acting on the working tool relative to $OY$ axis (figure 10).

To determine the degree of influence of soil type on the strength indicators of the process of digging plants, a series of computational experiments was carried out in which the specific resistance to cutting the soil $\sigma_{Pp}$ corresponds to lifting seedlings in chernozem, sand and wet sand (table 1).
Figure 10. The dependence of the total moment of external forces relative to the axis $OY$ on the diameter of the roots.

Table 1. The influence of soil type on the total moment of external forces relative to the $OY$ axis.

| Soil type                          | $M_{oy}$ kN·m |
|------------------------------------|---------------|
| Loamy and clayey chernozem         | 891.3         |
| Sand                              | 893.3         |
| Wet sand                           | 891.8         |

The parameters of the cultivated soil environment are important characteristics of the ongoing technological process of lifting. Studies have shown that the maximum values of the moment of all external $M_{oy}$ forces vary from 893.3 kN·m for sand to 891.3 kN·m for chernozem.

4. Conclusion

Thus, on the basis of the mathematical description of the basic physical processes that occur during the interaction of the working tool of the lifting equipment with soil and tree roots, computer experiments were carried out on the functioning of the plant lifter when lifting seedlings with a soil clod.

Within the framework of the performed calculations, the main moments of the acting forces, in particular, the total moment of all external forces acting on the working tool relative to $OY$ axis, were determined according to the specified parameters of the lifting mechanism and the conditions of its operation.

Based on the theoretical studies, it was found that the efficiency of the lifting process is most influenced by the design parameters of the working tool (distance from the axis of rotation to the soil surface), the geometric parameters of the knives (blade sharpening angle, cutting edge length and knife thickness) and the parameters of the processed soil and plant environment. The theoretical calculations reported in this paper can be utilized to further design and construct a pilot working tool for lifting the large-sized tree plants. The obtained patterns of changes in the power characteristics of the lifting process, depending on the parameters of the working tool, soil and roots, allow multicriteria optimization of the parameters of the lifting equipment.

Research on the construction of lifting mechanisms, performed by various scientists, is aimed at reducing the effort applied to the working tools in the process of lifting plants. The identified optimal parameters of the equipment working tool developed by the authors allow to reduce the energy consumption of lifting planting material with a soil clod.
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