Article

Discrete Seed Feeder Designing for Mobile Apparatus: Early Results for *Pinus sylvestris* L. Species

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Abstract: Discrete feeding of forest seeds is an urgent task for accurate detection of seeds during grading and reducing the seeding rate. The study used *Pinus sylvestris* L. seeds from cones collected in a natural stand of the Lisinsky educational-and-experimental forestry farm, Leningrad region, Russia, in 2017. Well-known methods for determining the properties of bulk materials were used; the results were processed by mathematical statistics using the MS Excel program. The physical and mechanical properties of uncalibrated seeds as a bulk material were determined. The angle of repose of *Pinus sylvestris* L. seeds, determined using a hollow cylinder by calculation, is 24.92°. The angle of repose of *Pinus sylvestris* L. seeds, determined using a hollow cylinder and a goniometer, is 32.7°. The significant discrepancy (~8°) in the values obtained by these methods is explained by the seeds shape. The flowability of *Pinus sylvestris* L. seeds corresponds to an excellent (free) category. The study will enable correct seed treatment protocols for sustainable forest management. However, some questions remained unresolved: how to orient a single seed in the right direction? How does seed-size calibration affect the angle of repose?

1. Introduction

The implementation of global forest landscape restoration initiatives [1] requires a huge amount of forest reproductive material. Regardless of whether planting seedlings [2] or seeding seeds [3,4] is the creation of forest crops, all of these purposes require a significant amount of high-quality seeds. The quality of seeds means, first of all, their germination and viability. For non-invasive determination of seed viability in stationary laboratory conditions, various advanced biophysical techniques can be used: spectrometric [5], nuclear magnetic resonance [6], and many others. However, in them, the sample is fixed in the cuvette manually, which does not allow the use of these methods in production field conditions. To perform seed sorting in the field, it is advisable to use spectrometric methods that use the Near InfraRed (NIR) and VISible (VIS) wavelength ranges of detecting radiation [7–12]. To ensure high-quality grading of seeds of scots pine [10,11] or acorns of oak petiolate [8], according to the spectrometric properties, a discrete seed supply to the diagnostic systems of separators based on new optoelectronic systems [12], and theoretical justification of the geometric and energy parameters of optical radiation [7] is necessary. In turn, the separation of seeds in the VIS range gives some differences in the growth of seedlings [9], and in the NIR range, an increase in ground germination in an automated nursery. These methods have the highest potential for the cost-quality ratio and do not

have a severe impact on the seed, unlike methods using X-rays or ultraviolet light. VIS-NIR techniques are implemented in the designs of mobile optoelectronic sorters [13–15], developed with the participation of one of the authors. The grader consists of several technological parts, including feeding, diagnostic, and grading modules. «The seeds are delivered from the dosing module to the vertical transparent pipeline at a frequency set by the microprocessor [16]». Without any doubt, the initial and slowest module was, and remains, the orienting (feeding) module. When striving for the ideal option, this module should provide the following:

- Simplicity of design;
- Storage of seed stock for the implementation of the technological cycle;
- Feeding seeds into the seed duct one at a time;
- Set and adjustable seed feeding frequency;
- A given orientation of the seeds in space or a clear detection of the initial position of the seed before entering the seed duct;
- Easy to pair with other modules.

The seeds obtained with the help of a mobile optoelectronic grader can be sown in several ways. The first option involves precise seeding in closed ground (containers) using a stationary automated gravity precision seeder (BCC, Landskrona, Sweden). The second option involves sowing seeds in the open ground using ground-based seeders, which are combined with a tractor. The design of ground-based seeders includes seeding devices of different types both according to the method of seed feeding [17] and the method of adaptive regulation of the seeding rate [18]. If it is impossible to implement the first and second options due to the climatic and geomorphic features of the sown areas, it is advisable to use a useful target load for adaptive aerial seeding [19] on the basis of micro Unmanned Aerial Vehicles (micro-UAVs) [20].

There may be a contradiction that needs to be resolved individually for each specific reforestation process. On the one hand, all precision seeding devices require mandatory sizing of the seeds. On the other hand, at the genetic level, sizing seeds by size can discard entire families [21].

