Aerial seeding of forests in Russia: A selected literature analysis

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Abstract. The study is intended for international readers or those unable to read Russian. Information search was carried out in Russian-language databases (Russian libraries and ELibrary.ru) and English-language databases. Currently, there are a large number of sites in the Russian forests that need to be restored. For many of them, reforestation by ground-based seeding or planting is inefficient or not available. Sowing forest from the air in Russia has more than half a century of history. The results of retrospective analysis show that the choice of the reforestation method depends on the site characteristics and the level of negative environmental impact. Generally, the cost of aerial seeding on such sites with unmanned aerial vehicles (UAV) is lower compared to the use of manned aerial vehicles (MAV). This study will aid in the planning of new forestry experiments to study reforestation with the assistance of natural reforestation in Russia. The study will enable correct plant propagation protocols for sustainable forest management. However, many questions remained unresolved: what types of UAV and sowing apparatus to use; how to position the UAV under a forest canopy?

1. Introduction
Forest regeneration is fundamental to sustainable forestry; and often, direct seeding is a low-cost and dependable method of creating desirable forests [1]. Direct seeding was recommended to foresters by early authors like Nartov [2], Bolotov [3], and Toumey [4]. Direct seeding can be classified as [1, 5-7] row, row-well, belt, biogroup, or broadcast [6, 8] sowing. Direct seeding can be performed manually, with ground-based machinery or from the air [1, 9]. In Russia, forest aerial seeding is applied mainly to promote natural regeneration, reducing the time required to restore the biological diversity of ecosystems [10]. However, very little information about aerial seeding and its future development in Russia is available to international readers or those unable to read Russian. Thus, the objective of this study was to present Russian information on aerial seeding, and to evaluate future trends in Russian aerial seeding development.

2. Material and Methods
Information search was carried out on the keywords ‘aerosev lesa’ (in Russian language) in the databases of Russian libraries and search engines eLibrary. It was found that there is no electronic archive from 1928 to 2015 of the largest forest journal of Russia ‘Forestry’ (ISSN 0024-1113). Therefore, the hard copies of this journal were viewed in the scientific library of Voronezh state University of Forestry and...
Technologies named after G.F. Morozov. The search by the keywords ‘aerial seeding & forestry’, ‘sowing air & forestry’ was carried out in the English-language databases WoS, Scopus, CABI. Further, the authors selected the most relevant documents for analysis.

3. Results and Discussion

Before assessing the development effectiveness of aerial seeding, it is necessary to introduce the terminology needed clarification. A promising direction of creation of forest crops on plots not available and(or) ineffective with traditional methods, is broadcast seeding: ‘sowing forest from the air’, designated in Russia with GOST RF 17559-82 as sowing forest using aircraft [11]. ‘Aerial seeding’ in accordance with GOST RF 54265-2010 includes sieving aviation method of different seeds plants on the land surface [12].

The application of forest aerial seeding in Russia was studied by N. Zakharov (1933) [13], G. G. Samoylovich (1935) [14], V. Ya. Olerinskiy (1939) [15], G. S. Batrakov (1940) [16], F. B. Orlov (1947) [17], A. P. Shimanyuk (1949) [18], A. P. Pesterev (1952) [19], I. S. Melekhov (1953, 1954, 1966) [20–22], V. F. Molchanov (1954) [23], F. I. Sulimov (1954) [24], O. E. Shergold (1954) [25], A. A. Alekseev (1955) [26], N. E. Dekatov (1955) [27], N. E. Dekatov and N. S. Zyzu (1956) [28], E. P. Sysove (1956) [29], I. A. Chernyshev (1956) [30], P. I. Voychal (1959) [31], I. A. Grigoryev et al. (1959) [32], L. A. Istomin (1959) [33], P. N. Lvov and A. I. Stalskiy (1959) [34], M. N. Prokopyev (1959) [35], G. S. Golutvin (1960) [36], Yu.V. Kurepin (1960) [37], A. I. Iroshnikov (1962) [38], I.S. Melekhov (1966) [20], A. A. Marusov (1966) [39], V. E. Kizenkov (1968) [40], P. A. Anishin (1977) [41], V.B. Linar and Yu. A. Pautov (1980) [12], N. N. Chernov (2002) [42], N. N. Nevolin (2007) [43], A. V. Ovodov (2010) [44], V.V. Kopytkov and A.R. Rodin (2015) [45], S.V. Sokolov и A.I. Novikov (2017) [46] and other scientists. Here are the most significant, in our opinion, the results of research.

