The complex of machines for low-cost artificial reforestation in the taiga zone

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Abstract. Problems of mechanization of artificial reforestation in the taiga zone are increasing the productivity of manual labour and reducing the costs of subsequent young stand treatment (early tending and early pre-commercial thinning). Petrozavodsk State University has developed the complex of machines and technologies capable to solve these problems. This complex includes: seeder, root-cutter, dynamic hole-maker and mechanical mounder. Seeder and root-cutter are intended for growing enlarged seedlings with an open root system in forest nurseries. Seeder provides mechanization of sowing seeds. Root-cutter is used for pruning the root systems of seedlings during cultivation. Dynamic hole-maker provides strip soil clearing, surface tillage and preparation of holes for manual planting of seedlings. The hole-maker is also capable to make soil scarification and sowing forest seeds. Mechanical mounder provides strip clearing in the forest plot and creation of humus mounds with mineral soil cover for manual planting of seedlings. Basic technological parameters of the complex of machines have been also substantiated at the Petrozavodsk State University.

1. Introduction

According to the Food and Agriculture Organization (FAO) of the United Nations, taiga, also called boreal forest, covers about 1,300,000,000 hectares (ha) or about 30% of global forest area. The taiga forms a “green belt” on the northern hemisphere stretching through Russia, Alaska, Canada and Scandinavia. The largest part of the taiga is in Russia (about 815,000,000 ha) [1].

As reported by Rosleskhoz, annual clear cuttings are carried out on the area of about 1,000,000 ha in Russia. In particular, in 2016, reforestation works were carried out on a total area of 781,100 ha, of which only 195,700 ha were artificial and combined reforestation (i.e., approximately 25% of the clear-cutted area). The problem is of a systemic nature: 40-50 years ago in Russia, forest was cut down on an area of about 3,000,000 ha annually, and the ratio of areas of artificial reforestation and natural regeneration was the same. For example, in 2019 in Finland, area treated with clear cuttings was about 114,000 ha. Artificial reforestation was carried out on a total area about 100,000 ha [2]. Nowadays Finland (about 22,400,000 ha of boreal forest) is the leading forestry country in the taiga.

The success of the reproduction of forest resources (i.e. the cultivation of plantations of the
required species composition) depends not only on the method of reforestation, but also on the volume and quality of subsequent young stand treatment. At the same time, thinning in young stands should be carried out at least twice – first pre-commercial thinning (at the age of up to 10 years), then second pre-commercial thinning (at the age of 11-20 years). According to Russian official data, the total area of pre-commercial thinning in young stands in 2012-2015 were near to 300,000 ha per year, which is almost 2.5 times lower than the area of reforestation. Thinning in older stands (where commercially valuable raw materials can be obtained) did not exceed 70% of the reforestation area, which is also many times lower than necessary. At the same time, in 2019 in Finland, area treated with pre-commercial thinning (PCT) was about 150,000 ha (150% of reforested area). Area treated with commercial thinning was 530,000 ha [2].

Moreover, according to Romanov E M, Eremin N V and Nureeva T V (Volga State Technological University), in the period from 1983 to 2003 in Russia, more than 50% of the created forest cultures died, which is a record value over the past 50-60 years. The main cause of death is the failure to complete the necessary thinning in young forest stands. The result of this long-term practice is the reduction of the areas of valuable coniferous forest stands in Russia, with a formal abundance of forests. The depletion of available commercial forests in Russia leads to the need to change the existing model of forestry and forest management, including more intensive use of secondary forests of the European part of the country that have been repeatedly cut by felling due to the development of various types of thinning, as well as the activation of artificial reforestation (i.e. sowing and planting forests). “Fundamentals of state policy in the field of use, protection, defense and reproduction of forests in the Russian Federation for the period up to 2030” (approved by the Government of the Russian Federation in 2013), among other measures, directly provide for the intensification of the use and reproduction of forests, preservation of the ecological potential of forests.

