environmental sciences proceedings

MDPI

Proceeding Paper

Correlation between the Spectrometric Parameters of Coniferous Seeds and the Molecular Indicators of Seedlings: Is It Possible to Apply It in Practice? †

Vladan Ivetić [1], Arthur Novikov [2,*], Abolfazl Daneshvar [3] and Masoud Ahmadi-Afzadi [4]

[1] Faculty of Forestry, University of Belgrade, 1, Kneza Višeslava, 11030 Belgrade, Serbia; vladan.ivetic@sfb.bg.ac.rs
[2] Mechanical Department, Voronezh State University of Forestry and Technologies Named after G.F. Morozov, 8, Timiryazeva, 394087 Voronezh, Russia
[3] Seed Sciences and Plant Restoration, Department of Biology, Gonbad Kavous University (GKU), Blv. Basirat, Shahid Fallahy Street, Gonbad Kavous Golestan, Golestan Province 49717991512, Iran; abolfazl.daneshvar@gonbad.ac.ir
[4] Biotechnology Department, Institute of Science, High Technology and Environmental Sciences, Graduate University of Advanced Technology, Kerman 7631818356, Iran; masoudahmadiafzadi@gmail.com
* Correspondence: arthur.novikov@vglta.vrn.ru
† Presented at the 1st International Electronic Conference on Forests—Forests for a Better Future: Sustainability, Innovation, Interdisciplinarity, 15–30 November 2020; Available online: https://iecf2020.sciforum.net.

Citation: Ivetić, V.; Novikov, A.; Daneshvar, A.; Ahmadi-Afzadi, M. Correlation between the Spectrometric Parameters of Coniferous Seeds and the Molecular Indicators of Seedlings: Is It Possible to Apply It in Practice? *Environ. Sci. Proc.* **2021**, *3*, 18. https://doi.org/10.3390/IECF2020-08084

Academic Editors: Angela Lo Monaco, Cate Macinnis-Ng and Om P. Rajora

Published: 13 November 2020

Abstract: Coniferous seeds as an integral part of Forest Reproductive Material (FRM) are a fairly valuable product that is transported by trade operations over long distances. Seed quality determines the rate of reforestation. Improving quality indicators and increasing the competitiveness of forest seeds is one of the promising directions of a few country's forestry development strategy and an opportunity to integrate into global reforestation initiatives. Based on the direct interaction of biophysical studies of seed spectrometric parameters, implementation of their genotype in different environmental conditions, biometric studies of seedling growth and development and genetic conditioning of these components, it is possible to develop and test a comprehensive concept for obtaining FRM with high quality indicators. What practical application can be expected? First, it is possible to study genetic variability among the seeds of the studied species, using molecular DNA markers. This would help obtain a comprehensive and categorical classification of samples that illustrates the genetic similarity and relationship structure relative to the desired characteristics of seedlings and seeds with high viability rates. Genetic and spectrometric data could be further combined to build a consensus tree of genetic similarity. Second, algorithms could be developed for integrating these parameters in the FRM-Library database to synchronize the quality indicators of forest reproduction material, with information processing devices of optoelectronic graders and phenoseeders. Third, methods and algorithms could be developed for optimal selection of technology for coniferous seeds grading of different breeding values. These would be developed based on data extracted from the FRM-Library database for the production of forest reproductive material, considering various goals and frontier methods of contemporary forest landscape restoration.

Keywords: coniferous seeds; seed spectrogram; seedling; genetic diversity—amplification curve; correlation; DNA markers; FRM-Library; forest seeds optoelectronic grader; forest seeds rapid analyzer

1. Introduction

When implementing contemporary forest landscape restoration [1–5], one of the main tasks is to obtain seedlings from seeds with improved properties. The first step in this direction is selection for the speed of growth and productivity of mother trees. This requires the development of new methods for diagnostics of Forest Reproductive (seed and planting) Material (FRM) of newly created or restored stands. In addition, when breeding high-quality breeds and improved forest tree crops, success primarily depends on reliable reproduction at an early age [6]. Forest woody plants are characterized by significant intraspecific variability that increases the level of biodiversity of forest ecosystems [7], which is formed on the basis of seed quality [8] in conditions of extensive ecologically heterogeneous areas of forest-forming species.