To develop mobile devices for both optical sorting and seeding, it is necessary to understand how seeds will behave in seed water, be able to determine their exact orientation in space and ensure free flow without the formation of arches and traffic jams. The aim of the study is to develop a design and technological scheme for the discrete supply of scots pine seeds. The device should have small dimensions, a simple design and provide a piece-by-piece supply of seeds to mobile devices: an optoelectronic grader or a seeding apparatus based on micro-UAVs. This article will answer the following questions. Is it possible to free hydraulic flow of pine seeds from the hopper? What physical and mechanical properties of seeds have the greatest impact on their expiration without arching? What is the effective size of the mini-hopper opening for feeding seeds?

2. Materials and Methods

2.1. Seed Samples

In this study, the seeds of *Pinus sylvestris* L. species (hereinafter referred to as seeds) were used. Seeds were obtained using standard technology [22] from cones collected in 2017 in the natural stand of Lisinsky educational-and-experimental forestry farm (Leningrad region, Lisino-Korpus, Russia). The seeds were extracted from the cones, dewinged, dried to a moisture content of 8%, and prepared on a gravity separator [9]. Seeds were not size-calibrated, and seed sizes were determined using the micrometer MK25-2 (Kalibr Moscow Tool Factory, Moscow, Russia). The seed shape is an ellipsoid that is asymmetrical along three axes [23] (see Figure 1a,b).
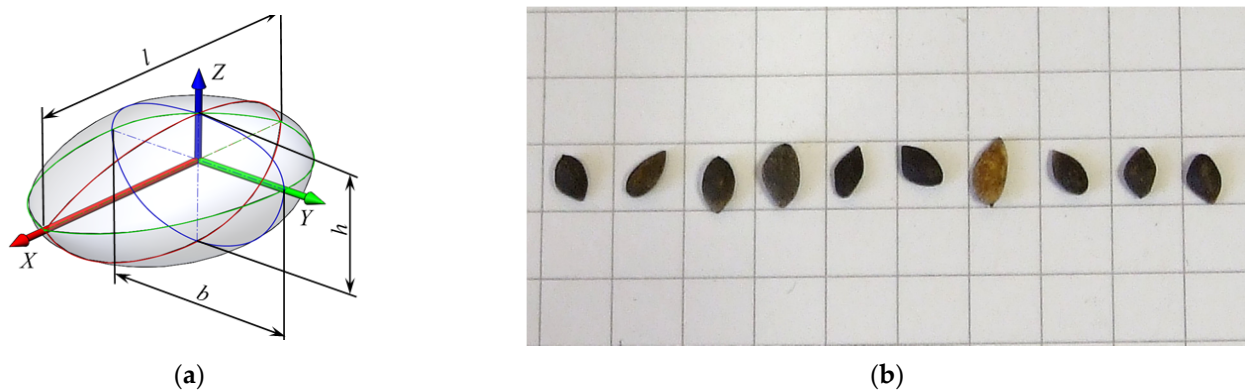
Figure 1. *Pinus sylvestris* L. seed shape used in study: (**a**) schematic [23]; (**b**) photo by authors. The size of one cell is 5 × 5 mm.

2.2. Pilot Experiments

For preliminary experiments to determine the behavior of pine seeds as a loose material, a cone and three cylinders with a height of 210 mm and a diameter of 10, 20, 30 mm were made of paper to determine the angle of natural slope. At the first stage of the preliminary experiment, the main task was to determine the required diameter of the outlet. By dropping the seeds one by one, it was possible to establish a tendency to get stuck in the outlet with a diameter of 5 mm due to the reversal of the seed. When filling the entire array of seeds into the cone, seeds-arch forming was observed, and the paused seeds tightly clogged the outlet feeder and required manual removal. When cutting the outlet feeder and, accordingly, increasing the diameter of the outlet hole to 6 mm, a tendency to free flow of two or more seeds at the same time was revealed. Based on the above, we can conclude about the required diameter of the outlet: 5.1 mm $\leq d_{out} \leq$ 5.9 mm.