Since 2015, Russia has been moving from a traditional “extensive model” of forestry, which implies a simplified procedure in the forest (only cutting of mature forests and subsequent reforestation) to an “intensive model” of forestry, which provides for a series of activities in forest areas: cutting of mature forests, reforestation, thinning, etc. In Finland, about 90% of reforestation areas are treated with mechanical soil preparation. Soil preparation supports the establishment and improves the development of tree seedlings, reducing competition from undesired vegetation [3,4]. Common soil preparation methods are soil scarification (by disc trenchers) with direct seeding, spot mounding (by excavators or mounders) [3,5]. Seedlings are planted manually into prepared soil. Pre-commercial thinning (PCT) in young stands is often needed in many reforestation areas [6,7]. Unnecessary soil disturbance should be avoided so as not to encourage regeneration of broadleaved species, soil erosion, or nutrient loss [3-5,8]. Thus, interest in using “spot” soil preparation methods and relevant machines is growing due to their higher productivity and cost-competitiveness, as well as recent technical development [3,5]. Also, costs of seedling supply systems could be streamlined among silvicultural costs [9-11]. Since the middle of the 1990s, pre-commercial thinning (PCT) has taken an increasingly larger share of silvicultural costs in Finland (80,000,000 EUR per year, doubling in last 20 years), and the need to optimize PCT-procedures has become quite necessary [7]. Using of “spot” soil preparation methods is seen as a valuable solution to reduce the time and labor required for PCT [3,5].

According to the experience of the Scandinavian countries (Finland, Sweden, etc.), intensive forestry will require a significant (4-6 times) increase in the volume of work on artificial reforestation (planting, sowing) and young stand treatment of target tree species in compare with “traditional” Russian practice. Thus, the Russian forestry will need not only high-quality seed and planting material, but also domestic productive and cost-efficient equipment for mechanization of artificial reforestation to achieve these goals. Existing machines should be critically analyzed and new ones are also needed.

2. Materials and methods
According to our assessment, the utilization of well-known machines for mechanical soil preparation on reforestation areas (disc trenchers such as PDN-1, Bracke, etc.) in combination with manual
planting under Kolesov’s sword or a planting pipe will not provide the necessary volume and quality of reforestation work for forest users in conditions of forestry intensification. According to the Finnish experience, the use of more complex and expensive machines will not boost productivity and quality of work on artificial reforestation expected by Russian timber producers [12]. We should also remember about the need for a significant increase in the volume of young stand treatment (early tending and early pre-commercial thinning). Money invested in young forest stands will be wasted without these treatments. Currently in the Russian Federation, such treatments are performed mainly by using motorized tools (hand-held brushcutters); a significant increase in such works is constrained by the lack of the necessary labor force and the poor forest road network [13]. Under these conditions, machines should not only reduce the time and labor required for artificial reforestation, but also reduce the need for subsequent young stand treatment. According to [3,5], such machines include machines for “spot” soil preparation (including creating humus mounds with mineral soil cover, etc.). Various specialized machines can be used to create humus mounds, for example: the domestic rotary machine ORM-1,5 or its foreign counterparts — a two-row mounder of the Bracke M24.a type and a three-row mounder of the Bracke M36.b type [4,6,14].

The creative team of Petrozavodsk State University (PetrSU), under the leadership of Honored Scientist of the Republic of Karelia, Tsypouk A M, together with specialists from the Forest Institute of the Karelian Scientific Center of the Russian Academy of Sciences, has developed the complex of machines and technologies for intensive reforestation in forest plots of the taiga zone. The complex of machines includes: seeder SVU-1,2, root-cutter PK-1,2, dynamic hole-maker L-2U and mechanical mounder MK-2. Seeder SVU-1,2 and root-cutter PK-1,2 are intended for growing enlarged seedlings with open root system in forest nurseries. Seeder SVU-1,2 provides mechanization of sowing seeds. Root-cutter PK-1,2 is used for pruning the root systems of seedlings during cultivation. Planting large seedlings reduces the cost of artificial reforestation and drastically reduces the cost of subsequent young stand treatment. Dynamic hole-maker L-2U is the basic machine of this complex. The dynamic hole-maker L-2U replaces a group of machines in a forest plot: it provides strip surface clearing, soil scarification and preparation of planting places (holes) for manual planting of seedlings. The hole-maker is also capable to scarificate the soil and to sow forest seeds. Mechanical mounder MK-2 provides the strip surface clearing in the forest plot and the creation of humus mounds for manual planting of seedlings.

3. Results
The vibrating universal seeder SVU-1,2 (figure 1, table 1) is designed for scattered and wide-line sowing of coniferous seeds in order to grow large-sized planting material (enlarged seedlings) without sparse transplantation of seedlings (overschooling).