Seed quality is defined as "*a measure of the attributes or attributes that will determine seed performance during sowing or storage*" [9]. This is a multiple concept that covers the physical, physiological, genotypic, pathological, and entomological factors that affect the seedlot productivity [10,11].

Many tree produce significant amounts of empty and fossilized seeds due to inbreeding, mismatch of phenological phases, or post-zygotic degenerations [12]. This is a major problem that reduces the quality of seedlots [13].

These seeds lack the miniature plant—embryo, and do not produce seedlings when sown. In addition, insect infestation [14–16], environmental conditions during seed development [17], and the genetic constitution [18] of the seedlots influence their performance when sown or stored. Seeds partially consumed by larvae are usually less vigorous, while seeds that are severely attacked are completely empty of their contents, and hence fail to germinate. Despite several attempts to improve seed yield of several species, a substantial amount of empty, insect-infested, and dead-filled seeds is still encountered in seed bulks, as there is no way of avoiding these seeds during collection. It is, therefore, imperative that such non-germinable seeds should be removed from the seed bulk, prior to sowing, in order to enhance the performance of seedlots when sown in the nursery.

A preliminary analysis of biophysical methods [19] for seed research showed that there is a significant difference between the coniferous seed's spectrometric parameters of different geographical and species origin. Theoretical studies of optical radiation formation [20] for detecting such seeds in the mobile rapid analyzer's optoelectronic system (patent RU 2,675,056 [21]), developed under the guidance of one of the authors, show a fairly high accuracy and the possibility of their analysis and grading.

Interdisciplinary interaction is designed to achieve a comprehensive solution to the problem of obtaining improved FRM in the future, by studying the spectrometric properties of coniferous seeds of different breeding potential, and predicting the rate and quality of ontogenetic development of seedlings on this basis

What practical application could be expected from possible correlations between the spectrometric parameters of coniferous seeds and the molecular indicators of seedlings?

This requires interdisciplinary research that brings together specialists in the fields of molecular genetics, quantitative trait genetics, ontogeny genetics, fundamental optics (spectrometry), development of professionally oriented information systems (databases), and automation of forestry processes.

2. First Application

First, the molecular variation among forest seeds might be examined with DNA markers, exploring the genetic similarity/distance using the plant genetic materials. Utilizing molecular characteristics would illustrate the seed population structure and relationship with the tested quantitative variables, and would help to differentiate seedlings and seeds with high rates of viability. The genetic and spectrometric data might be further integrated for constructing a consensus genetic similarity tree.

Woody species naturally exist in populations or communities. Population as a level of organization of individuals is characterized by the following processes—migration, mutation, gene drift, and inbreeding. During the ontogenesis of each tree, both the interaction of genes and their expression occur. For example, gene expression was studied in detail in coniferous tree species that have a high economic value, in particular, in frankincense pine [19]. In this species, genes were identified whose variability is associated with adaptive traits, as well as affects the expression of genetic information and the level of metabolites. For this purpose, a genome-wide approach was applied, i.e., a description of the sequence of nucleotides of all exons of the body, i.e., sections of DNA encoding proteins. Single-nucleotide polymorphisms were used as marker-differences between two sequences per nucleotide that occurred as a result of point mutations and were steadily transmitted from generation to generation. This change, as it turned out, could dramatically affect the body. A correspondence was found between the variability of the studied single-nucleotide polymorphisms and the expression of a number of genes, as well as the corresponding plant traits. As a result, gene networks were obtained, the analysis of which revealed the key genes responsible for adaptation to various environmental factors, including drought. There were also studies that showed that evolutionary and transgenerational processes affected the expression of the offspring trait; the parent environment could pre-adapt the offspring to similar environmental conditions; the degree of influence of maternal traits on the offspring depended on the context; and changes in the seedling growth environment have a profound effect on the productivity of the offspring [20].

Genomic techniques are a valuable and useful tool for the genetic study of many organisms from simple prokaryotic cells to eukaryotes, e.g., tree plants. These methods enable scientists to investigate the genetic mechanism behind different plant characteristics and perform evolutionary evaluation, and enable biologists to conduct fundamental tasks such as inferring recent and historical demographic trends of populations in response to environmental changes.