I.S. Melekhov (1905-1994) has established the feasibility of combining sowing air with a contoured crops, and argued that ‘when applied correctly, aerial seeding is an effective way of renewal of softwood on certain types of burn scars and after deforestation. The speed of sowing seeds from the aircraft cannot be surpassed by ground methods’ [20]. Aerial seeding of tree species found wide application in USSR forestry including: coniferous trees in the Central areas; haloxylon in desert and semi-desert areas, and grasses in numerous areas. In 1932, aerial sowing was performed on 58 thousand hectares [19], and on 22.6 thousand hectares of taiga in 1953 [22]. In the Republic of Komi during the period of 1950 to 1959 the cutting was allocated 114-165 thousand hectares per year. Recovered annually 1000 ha, of which 64 % using aerial seeding [12]. When creating forest plantations on the territories with radioactive contamination, the effectiveness of aerial seeding pellets accounted for 43.8 % [45].

In the 1960s, aerial seeding of Monterey pine (Pinus Radiata) at the seeding rate of 2.24 kg/ha was used in combination with natural regeneration in Kaingaroa forests of New Zealand, but was subsequently discontinued because of the increased consumption of seeds and of the difficulty in achieving equal germination [47]. Aerial seeding in the USA has been successfully applied on areas after storms or fires where ground vehicles were unsuitable due to stumps and other obstacles. Almost 75 % of the aerial seeding was done with the use of manned aircraft and helicopters. In areas for reforestation in excess of around 200 ha, aerial seeding comparable to the cost of most of the ground broadcast methods of sowing, and allows one to complete the work in a short time [48]. Aerial seeding of forests in China has a 55-year history, and in 2012 work was carried out on the area of 136 400 hectares. Although the bulk of works on afforestation is the planting of seedlings, aerial seeding successfully used in remote mountainous provinces, such as Guanxi, Yunnan, Sichuan, Hunan and Shaanxi with such species as Pinus massoniana, Pinus Yunnanensis and Pinus armandi [49].