![Figure 1. Seeder SVU-1,2.](image_url)
Table 1. Technical characteristics of the seeder SVU-1,2.

| Parameter                                           | Value                      |
|-----------------------------------------------------|----------------------------|
| Overall dimensions, mm                             | 2,190x1,550x750             |
| Weight, kg                                          | 400                        |
| Power take-off shaft rotation frequency, rpm: with tractor MTZ-82 | 545-560                    |
| Torque on the input shaft of the worm gear, Nm, not more | 170                        |
| Service personnel, men, including: tractor driver of the 5th category | 1                          |
| Unit work speed, km/h                              | 6.5-6.7                    |
| Performance, ha/hour, not less                      | 0.25                       |
| Working width (on the track of the tractor), m      | 1.2-1.5                    |
| Seeding depth (adjustable), cm                      | 0-4                        |
| Seeding rate (adjustable), kg/ha                    | 20-70                      |
| Seed material                                       | Pine and spruce seeds      |

During one pass, the seeder evens out the surface of the field, loosens the soil to the depth of seeding, compacts the sowing bed, distributes seeds in a spreading or wide-line method, covers the seeds with soil and can, if necessary, compact the soil over the seeds completely or partially.

Root-cutter PK-1,2 (figure 2) consisting of front vertical and rear horizontal knives, is designed to form the root system of enlarged seedlings with an open root system, when growing without overschooling.

Figure 2. Root-cutter PK-1,2.

Yield of enlarged planting material per hectare increases 2.6 times using of seeder SVU-1,2 and root-cutter PK-1,2 in the nursery in compare with traditional seeders and other machines. 1 ha of nursery area can produce 1,000,000 pieces (pcs) of enlarged planting material, i. e. 4 times more in compare with growing seedlings in a “school” using traditional technology. Also, seeder SVU-1,2 provide significant saving of seeds when sowing: 30 kg/ha versus 70 kg/ha using traditional technology (i. e., seeds consumption is 2.5 times less). The technical characteristics of the root-cutter PK-1.2 are presented in table 2.

Dynamic hole-maker L-2U (figure 3, table 3) is aggregated with tracked or wheeled tractors (including the forestry modification of the tractor TLT-100), equipped with rear hitch system and mechanical power take-off shaft or hydraulic motor. Using of the hole-maker L-2U allows to mechanize the process of preparation of planting places (holes) for seedlings in forest plots with tree stumps. Also, planting large-sized seedlings with the hole-maker L-2U allows to radically reduce the number of subsequent young stand treatments. The main purpose of the hole-maker L-2U is to prepare holes up to 23 cm depth for planting seedlings and enlarged seedlings.
Table 2. Technical characteristics of the root-cutter PK-1,2.

| Parameter                                                   | Value                      |
|-------------------------------------------------------------|----------------------------|
| Overall dimensions (with MTZ-82 tractor), mm                | 5,400x2,000x2,500           |
| Weight (without tractor), kg                                | 480                        |
| Power take-off shaft rotation frequency, rpm: with tractor MTZ-82 | 1013                       |
| Torque on the input shaft of the worm gear, Nm, not more    | 60                         |
| Service personnel, men, including: tractor driver of the 5th category | 1                           |
| Unit work speed, km/h                                      | 4.26                       |
| Performance, ha/hour, not less                             | 0.28                       |
| Working width (on the track of the tractor), m              | 1.2-1.5                    |
| Number of processed rows, no more                          | five                       |
| Age of planting material during the pruning period, years   | 2-4                        |
| Species of planting material                               | Pine, spruce               |

The planting rate for enlarged seedlings can be reduced to 2,500 pcs/ha compared to 4,000 pcs/ha for ordinary seedlings. The hole-maker is also equipped with replaceable working bodies to prepare holes for ordinary seedlings (up to 16 cm deep). Hole-maker L-2U can be used for planting of forests with seedlings with an open or closed root system.

Figure 3. Hole-maker L-2U.

Using of the L-2U for the preparation of planting places (holes) reduces energy consumption about 3 times in compare to machines that form a continuous furrow in the soil. Thus, significant fuel saving is provided for the reforestation. It was found that if a tractor with a machine for continuous soil preparation works in difficult soil conditions, the fuel tank lasts about a day. If a tractor with a machine for continuous soil preparation works in normal soil conditions, the fuel tank lasts about three days. If a tractor operates with a hole-maker, the fuel tank lasts about a week. Labor productivity of planting seedlings into holes prepared by L-2U increases up to 2.5...3 times compared to hand tools. Performance standard for manual planting with Kolesov’s sword is 800...900 pieces per shift (in rocky soils – not more than 500 pieces). Performance standard for manual planting into holes prepared by L-2U is 1,800...2,800 pieces per shift. Combined planting (combination of standard seedlings and enlarged seedlings) is also possible in the prepared by L-2U forest plot. The recommended ratio of large-sized and ordinary seedlings is on average 2:1 for the taiga conditions of the Russian Federation. The hole-maker L-2U can be equipped with a seeding device L-2US (figure 4, table 4), which provides surface clearing by removing the forest residues in strips of 30, 40 and 50 cm width and sowing forest seeds.
Table 3. Technical characteristics of the hole-maker L-2U.