At the second stage of the preliminary experiment, it was necessary to characterize the seeds flowability and establish the possibility of seeds-wall forming. Moreover, 30 trials with 10, 20, 30 mm cylinders were performed. The character of seed flow in the absolute majority of experiments is hydraulic, without pause and seeds-wall forming. For a 10 mm diameter cylinder, a single case of seeds-arch forming, which collapsed from an external impact on the cylinder wall, was recorded (see Data Set).

Determination of the seeds static angle of repose was carried out according to the methods described in [24,25] using a hollow cylinder, ruler and goniometer. First, we determined the angle of the natural slope calculated value $\alpha_{0\ calculated}$, measure the height of the formed of seeds heap and the diameter in three directions through 120° and substituting these values into the equation

$$\alpha_{0\ calculated} = arctg\left(\frac{2H_{heap}}{D_{heap}}\right),\tag{1}$$

where H_{heap} is the height of seeds heap, mm; D_{heap} is the diameter of seeds heap, mm.

Second, the measured value of the angle of the natural slope was determined, the height of the formed seeds heap and the diameter in three directions through 120° are measured.

From the papers [26,27], a simple formula is known for determining the size of the hopper outlet, based on the use of the equivalent diameter [28] of the particle:

$$r = 4 \cdot \sqrt{l \cdot b}\tag{2}$$

where r is the radius of the outlet, mm; l is the particle length of the bulk material, mm; b is the width of the particle of the bulk material, mm.

The seed sample was mixed for 5 min, quartered three times, then 30 seeds were selected and the length l and width b of the seeds were measured using a micrometer.

Well-known methods for determining the properties of bulk materials were used; the results were processed by mathematical statistics using the MS Excel program.

3. Results

3.1. Scots Pine Seeds Static Angle of Natural Slope

The results of the experiments were summarized in Table 1.

Table 1. Results of experiments to determine the angle of natural slope for seed samples used in study (N = 100).

Trial Number	Seed Heap Height H, mm	Seeds Heap Diameter d_{heap}, mm				Angle of Natural Slope, Calculated $\alpha_{0\text{ calculated}}$	Angle of Natural Slope, Measured $\alpha_{0\text{ measured}}$				$\Delta(\alpha_{0\text{ calculated}} - \alpha_{0\text{ measured}})$
		1	2	3	Average		1	2	3	Average	
Average	18.6	79.6	79.6	78.4	79.2	25.1	32.3	33.3	32.5	32.7	−7.6
Mode	18	79	78	78	79.33	24.41	31	34	34	33.67	−8.43
Min	14	73	73	72	76.00	19.00	28	24	27	27.00	−13.12
Max	25	89	85	86	85.33	32.22	38.5	39	39	37.17	−0.78
Median	18	79	80	78	79.33	24.92	32	33.75	32.5	32.75	−7.97
Variance σ^2	3.60	6.21	6.32	8.24	3.48	5.36	4.69	7.34	4.45	3.19	6.54
Standard deviation σ	1.90	2.49	2.51	2.87	1.87	2.32	2.17	2.71	2.11	1.79	2.56
Measurement error by Kornfeld method	5.50	8.00	6.00	7.00	4.67	6.61	5.25	7.50	6.00	5.08	6.17

Scots pine seeds can have an angle of repose ranging from 28 to 40°, and humidity is a significant factor affecting the natural slope angle [29]. Similar information on the seeds of *Pinus sibirica* Du Tour is given in paper [30].

3.2. Model of the Feeder and Vibration Experiments

According to the scientific review by Lukynenko [31], the seed size of Scots pine varies and is 3–5 mm in length, 1.4–3.3 mm in width, and 1.0–2.2 mm in thickness. The results were entered in Table 2.