Taking into account the frequency of references in the works to the factors affecting the efficiency of the forest, we place them in Table 1, indicating the authors and the time of the study. The basis of amalgamated classification, consider the possibility of soil preparation, because, as rightly observed by I.S. Melekhov, ‘at the same time the soil can be effectively combined and ground seeding’ [22]. Further, possible site for reforestation were taken into account, and, ultimately, the basic level of the applied technical means (aircraft seed systems and apparatus).
| Site Preparation¹ | Site Type | Technical means level | MAV² | UAV³ |
|-------------------|-----------|------------------------|------|------|
| Cutting of fireweed-burning *in combination with a contoured seed crops* [20] | Disturbed site, including after man-made disasters, complicated by increased radiation background | N. Zakharov (1933) [13], G. G. Samoylovich (1935) [14], V. Ya. Olerinskii (1939) [15], G. S. Batrakov (1940) [16], F. B. Orlov (1947) [17], A. P. Shimanyuk (1949) [18], A. P. Pesterev (1952) [19], I. S. Melekhov (1953, 1954, 1966) [20–22], V. F. Molchanov (1954) [23], F. I. Sulimov (1954) [24], O. E. Shergold (1954) [25], A. A. Alekseev (1955) [26], N. E. Dekatov (1955) [27], N. E. Dekatov and N. S. Zuyz (1956) [28], E. P. Sysoev (1956) [29], I. A. Chernyshev (1956) [30], P. I. Voychal (1959) [31], I. A. Grigoryev et al. (1959) [32], L. A. Istomin (1959) [33], P. N. Lyov and A. I. Stalskiy (1959) [34], M. N. Prokopyev (1959) [35], G.S. Golutvin (1960) [36], Yu.V. Kurepin (1960) [37], I.S. Melekhov (1966) [20] etc. Kopytkov (2015) [45] etc. | n.a. |
| No | Site inaccessible to ground equipment, characterized by difficult terrain | Dekatov (1936), Iroshnikov (1962); Derr & Mann (1971); Levack (1973); Anishin (1977); Larin and Pautov (1980); SFA (1981); Chernov (2002); Beyers (2004), Gribov (2007), Konovalov (2007), Nevolin (2007), Avdeev (2010), Ovodov (2010), Xiao et al. (2015) etc. Elliott et al. (2013) | Elliott et al. (2013) | Steurmer (2017) Sokolov & Novikov (2017) |
| | Burning | Allen at al. (1955), Siren (1955), Revel (1963), Derr & Mann (1971), Faulkner et al. (1972), Levack (1973), SFA (1981), Li et al. (2009), Peppin et al. (2010), Pyke et al. (2013), Xiao et al. (2015), Zhang et al. (2018) etc. | n.a. |
| Yes | Cutting of Deschampsia cespitosa, Calamagrostis and Filippendula | Orlov (1947) [17], Melekhov (1966) [20] etc. | n.a. |

Notes: 1. The feasibility of aerial seeding in combination with the special measures for the soil preparation is highly conditional on the efficiency of the total costs; 2. MAV – manned aircraft vehicles fixed-wing and rotary-wing types; 3. UAV – unmanned aerial vehicles of fixed-wing, rotary-wing and hybrid types.

Let's say that the main trend of aerial seeding is soil preparation and the method of its implementation. Then the absence of the above operations, noted by the majority of researchers, should be the key and
the only criterion for development. However, there is a limitation. If reforestation does not soil treatment, it is equally possible to carry out both manual broadcast seeding and aerial seeding.

Let’s say that the main trend of aerial seeding is the type of the restored site. Then the inaccessibility of these sites, according to the unity of researchers in accordance with Table 1, should be the key and the only criterion for development. However, there is also a limitation, expressed in the possibility of reforestation of steep slopes at a distance of ground technology, capable of giving the capsule with seeds initial kinetic energy.

In all references listed in Table 1 up to 2013, as aerial seeding used manned aircraft systems of fixed-wing and rotary rotary-wing types. Clearly the temporal relationship between emergence of a new type of aircraft and early use in aerial seeding. However, there are also some limitations that require comparison of seeding methods depending on the degree of mechanization.

Table 2 shows a comparison of the methods of aerial seeding, depending on the type of aircraft used. For convenience, the above-ground mechanized and ground manual methods are given. To identify the economic component of each of the methods, the cost of restoration of one hectare in US dollars is given (cost values are given in the prices at research time).