| Parameter                                                                 | Value                      |
|---------------------------------------------------------------------------|-----------------------------|
| Overall dimensions, mm                                                   | 2,400x2,250x1,800           |
| Weight, kg                                                               | 800±50                      |
| Speed of the input shaft of the worm gear, rpm:                           |                             |
| - with tractor MTZ-82                                                     | 540 or 1000                 |
| - with tractor LHT-100                                                    | 540                         |
| Torque on the input shaft of the worm gear, Nm, not more                  | 300                         |
| Service personnel, people, including:                                    |                             |
| tractor driver of the 5th category                                        | 1                           |
| planter of the 4th category                                               | 4-6                         |
| Unit work speed, km/h                                                    | 1-2.5                       |
| Performance:                                                              |                             |
| - ha/hour, not less                                                      | 1.0                         |
| - holes/hour, not less                                                   | 3000                        |
| Row spacing, m                                                           | 1.8±0.1                     |
| Hole preparation step in a row, m when aggregated with tractors:          |                             |
| - MTZ-82                                                                 | 0.43-1.18                   |
| - LHT-55 (without speed reducer)                                          | 0.88-1.18                   |
| - LHT-100 (with speed reducer)                                           | 0.43-1.18                   |
| Holes dimensions, mm:                                                    |                             |
| - depth                                                                  | 230±20                      |
| - width at the soil surface                                              | 90±30                       |
| - length at the soil surface                                              | 120±30                      |
| Planting material                                                        |                             |
| Seedlings by Federal standard 24835-81 [15]                              |                             |

Figure 4. Replaceable device for sowing seeds L-2US.

The main purpose of the two-row mechanical mounder MK-2 (figure 5, figure 6) is the creation of humus mounds with mineral soil cover during the continuous movement of a silvicultural unit based on a caterpillar or wheeled tractor (including a forwarder), equipped with a rear hitch system and a mechanical power take-off shaft or a hydraulic motor. The mounder MK-2 is devoid of the drawbacks that its domestic analogue ORM-1.5 has, since it does not need to re-adjust the brake systems to work on different types of soil. The mounder MK-2 is equipped with a simple mechanical device for programming the trajectory of formation of mounds on the soil. The reliability of such mechanical
device is higher than the electronically controlled hydraulic drive used on the imported analogs like Bracke M24.a.

Table 4. Technical characteristics of the replaceable device L-2US.

| Parameter                                           | Value           |
|-----------------------------------------------------|-----------------|
| Overall dimensions, mm                             | 800x700x800     |
| Weight, kg                                          | 100             |
| Service personnel, men, including: tractor driver of the 5th category | 1               |
| Unit work speed, km/h                              | 1-2.5           |
| Performance, ha/hour, not less                     | 1.5             |
| Row spacing in one pass (in the centers of the rows), m | 1.6±0.05        |
| Mineralized strip width in one row, m              | 0.1; 0.3; 0.4; 0.5 |
| Distance between adjacent sowing in places (seeding step), m | 0.37; 0.74; 1.48 |
| Seed material                                       | Seeds, clean, free-flowing |
|                                                     | Federal standard 14161-86 [16] |

The main advantages of the mounder MK-2 are:

− if compared with the machine ORM-1.5 – no adjustment of the brakes of the working bodies (blades), the constancy of the mounds’ size;
− if compared with mounders like Bracke M25.a and Bracke M36.a – simple and reliable design of the drive of the working bodies, reliable operation, low cost;
− if compared with excavators with a special small bucket for making mounds – high productivity, due to continuous movement through the forest plot, simple design, low cost.

To the present time, PetrSU has developed a methodology for calculating the technological parameters of the mounder MK-2 and a set of design documentation that allows to manufacture a prototype machine. The expected performance of the mounder MK-2 is 0.2 ha/hour.