Table 2. Results of examination of seeds dimensions (N = 30). The dash in place of the mode value of the *r*-parameter is explained by the absence of duplicate values.

| Trial Number	Seed Length l, mm	Seed Width b, mm	Calculated Radius of the Outlet r, mm
Average	4.2	1.4	9.7
Mode	4.27	1.54	—
Min	3.19	1.08	8.02
Max	5.03	1.81	11.62
Median	4.18	1.41	9.70
Variance σ^2	0.18	0.03	0.73
Standard deviation σ	0.43	0.17	0.85
Measurement error by Kornfeld method	0.92	0.37	1.80

Thus, based on the results in Tables 2 and 3, and guided by Equations (1) and (2), the size of the exhaust feeder should be assumed to be at least 5.5 mm. However, taking into account the purpose of the work—piece seeding, i.e., only one seed should pass through the aperture of the outlet feeder per unit of time, the diameter of the outlet hole should be 5 mm.

Table 3. Vibromotors parameters.

Vibromotor Brand	Vibromotor Type	Revolutions Per Minute, (r min^{-1}) Hz	Voltage, V
MTR-VIBRATING	coin (shaftless) motor	(10,000) 166.67 Hz	3
QX-6A-3V	brushless with nozzle	(9000) 150 Hz	3

A paper feeder was made with the following dimensions: 60 × 60 mm in the upper part, 5 × 5 mm—the size of the outlet, the angle of inclination of the walls—40° (Figure 2). The upper part of the feeder was reinforced with stiffeners, vibration motors were placed manually to the wall of the feeder (Figure 3, Table 3).

| (a) | (b) | (c) |
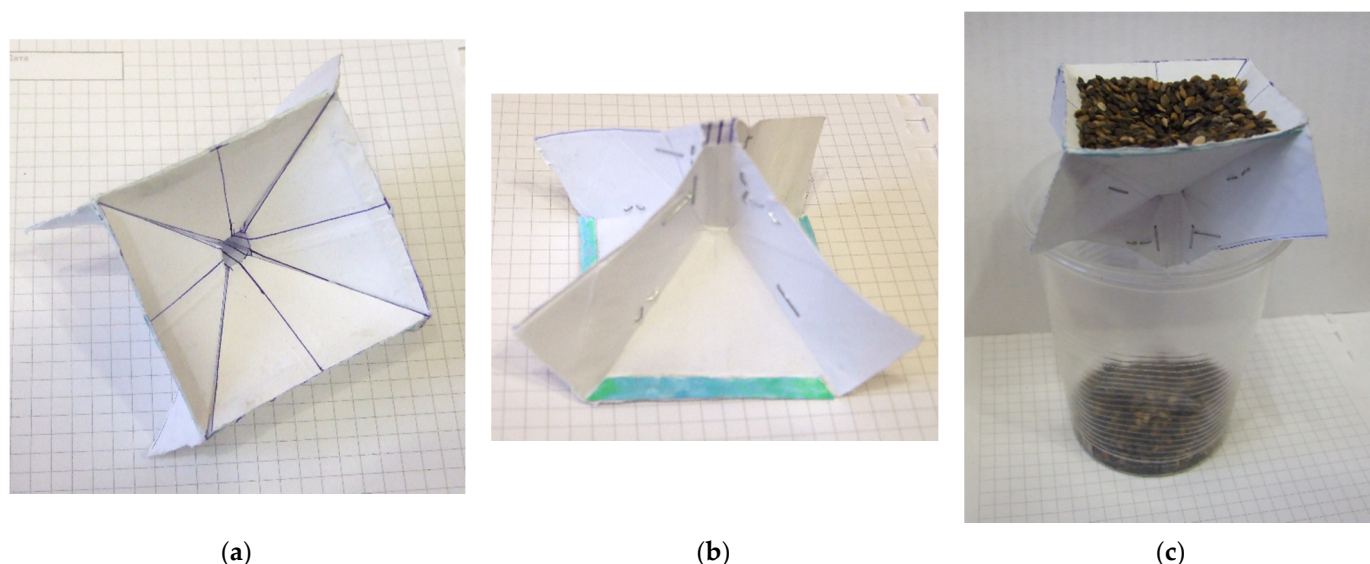
Figure 2. Feeder model: (**a**) front view; (**b**) bottom view; (**c**) feeder with seeds.