However, due to some limitation in trees, i.e., the large size and the complexity of many tree genomes, application and development of species-specific genomic techniques could be challenging. Many tree plants like gymnosperms are polyploid with a large genome with a high proportion of repetitive content, which makes genetic studies more complicated. In addition, the wide geographical distribution of forest trees along with a large ecological range determine the formation of various life forms (from prostrate shrubs to trees). Challenges in taxonomic classification of subspecies are also related to a high variability of morphological traits in trees. Many species in forest trees are polymorphic species with intricate and often controversial taxonomy [21]. In addition, a strong geographic bias towards temperate tree species constrains our ability to decipher the long-lasting evolutionary impact of climate change across forested lands worldwide—a task of utmost importance to forecast the response of forests to emerging mega-disturbances [22–24]. Even with the advent of reliable and fast modern techniques to study genomes (e.g., genome-wide sequencing and association studies), genomic research on forest trees still remains partly unsolved regarding the genetic factors and their interaction with environmental factors.

A comprehensive study of the relationship between the spectrometric parameters of seeds of promising woody plants obtained by different breeding techniques, their sowing qualities, quantitative characteristics of gene expression, and biometric parameters of seedlings would allow us to obtain reliable correlation models of growth and development of coniferous trees.

3. Second Application

Second, algorithms could be developed for integrating spectrometric (spectral absorption bands, etc.), genetic (DNA markers, amplification curve, etc.), and biometric (growth rate, etc.) parameters into the FRM-Library (FRMLib) database [25]. This would allow us to synchronize FRM quality indicators with optoelectronic graders [26] and phenoSeeders [27], based on fuzzy logic algorithms [28,29], moving to the implementation of a closed-loop control system that is most effective in terms of accuracy of analysis and grading.

The solution to this problem requires the following conditions to be met:

- there is a universal criterion for selecting viable seeds with certain improved genetic characteristics;
- availability of an optimal method for conducting such testing; and
- availability of technical means for such testing that meet the requirements of energy conservation and environmental safety.

To date, the implementation of all these conditions in the practice is carried out mainly in two directions—quantitative and qualitative.

The quantitative approach assumes the use of geometric parameters of seeds and their mass as a selection criterion. In its pure form, seed size separation could change the genetic diversity of the seedlot [30]. It is a rather invasive method and does not fully take into account hereditary features.

The qualitative approach assumes the use of spectrometric parameters of seeds obtained in the visible, infrared, or submillimeter wavelength ranges as a selection criterion. At the same time, there is currently no consensus on which division range best predicts the subsequent growth and development of seedlings [31]. At the same time, the optical radiation plays an important role in the evaluation and preparation of forest seeds for sowing and storage. The different ability of radiation absorption by seeds has a certain significance in genetic diversity [32], due to the high heritability of the seed coloration gene [33–36]. For example, the offspring of Scots pine obtained from seeds with a light skin color sharply "*changes the ranks of germination time and fluctuations in the frequency of the best families from 0 to 400% of the norm*" [37]. Many scientists studied the mechanisms of using optical radiation for diagnostics, analysis, and prediction of further development of seeds [37–46]. However, there is no holistic approach to conducting spectrometric studies of forest seeds and mobile equipment for rapid analysis, and data on the existence (or not) of correlation interactions between the spectrometric characteristics of seeds and the biometric indicators of seedlings obtained from these are poorly presented in the scientific forestry literature [5].

Research is conducted with the support of universities' own funds under the project "Development of technology for the production of forest seed material with specified quality characteristics" (https://www.researchgate.net/project/Development-of-forest-seeds-production-with-the-specified-characteristics). The goal of the project is to increase the efficiency of forest seed production for direct automated seeding (ground or air seeding [47,48]) by developing technology and designing automated technical means for high-quality seed grading based on photon technologies.

The current level of technology development, the presence of positive international and domestic experience in the field of genetics, biophysics, biochemistry, optics, electronics, and mechanics, makes it possible for the research team to develop the design of devices [26,49–51] that could separate forest seeds by quality (spectrometric) characteristics.

At the same time, a prerequisite for improving the design is the availability of experimental data on the expression of seedling genes during ontogenesis, depending on the spectrometric characteristics of coniferous seeds, which are negligible at this time.

4. Third Application

Third, based on data extracted from FRMLib, and taking into account frontier interdisciplinary (biophysical, biochemical, biological, engineering, and other) methods, optimal technological regulations could be developed for non-destructive quality control and sorting of coniferous seeds of various breeding values, for the production of forest reproductive material, taking into account various purposes (reforestation, plantation forestry, etc.) and methods (for storage, for ground-based directive seeding, for aerial seeding, for planting, etc.).