Figure 5. General view of the mounder MK-2 (3D-model): 1 – rotor (left); 2 – reducer; 3 – skeleton; 4 – support ski (left); 5 – tractor coupling device.
Figure 6. Scheme of soil preparation by the mounder MK-2: 1 – hole; 2 – the hole transverse wall; 3 – micro-elevation (mound); 4 – tangent; 5 – a plant planted in a mound; \( \alpha \) – the hole transverse wall inclination angle to the horizon; \( F_B \) – the hole sidewall area; \( S \) – step for preparing holes; \( t_1 \) – a point on the trajectory corresponding to the moment the end of the rotor beam enters the soil; \( t_2 \) – the trajectory point that corresponds to the beam reaching the bottom of the hole; \( H = Y_i \) – hole depth; \( X_1 \) and \( X_2 \) – abscissas.

4. Discussion

Studies of the survival rate and growth rate of forest cultures, created by planting one-year seedlings with a closed root system into holes prepared by the hole-maker L-2U, confirmed the possibility of successful use of L-2U for reforestation using such material. Studies were carried out by scientists from the Forest Institute of the Karelian Scientific Center of the Russian Academy of Sciences and PetrSU.

In 1988, experimental spruce forest stand was planted by seedlings 20-40 cm high with an open root system into holes prepared by the holemaker L-2U in the Yurkostrovsky forestry (Kondopozhsky district of the Republic of Karelia, Russia). The hole-maker provided the preparation of high-quality planting places (holes) for reforestation with a density of 4,500 pcs/ha on forest sites with tree stumps and soil rockiness about 50% (figure 7).

Figure 7. Experimental spruce stand in Yurkostrovsky forestry, the Republic of Karelia, Russia.

It should be noted that preparation of 2,000-3,000 pcs/ha of high-quality planting places is enough
for artificial reforestation. The hole-maker can easily create such amount of planting places within 1 hour of working time. Experts from the Forest Institute of the Karelian Scientific Center of the Russian Academy of Sciences are observing the development of the experimental forest stand in Yurkostrovsky forestry. According to Sokolov A I (Forest Institute of the Karelian Scientific Center of the Russian Academy of Sciences), the experimental forest stand was grown all these years without any young stand treatment. Preservation of seedlings is about 90% to the moment. The experimental forest stand was not inferior in height to deciduous species (birch, aspen) growing in the control plot with natural reforestation by the 11th year of life. According to Sokolov A I, the hole-maker can be used for artificial reforestation using large-sized planting material in cereal forest plots, for soil scarification to promote natural forest regeneration and mechanized sowing in former pine forest plots covered by lichen, heather and lingonberry, as well as for making planting places (holes) after plowing on wet soils. L-2U can be used to prepare holes for planting standard seedlings after replacing the working bodies (needles) with a smaller size.

At present, PetrSU has developed methods for calculating the technological parameters of a complex of machines and a set of design documentation that allows to manufacture a prototype machines. Recommendations for the practical application of the proposed complex in various conditions are also developed.

Further studies to improve the design of the developed machines should be carried out in the following directions:
- refinement of design parameters based on the results of machine testing in forest conditions;
- development of technologies for the rational use of machines for reforestation, with the development of regulatory documentation (technological maps, production rates, etc.).

5. Conclusion

Petrozavodsk State University has developed the complex of machines and technologies capable to increase the productivity of manual labor and reduce the costs of subsequent young stand treatment (early tending and early pre-commercial thinning).

This complex includes: a seeder SVU-1,2, a root-cutter PK-1,2, a dynamic hole-maker L-2U and a mechanical mounder MK-2. Seeder and root-cutter are intended for growing enlarged seedlings with an open root system in forest nurseries. Dynamic hole-maker provides strip soil clearing, surface tillage and preparation of holes for manual planting of seedlings. Mechanical mounder provides strip clearing and creation of humus mounds with mineral soil cover for manual planting of seedlings.

Yield of enlarged planting material per hectare increases 2.6 times using of seeder SVU-1,2 and root-cutter PK-1,2 in the nursery in compare with traditional seeders and other machines. 1 hectare of nursery area can produce 1,000,000 pieces of enlarged planting material, i. e. 4 times more in compare with growing seedlings in a “school” using traditional technology. Also, seeder SVU-1,2 provide significant saving of seeds when sowing: 30 kg/ha versus 70 kg/ha using traditional technology (i. e., seeds consumption is 2.5 times less). Labor productivity of planting seedlings into holes prepared by L-2U increases up to 2.5…3 times compared to hand tools. Performance standard for manual planting into holes prepared by L-2U is 1,800...2,800 pieces per shift. Using of the L-2U for the preparation of planting places (holes) reduces energy consumption about 3 times in compare to machines that form a continuous furrow in the soil.