**Table 2.** Comparison of methodologies reported for the sowing forestry from the air.

| Methods          | Features sites; Country                                                                 | Seeding rate, kg/ha | Cost, US$/ha (at the time of the study) |
|------------------|-----------------------------------------------------------------------------------------|---------------------|---------------------------------------|
| MAV<sup>1</sup> fixed-wing type | open terrain, not less than 25-100 hectares, correct geometric shape, in some cases it is necessary to roll or harrow [20]; protection from predation is necessary [50]; Russian Federation; Canada; USA | 2.24 (*Pinus Radiata* [47]) | 19.59 (1973) [47] |
| MAV<sup>1</sup> rotary-wing type   | open terrain, from 5 to 25 hectares, any geometric shape, in some cases it is necessary to roll or harrow [20], protection from predation is necessary [50]; Russian Federation; USA, Canada | 0.45-0.67 (49,000 to 99,000 viable seeds *Pinus contorta* [52]) | 8.5-11 (1972) [52] |
| UAV<sup>2</sup> fixed-wing type    | open terrain (perhaps with radiation background); correct geometric shape; in some cases; protection from predation is necessary [50]; No specific country | n.a. | n.a. |
| UAV<sup>2</sup> rotary-wing type   | open terrain and closed terrain (forest canopy), perhaps with radiation background; any geometric shape; any complex relief; any soil moisture; in some cases it is necessary to roll or harrow [20]; in some cases, protection from predation is necessary [50]; Russian Federation; Canada, USA, China, Australia, Thailand | n.a. | n.a. |
| UAV<sup>2</sup> hybrid type       | open terrain and closed terrain (forest canopy), perhaps with radiation background; any geometric shape; any complex relief; any soil moisture; in some cases it is necessary to roll or harrow [20]; in some cases, protection from predation is necessary [50]; Russian Federation; Canada, USA, China, Australia, Thailand | n.a. | n.a. |
On the one hand, Table 2 shows that manned aircraft (fixed-wing and rotary-wing types) were widely used in the world and are used in some cases to date, mainly in agricultural applications. In the years 1958-1963 both provided ‘excellent distribution and precision of planting in reforestation of large-scale site – up to 1500 acres (607 ha) light aircraft and about 3000 acres (1214 ha) by helicopter on the day’ [48, 54].

On the other hand, when using planes, the area to be reforested should not be less than 25 hectares. The seeding rate should be 6 kg/ha. Use of helicopters allows for aerial seeding on smaller sites with the irregular shape. The seeding rate of pine and spruce is 1.5-2 kg/ha.

The cost structure for aerial seeding includes the cost of reproductive material (87 %), the cost of flights (12 %) and, if necessary, the cost of the ground follow-up (about 1 %). 12 % includes the cost of fuel and lubricants, the operation of an aircraft, and the device for sowing seeds (hoppers). When sowing from the air, there are no nursery costs, no seedling transportation costs, and no need for the construction of roads and camps to house the workers [51]. On well-drained sites with open terrain larger than 200 hectares, average savings of up to $ 7 per hectare can be realized; and on sites with variable terrain clogged with cutting residues, up to $ 50 per hectare cost savings can be realized [51].

It should be noted that the cost of the aerial seeding from the helicopter Pinus contorta ranged from 8.5-11 US$/ha compared to 17-25 US$/ha using ground mechanized equipment and more than 250 US$/ha in the prices of the year of research at manual planting of seedlings [52]. Sowing forests from the air using manned aircraft systems (fixed-wing and rotary-wing types) has low economic efficiency in small-scale site, while the cost of ground sowing is still lower than the cost of planting [50]. When aerial seeding in MAV (fixed-wing type) of possible unequal growth of subsequent crops, and also a considerable dependence on weather conditions [47]. Moreover, it is necessary to constantly adjust the conditions of the pilots, affecting the maintenance of the required speed and course [48]. A significant part of the researchers noted that the cost (seeds, planting material, labor) for planting is two to three times higher than the cost of air sowing [13, 14, 16, 27, 29, 30, 32-34, 36, 38, 50, 55-58].

For reforestation, for example, under the canopy, or with high accuracy with a reduction in seeding rates and the size of the sown areas, a transition to a new level of development of aviation technology is required. The use of UAV in the forest aerial seeding devoted sufficient research [46, 59-61].

In Northern Thailand, reforestation is difficult because of the steep slopes inaccessible to people and equipment. As a result, the Department of biology of the University of Chiang Mai (FORRU) is conducting research on the aerial seeding with using UAV capable of carrying and dumping seeds on specified areas [61]. Data on the type of UAV is not given.