| (a) | (b) |
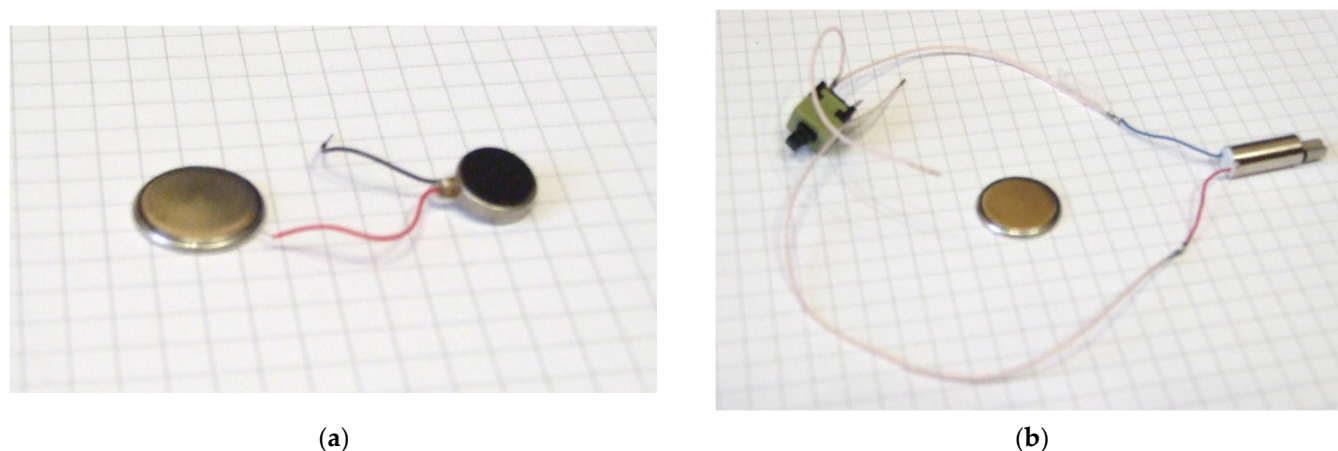
Figure 3. Vibromotors used in this study: (**a**) coin motor MTR-VIBRATING; (**b**) vibromotor QX-6A-3V.

The angle of repose of the *Pinus sylvestris* L. Seeds used in this study, determined using a hollow cylinder by the even method, is 24.92°. The angle of natural slope of *Pinus sylvestris* L. seeds, determined with the help of a hollow cylinder and a goniometer, is 32.7°. The significant discrepancy (~8°) in the values obtained by these methods exceeds that described in [25], which can be explained by the shape of the particles of the bulk material. The flowability of *Pinus sylvestris* L. seeds corresponds to an excellent (free) [25,32] category.

The method of estimating the size of seeds of this size using a micrometer cannot be recommended for use, since it is extremely time-consuming, often leading to crushing of the seed during measurement.

The selected angle of inclination of the walls of the outlet hopper (40°) of the feeder corresponds to the accepted standards [27] in the design and the recommendations proposed [25], however, there is a phenomenon of self-formation, which indicates the need for further improvement of the proposed methods.

4. Discussion

The static angle of the natural slope of *Pinus sylvestris* L. seeds was determined and the known data on the length and width of scots pine seeds were partially confirmed [33,34].

The known conclusion [25,35] that the method of measuring the angle of natural slope affects the measured value of the angle of natural slope was confirmed.

For further experiments, it is planned to assemble a metal model of the hopper with four installed agitators, solder the control board for the piece-by-piece connection of the agitators.

In general, it can be argued that the problem of seeds-arch forming and gravitational outflow of *Pinus sylvestris* L. seeds for this feeder design is overcome, but in the future, it is necessary to study the following:

- The need to calibrate the seeds before serving.
- How does seed calibration affect the angle of natural slope?
- If calibration is affected, is there a need to create different feeders for different seed size categories?

5. Conclusions

The static angle of the natural slope in *Pinus sylvestris* L. seeds was determined by two methods. The recommended slope angle of hopper walls for storage of *Pinus sylvestris* L. seeds is 40°. Directions for further research on properties of *Pinus sylvestris* L. seeds as a bulk material were determined.

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