The mounder MK-2 is equipped with a simple mechanical device for programming the trajectory of formation of mounds on the soil. The reliability of such mechanical device is higher than the electronically controlled hydraulic drive used on the imported analogs like Bracke M24.a. The expected performance of the mounder MK-2 is 0.2 ha/hour. Utilization of machines developed at PetrSU allows: to reduce budget and business expenses for reforestation; to reduce labor and time expenses for reforestation; to increase the share of the best domestic machines in the forests.

The presented complex of machines can provide effective mechanization of artificial reforestation in the taiga zone in Russia and other countries with similar nature conditions. Introduction of the presented complex of machines into Russian forestry practice requires support from the state.
Individual forest users do not have the ability to solve the state problem – technical re-equipment of forestry as a branch of social production. However, forest users are ready to invest into the machines and technologies that meet their needs.

References
[1] FAO 2020 Global Forest Resources Assessment 2020: Main report (Rome, Italy), available at: https://doi.org/10.4060/ca9825en
[2] LUKE 2021 Statistics database (Helsinki, Finland), available at: https://statdb.luke.fi/PXWeb/pxweb/en/LUKE/
[3] Saksa T, Miina J, Haatainen H and Kärkkäinen K 2018 Quality of spot mounding performed by continuously advancing maunders. Silva Fenn. 52(2) 13 doi: org/10.14214/sf.9933
[4] Karlsson M, Nilsson U and Orlander G 2002 Natural regeneration in clear-cuts: effects of scarification, slash removal and clear-cut age. Scand. J. For. Res. 17(2) 8 doi: 10.1080/028275802753626773
[5] Saksa T, Miina J and Uotila K 2016 Taimikonhoito – Tavoitteet, Menetelmät ja Kustannukset Metsäkustannus (Jelgava, Latvia: Paino Jelgava Printing House) p 128
[6] Löf M, Ersson B, Hjältén J, Nordfjell T, Oliet J and Willoughby I 2015 Site Preparation Techniques for Forest Restoration Restoration of Boreal and Temperate Forests eds J Stanturf et al. (Boca Raton: CRC Press) chapter 5 pp 85–102
[7] Uotila K, Miina J, Saksa T, Store R, Kärkkäinen K and Härkönen M 2020 Low cost prediction of time consumption for pre-commercial thinning in Finland. Silva Fenn. 54(1) 18 doi: 10.14214/sf.10196
[8] Palviainen M, Finér L, Laurén A, Launiainen S, Piirainen S, Mattsson T and Starr M 2014 Nitrogen, phosphorus, carbon, and suspended solids loads from forest clear-cutting and site preparation: long-term paired catchment studies from Eastern Finland. Ambio 42(2) 15 doi: 10.1007/s13280-013-0439-x
[9] Haase D and Davis A 2017 Developing and supporting quality nursery facilities and staff are necessary to meet global forest and landscape restoration needs. Reforesta 4 25 doi: 10.21750/REFOR.4.06.45
[10] Masarei M, Guzzomi A, Merritt D and Erickson T 2019 Factoring restoration practitioner perceptions into future design of mechanical direct seeders for native seeds. Restor. Ecol. 27(6) 12 doi: 10.1111/rec.13001
[11] Nef D, Kettle C and Gotor Y 2019 Costs of Tree Seed and Seedling Supply Systems – the Cost of Integrating Genetic Diversity into Forest Landscape Restoration (Rome, Italy: Bioversity International) p 42
[12] Kukkonen E and Kukkonen M 2014 Forestry Works Mechanization: A Tutorial (Joensuu, Finland: Grano Oy, Mikkeli) p 46
[13] Lopatin E 2016 Methodology for identifying forest areas most promising for intensive sustainable forestry. Sustain. For. Manag. 2 16
[14] Mounders Bracke Forest AB, available at: https://www.brackeforest.com/products/mounders, last accessed: 2020/02/10
[15] Federal Standard 24835-81 1981 Tree and shrub transplants. Specifications, available at: https://docs.cntd.ru/document/1200025552, last accessed: 2021/08/28
[16] Federal Standard 14161-86 1986 Seeds of coniferous tree species. Sowing characteristics. Specifications, available at: https://docs.cntd.ru/document/1200025549, last accessed: 2021/08/28