In the future, the forest restoration method on hard-to-recover forest sites [52] could be upgraded, based on updated technological regulations. Sites that are difficult to restore include:

- released as a result of felling (including burning felling), which makes it inefficient for the operational technology of ground-based seeding or planting;
- released as a result of forest fires that are not effective for the operational technology of ground-based seeding or planting;
- inaccessible to ground-based mechanization facilities for climatic and geomorphological reasons; and
- inaccessible to people due to the complication of the radiation background and after man-made disasters.

When implementing the forest restoration method, including group of site preparation operations [53], group of FRM preparation operations , group of seeding [47,54,55] or planting [56,57] on site, it additionally includes group of monitoring operations [58,59]. Alternative rapid analysis [16,31] and encapsulation [60] operations carried out in field conditions using mobile equipment [26,49–51] are additionally introduced into a group of FRM preparation operations. In the group of seeding or planting operations, the additional operation of spot sowing of seeds or planting of seedlings from air is carried out. This is carried out using unmanned aerial vehicles of helicopter, aircraft or hybrid types, equipped with taking into account their take-off mass navigation equipment, based on closely-integrated inertial-satellite system [61–64], equipment [65] for simultaneous storage of sown seeds or planted seedlings, control of specified seeding rate of seeds, or planting seedlings by quantitative or on a mass basis, and accurate seeding or planting of seedlings depending on the specified scheme of location of forest crops and speed of unmanned aerial vehicle, energy accumulating equipment.

Advantages of the proposed forest restoration method on hard-to-recover sites are the acceleration of the reforestation process and the higher environmental safety by reducing the number of operations that disturb the forest ecosystem; use of environmentally safe energy sources in technical means of monitoring; preparation of reproductive material—sowing or planting; reduction of costs for performance of energy-intensive operations of site preparation; and transportation of seed to the place of preliminary preparation and back.

The socio-economic effect of the use of new technological regulations is explained by the fact that coniferous seeds as part of an integral FRM are a fairly valuable product that is moved by trade operations over long distances [66]. The role of seeds is quite significant [8]. Their quality determines the rate of reforestation and afforestation. Improving quality indicators and increasing the competitiveness of forest seeds is one of the most promising areas for the development of the forest complex in many countries. This direction involves active interaction between the triad "state forest owners—private forest owners—forest seed producers", which corresponds to the main provisions of the methodology for assessing recovery opportunities [67] for use in global reforestation initiatives [68–70]. According to Dominic DellaSala et al. "*we must commit to thoughtful, science-based restoration to ensure that future generations can experience and enjoy pristine, diverse forest landscapes with the highest ecological integrity* [71]".

5. Conclusions

Thus, based on the direct interaction of biophysical studies on the spectrometric parameters of seeds, the implementation of their genotype in different environmental conditions, biometric studies of the growth and development of seedlings, and the genetic conditionality of these components, we plan to develop and test a comprehensive concept for obtaining FRM with high quality indicators.

Integration of the claimed approaches would allow the creation of a fundamentally new information and analytical FRMLib-database [25]. This provides a solution to the problem of synchronization of FRM quality indicators with the decision-making module, when performing the technological process of reforestation [52]. Additionally, software complexes of automated optoelectronic devices [26,49–51,60,65] for rapid analysis, grading, encapsulation, seeding, and monitoring of the reforestation results can also be used.

The authors' interdisciplinary collaboration resulted in the preparation and submission of a grant proposal, which is currently under review.

The authors hope to establish and expand interdisciplinary relations with colleagues from other countries.