In Australia, the technology of aerial germination seeds on steep slopes, as well as the restoration of land disturbed by minefields [60]. Reconnaissance of the area is carried out with the help of an aircraft-type UAV equipped with modern optical equipment and an appropriate information system, then a helicopter-type UAV (quadcopter) at the obtained coordinates produces point sowing. Technology,
according to the developer, Dr. Susan Graham, that will ‘increase 10 times the speed of sowing compared to manual and 20% lower the cost of work’ [60]. Data on the design features of the UAV, safety and survival of seedlings is not given.

Note that the economic efficiency of aerial seeding will also depend on the sowing qualities of seeds, first and foremost, viability, determined by nondestructive express-analysis (testing) and improving pre-sowing treatment on quality characteristic [62, 63].

From the point of view of the degree of elaboration of the technical component of aerial seeding at the moment, it is necessary to state the prevalence in the design of hoppers, aggregated with both manned aircraft systems and unmanned aerial vehicles, units and elements that provide support for quantitative characteristics with exceptional seeding, effective, in our opinion, when restoring the ground cover with plants that are not particularly sensitive to the lack moisture and unevenness of the region of plant alimentation (grass, etc.).

Along with this, there is a problem of seeding in the soil. It can be solved by simple surface harrowing, but then there will be a rise in price due to the use of ground equipment. Or, providing a certain amount of energy on Board the UAV, give the initial acceleration of the seed capsule containing the seed and stocks of nutrients and protective substances, in order to bury it. For example, for Scots pine, the depth of seeding is insignificant (from 0.5 to 2 cm depending on the soil).

Particularly relevant aerial seeding fine-seed crops on sites with excessive moisture, where the waterlogged soil is often not able to travel to the place of seeding in conventional technology as well as on all types of inefficient traditional development site. Thus, the most interesting for the widespread introduction is the option of using drones for aerial small-seeded crops with a small hectare seeding rate.

Specialists of Bio Carbon Engineering (Oxford, United Kingdom) in an interview with national Geographic magazine (November 27, 2017) claim (video from the company's website https://www.facebook.com/cnnmoney/videos/10155283625853067/) that the cost savings when planting seeds from unmanned aerial vehicles will amount to 150 000 dollars per 100 hectares of reforestation area. Moreover, depending on the scheme, the company claims that aerial seeding of 1 hectare will take 45 minutes using seeding 750 seeds.

4. Conclusions

In 2017, for the purposes of reforestation in Russia the cost of sowing amounted to about 55 million Russian rubles on an area of 15633 hectares (on average, about 3500 rubles/ha), of which about 6 million rubles were state subsidies and 49 million rubles were at the expense of forest tenants.

Our forecasts are not as optimistic as those of Bio Carbon Engineering, due to various technological reasons, however, given the fact that with ground-based direct seeding the clearing of land and soil preparation about 40 % of energy and 25 % of labor costs, it is not uncommon that aerial seeding can cost 45-50% less per established hectare than ground-based direct seeding [52].

Taking into account the fact that 300 acorns on average have a mass of 1-1.2 kg, and 300 seeds of ordinary pine – only an average of 5 g, even taking into account the encapsulation of small seeds, the payload will allow, without changing the existing in Russia UAV designs, to provide significant needs for reforestation of remote and inaccessible (including for humans) sites, carrying out by changing the breeds of the social effect of the recreational value of stands. Thus, aerial seeding with the use of drones might be one of the cheapest forms of artificial reforestation, requiring further research in the field of navigation, energy saving, precision seeding.

Despite the higher seeding rate during traditional aerial seeding, the use of UAVs in Russia might be preferred during the following cases (according to Table 2):

– on sites where today’s ground-based seeding equipment is ineffective (e.g. because of rough terrain, forest fires, etc.);

– with the assistance of natural regeneration and artificial reforestation on sites inaccessible to ground-based equipment for climatic and geographical reasons;

– with the assistance of natural regeneration on sites inaccessible to people due to the complication of background radiation after man-made disasters.
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