Author Contributions: Conceptualization, V.I., A.N., and M.A.-A.; methodology, V.I., A.N., A.D., and M.A.-A.; validation, V.I., A.N., A.D., and M.A.-A.; formal analysis, V.I., A.N., A.D., and M.A.-A.; investigation, X.X.; resources, V.I., A.N., A.D., and M.A.-A.; data curation, V.I., A.N., A.D., and M.A.-A.; writing—original draft preparation, V.I., A.N., A.D., and M.A.-A.; writing—review and editing, V.I., A.N., A.D., and M.A.-A.; supervision, V.I.; project administration, A.N. and A.D.; funding acquisition, A.N. and A.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors acknowledged affiliated higher education institutions for their administrative and technical support in conducting preliminary research.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Mansuy, N.; Burton, P.J.; Stanturf, J.; Beatty, C.; Mooney, C.; Besseau, P.; Degenhardt, D.; MacAfee, K.; Lapointe, R. Scaling up forest landscape restoration in Canada in an era of cumulative effects and climate change. *For. Policy Econ.* **2020**, *116*, 102177.
2. Stanturf, J.A.; Palik, B.J.; Dumroese, R.K. Contemporary forest restoration: A review emphasizing function. *For. Ecol. Manag.* **2014**, *331*, 292–323.
3. Elliott, S.; Chairuangsri, S.; Kuaraksa, C.; Sangkum, S.; Sinhaseni, K.; Shannon, D.; Nippanon, P.; Manohan, B. Collaboration and Conflict—Developing Forest Restoration Techniques for Northern Thailand's Upper Watersheds Whilst Meeting the Needs of Science and Communities. *Forests* **2019**, *10*, 732.
4. Sabogal, C.; Besacier, C.; McGuire, D. Forest and landscape restoration: Concepts, approaches and challenges for implementation. *Unasylva* **2015**, *66*, 3.
5. Novikov, A.I.; Sokolov, S.; Drapalyuk, M.; Zelikov, V.; Ivetić, V. Performance of Scots pine seedlings from seeds graded by colour. *Forests* **2019**, *10*, 1064.
6. Mattheus, R.E.F. *Plant Virology*; Academic Press Inc.: New Work, NY, USA, 1970; 685p.
7. González-Martínez, S.C.; Krutovsky, K.V.; Neale, D.B. Forest-tree population genomics and adaptive evolution. *New Phytol.* **2006**, *170*, 227–238.
8. Ivetić, V.; Novikov, A.I. The role of forest reproductive material quality in forest restoration. *For. Eng. J.* **2019**, *9*, 56–65.
9. Hampton, J.G. What is seed quality? *Seed Sci. Technol.* **2002**, *30*, 1–10.
10. Basu, R.N. Seed viability. In *Seed quality: basic mechanisms and agricultural implications*; Basra, A.S.; CRC Press, Taylor & Francis: New York, USA, 1995, Volume 1, pp. 1–44.
11. Alekseychuk, G.N.; Laman, N.A. *Physiological Quality of Seeds of Agricultural Crops and Methods of Its Assessment*; Law and Economics: Minsk, Belarus, 2005.
12. Owens, J.N.; Morris, S.J.; Catalano, G.L. How the pollination mechanism and prezygotic and postzygotic events affect seed production in *Larix occidentalis*. *Can. J. For. Res.* **1994**, *24*, 917–927.
13. Tigabu, M.; Daneshvar, A.; Wu, P.; Ma, X.; Christer Odén, P. Rapid and non-destructive evaluation of seed quality of Chinese fir by near infrared spectroscopy and multivariate discriminant analysis. *New For.* **2020**, *51*, 395–408.
14. Tigabu, M.; Odén, P.C. Simultaneous detection of filled, empty and insect-infested seeds of three *Larix* species with single seed near-infrared transmittance spectroscopy. *New For.* **2004**, *27*, 39–53.
15. Tigabu, M.; Odén, P.C.; Shen, T.Y. Application of near-infrared spectroscopy for the detection of internal insect infestation in *Picea abies* seed lots. *Can. J. For. Res.* **2004**, *34*, 76–84.
16. Tigabu, M.; Odén, P.C. Rapid and non-destructive analysis of vigour of *Pinus patula* seeds using single seed near infrared transmittance spectra and multivariate analysis. *Seed Sci. Technol.* **2004**, *32*, 593–606.
17. Gutterman, Y. Maternal effects on seeds during development. In *Seeds: The Ecology of Regeneration in Plant Communities*, 2nd ed.; Fenner, M., Ed.; CABI Publishing: New York, NY, USA, 2000; pp. 59–84.
18. Mamo, N.; Mihretu, M.; Fekadu, M.; Tigabu, M.; Teketay, D. Variation in seed and germination characteristics among *Juniperus procera* populations in Ethiopia. *For. Ecol. Manag.* **2006**, *225*, 320–327.
19. Koralewski, T.E.; Brooks, J.E.; Krutovsky, K.V. Molecular evolution of drought tolerance and wood strength related candidate genes in loblolly pine (*Pinus taeda* L.). *Silvae Genet.* **2014**, *63*, 59–66.

20. Lázaro-Lobo, A.; Herrera, M.; Campos, J.A.; Caño, L.; Goñi, E.; Ervin, G.N. Influence of local adaptations, transgenerational effects and changes in offspring's saline environment on *Baccharis halimifolia* L. under different salinity and light levels. *Environ. Exp. Bot.* **2020**, *177*, 104134.
21. Knyazeva, S.G.; Hantemirova, E. V Comparative analysis of genetic and morpho-anatomical variability of common juniper (*Juniperus communis* L.). *Russ. J. Genet.* **2020**, *56*, 48–58.
22. Ellegren, H. Genome sequencing and population genomics in non-model organisms. *Trends Ecol. Evol.* **2014**, *29*, 51–63.
23. Millar, C.I.; Stephenson, N.L. Temperate forest health in an era of emerging megadisturbance. *Science* **2015**, *349*, 823–826.
24. Soltis, P.S.; Marchant, D.B.; Van de Peer, Y.; Soltis, D.E. Polyploidy and genome evolution in plants. *Curr. Opin. Genet. Dev.* **2015**, *35*, 119–125.
25. Novikov, A.I.; Ivetić, V.; Novikova, T.P.; Petrishchev, E.P. Scots pine seedlings growth dynamics data reveals properties for the future proof of seed coat color grading conjecture. *Data* **2019**, *4*, 106.
26. Albekov, A.U.; Drapalyuk, M.V.; Morkovina, S.S.; Vovchenko, N.G.; Novikov, A.I.; Sokolov, S.V.; Novikova, T.P. Express Analyzer of Seed Quality. RU Patent 2,675,056, 14 December 2018.
27. Jahnke, S.; Roussel, J.; Hombach, T.; Kochs, J.; Fischbach, A.; Huber, G.; Scharr, H. phenoSeeder—A robot system for automated handling and phenotyping of individual seeds. *Plant Physiol.* **2016**, *172*, 1358–1370.
28. Kovalev, S.M.; Sokolov, S. V; Kucherenko, P.A. Intelligent processing of temporal data based on hybrid fuzzy-stochastic models. *Autom. Control Comput. Sci.* **2015**, *49*, 1–10.
29. Sokolov, S.V.; Kovalev, S.M.; Kucherenko, P.A.; Smirnov, Y.A. *Methods for Identifying Fuzzy and Stochastic Systems*; Fizmatlit: Moscow, Russia, 2018; 432p.
30. Ivetić, V.; Devetaković, J.; Nonić, M.; Stanković, D.; Šijačić-Nikolić, M. Genetic diversity and forest reproductive material—from seed source selection to planting. *iForest Biogeosci. For.* **2016**, *9*, 801–812.
31. Novikov, A.I. Forest seeds rapid analysis: The choice of the effective quality indicator. In Proceedings of the Proceeding in Ecological and Biological Bases of Increasing Productivity and Sustainability of Natural and Artificially Renewed Forest Ecosystems, Voronezh, Russia, 4–6 October 2018; Voronezh State University of Forestry and Technologies Named after G.F. Morozov: Voronezh, Russia, 2018; pp. 559–567.
32. Ivetić, V.; Grossnickle, S.; Škorić, M. Forecasting the field performance of Austrian pine seedlings using morphological attributes. *iForest Biogeosci. For.* **2016**, *10*, 99–107.
33. Pravdin, L.F. The main regularities of the geographical variability of Scots pine (*Pinus sylvestris* L.) In *Fundamentals of Forest Science and Forestry*; Forestry Publ.: Moscow, Russia, 1960; pp. 245–250.
34. Tikhonova, I.V.; Tarakanov, V.V.; Tikhonova, N.A.; Barchenkov, A.P.; Ekart, A.K. Population variability of cones and seeds of scots pine by phenes of color and traits-indices in the south of Siberia. *Contemp. Probl. Ecol.* **2014**, *7*, 60–66.
35. Rogozin, M.V. Cryptic effect of tree characters on the growth of the progeny. In *Proceedings of the Lesnaya Genetika*, Selektsiya i Fiziologiya Drevesnykh Rasteniĭ; Voronezh, Russia: VFEI Publ., 1989; pp. 177–179. (In Russian)
36. Vidyakin, A.I. Phenes of woody plants: Identification, scaling, and use in population studies (An Example of *Pinus sylvestris* L.). *Russ. J. Ecol.* **2001**, *32*, 179–184.
37. Müller-Olsen, C.; Simak, M.; Gustafsson, Å. Germination analyses by the X-ray method. *Rep. For. Res. Inst. Swed.* **1956**, *46*, 1–12.
38. Simak, M. The X-ray contrast method for seed testing Scots Pine—*Pinus silvestris*. *Medd. från Statens skogsforskningsinstitut* **1957**, *47*, 1–22.
39. Linskens, H.F.; Jackson, J.F. *Seed Analysis*; Linskens, H.F., Jackson, J.F., Eds.; Modern Methods of Plant Analysis; Springer: Berlin/Heidelberg, Germany, 1992; 380p.
40. Tillman-Sutela, E.; Kauppi, A. The morphological background to imbibition in seeds of *Pinus sylvestris* L. of different provenances. *Trees* **1995**, *9*, 123–133.
41. Lestander, T.A.; Odén, P.C. Separation of viable and non-viable filled Scots pine seeds by differentiating between drying rates using single seed near infrared transmittance spectroscopy. *Seed Sci. Technol.* **2002**, *30*, 383–392.
42. Repo, T.; Paine, D.H.; Taylor A.G. Electrical impedance spectroscopy in relation to seed viability and moisture content in snap bean (*Phaseolus vulgaris* L.). *Seed Sci. Res.* **2002**, *12*, 17–29.
43. Tigabu, M.; Oden, P.C.; Lindgren, D. Identification of seed sources and parents of *Pinus sylvestris* L. using visible–near infrared reflectance spectra and multivariate analysis. *Trees* **2005**, *19*, 468–476.
44. Farhadi, M.; Tigabu, M.; Odén, P. Near infrared spectroscopy as non-destructive method for sorting viable, petrified and empty seeds of *Larix sibirica*. *Silva Fenn.* **2015**, *49*, 1340.
45. Olesen, M.H.; Nikneshan, P.; Shrestha, S.; Tadayyon, A.; Deleuran, L.C.; Boelt, B.; Gislum, R. Viability Prediction of *Ricinus cummunis* L. Seeds Using Multispectral Imaging. *Sensors* **2015**, *15*, 4592–4604.
46. Timchenko, S.P. Spectral-Optical Criteria for Determining Seed Germination. Ph.D. Thesis, Moscow Timiryazev Agricultural Academy, Moscow, Russia, 1993.
47. Grossnickle, S.C.; Ivetić, V. Direct Seeding in Reforestation—A Field Performance Review. *Reforesta* **2017**, *4*, 94–142.
48. Novikov, A.I.; Ersson, B.T. Aerial seeding of forests in Russia: A selected literature analysis. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *226*, 012051.
49. Albekov, A.U.; Drapalyuk, M.V.; Morkovina, S.S.; Novikov, A.I.; Vovchenko, N.G.; Sokolov, S.V.; Novikova, T.P. Seed Sorting Device. RU Patent 2,687,509, 14 May 2019.

50. Drapalyuk, M.V.; Morkovina, S.S.; Novikov, A.I.; Vovchenko, N.G.; Sokolov, S.V.; Novikova, T.P. Seed Sorting Device. RU Patent 2,700,759, 14 September 2019.
51. Albekov, A.U.; Drapalyuk, M.V.; Morkovina, S.S.; Vovchenko, N.G.; Novikov, A.I.; Sokolov, S.V.; Novikova, T.P. Device for Seeds Sorting. RU Patent 2,682,854, 21 March 2019.
52. Novikov, A.I. Forest Restoration Method. RU Patent 2,714,705, 20 May 2019.
53. Löf, M.; Ersson, B.T.; Hjältén, J.; Nordfjell, T.; Oliet, J.; Willoughby, I. Site Preparation Techniques for Forest Restoration. In *Restoration of Boreal and Temperate Forests*, 2nd ed.; Stanturf, J.A., Ed.; CRC Press: Boca Raton, FL, USA, 2016; pp. 85–102.
54. Guignabert, A.; Augusto, L.; Delerue, F.; Maugard, F.; Gire, C.; Magnin, C.; Niollet, S.; Gonzalez, M. Combining partial cutting and direct seeding to overcome regeneration failures in dune forests. *For. Ecol. Manag.* **2020**, *476*, 118466.
55. Sudrajat, D.J.; Rustam, E. Reforestation by direct seeding of Gmelina arborea using seed briquettes: Composition, size and site preparation, and sowing date. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *533*, 012014.
56. Ramantswana, M.; Guerra, S.P.S.; Ersson, B.T. Advances in the Mechanization of Regenerating Plantation Forests: A Review. *Curr. For. Rep.* **2020**, *6*, 143–158.
57. Ersson, B.; Laine, T.; Saksa, T. Mechanized Tree Planting in Sweden and Finland: Current State and Key Factors for Future Growth. *Forests* **2018**, *9*, 370.
58. Zhao, D.; Pang, Y.; Liu, L.; Li, Z. Individual Tree Classification Using Airborne LiDAR and Hyperspectral Data in a Natural Mixed Forest of Northeast China. *Forests* **2020**, *11*, 303.
59. Kampen, M.; Vienna, L.S.; Immitzer, M.; Vienna, L.S. UAV-Based Multispectral Data for Tree Species Classification and Tree Vitality Analysis. In *Proceedings of the Dreilandertagung der DGPF, der OVG und der SGPF*; Publ. der DGPF: Vienna, Austria; 2019; pp. 623–639.
60. Albekov, A.U.; Drapalyuk, M.V.; Morkovina, S.S.; Vovchenko, N.G.; Novikov, A.I.; Sokolov, S.V.; Novikova, T.P. Seed Encapsulation Method for Aerial Seeding. RU Patent 2,710,721, 20 January 2020.
61. Sokolov, S.V.; Novikov, A.I. Adaptive estimation of UVs navigation parameters by irregular inertial-satellite measurements. *Int. J. Intell. Unmanned Syst.* (in press).
62. Sokolov, S.V.; Novikov, A.I. Suboptimal stochastic estimation of the initial orientation parameters of a strapdown inertial navigation system on an unmanned vehicle perturbed base. *Int. J. Intell. Unmanned Syst.* (under review).
63. Sokolov, S.V.; Kamenskij, V.V.; Novikov, A.I.; Ivetić, V. How to increase the analog-to-digital converter speed in optoelectronic systems of the seed quality rapid analyzer. *Inventions* **2019**, *4*, 61.
64. Sokolov, S.; Novikov, A.; Ivetić, V. Determining the initial orientation for navigation and measurement systems of mobile apparatus in reforestation. *Inventions* **2019**, *4*, 56.
65. Morkovina, S.S.; Vovchenko, N.G.; Novikov, A.I.; Sokolov, S.V.; Dornyak, O.R. Seed Aerial Sowing Device. RU Patent 2,712,516, 21 May 2019.
66. Jansen, S.; Konrad, H.; Geburek, T. Crossing borders—European forest reproductive material moving in trade. *J. Environ. Manag.* **2019**, *233*, 308–320.
67. McLain, R.; Lawry, S.; Guariguata, M.R.; Reed, J. Toward a tenure-responsive approach to forest landscape restoration: A proposed tenure diagnostic for assessing restoration opportunities. *Land Use Policy* **2018**, in press.
68. Dumroese, R.K.; Balloffet, N.; Crockett, J.W.; Stanturf, J.A.; Nave, L.E. A national approach to leverage the benefits of tree planting on public lands. *New For.* **2019**, *50*, 1–9.
69. Stanturf, J.A.; Kleine, M.; Mansourian, S.; Parrotta, J.; Madsen, P.; Kant, P.; Burns, J.; Bolte, A. Implementing forest landscape restoration under the Bonn Challenge: A systematic approach. *Ann. For. Sci.* **2019**, *76*, 50.
70. Verdone, M.; Seidl, A. Time, space, place, and the Bonn Challenge global forest restoration target. *Restor. Ecol.* **2017**, *25*, 903–911.
71. DellaSala, D.A.; Martin, A.; Spivak, R.; Schulke, T.; Bird, B.; Criley, M.; Van Daalen, C.; Kreilick, J.; Brown, R.; Aplet, G. A citizen's call for ecological forest restoration: Forest restoration principles and criteria. *Ecol. Restor.* **2003**, *21*, 14–23.