Improving the quality of automated VIS-grading of Scots pine seeds using fuzzy logic algorithm

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Abstract. The automation of Scots pine seeds grading in the visible wavelength region – VIS-grading – is promising for conducting breeding and genetic experiments. This will reduce time costs and increase the accuracy of seed color classification compared to organoleptic techniques. When controlling VIS-grading, it is necessary to accurately detect and process the optical signal reflected from a single seed. The signal is based on the wavelength and amplitude of the optical beam. Earlier, using a spectrometer for Scots pine seeds from a natural stand of the Pavlovsky district of the Voronezh region, Russia, the boundaries of three spectrometric groups were established. In the real VIS-grading process, it is necessary to take into account the probabilistic deviations of random values of wavelengths and amplitudes. Therefore, on the basis of the Mamdani fuzzy logic theory developed an analyzing algorithm for controlling the VIS-grading quality. The algorithm consists of a sequence of logical terms that clearly define the specified VIS-grading seeds spectrometric parameters by a combination of wavelength and amplitude. The efficiency of Scots pine seeds VIS-grading using the algorithm is 98.9%.

1. Introduction

Forests form the ecological framework of the Earth, performing the most important protective, water protection, climate control, biosphere, air purification and other environmental functions.

Increasing forest cover and expanding reforestation functions is an important measure for the production of oxygen and carbon deposition in forest ecosystems, as well as ensuring environmental, food and social security with sustainable management using specialized information systems. According to the global forest Resources assessment conducted by the Food and Agriculture Organization of the United Nations (FAO, Rome, Italy), “total forest area declined by 3 %, from 4,128 M ha in 1990 to 3,999 M ha in 2015 [1]”, and increased to 4,060 million hectares in 2020 [2]. The indicator of net loss of forest areas
decreased from 7.8; 5.2 to 4.7 million ha per year in the decades 1990-2000, 2000-2010 and 2010-2020, respectively [2].

Active human forestry activity leads to a sharp reduction in the forest area and biomass of forest stands. In Russia, according to official data, 1.2 million ha of forest are cut down annually, while more than 800 thousand ha are cut down illegally [3]. Forest fires also lead to a reduction in forest areas. According to the official data of the Unified Interdepartmental Information and Statistical System (EMISS), the area of forest land covered by fires in the Russian Federation was [4]: in 2009 – 2.57 million ha, in 2010-1.96 million ha, in 2011 – 1.37 million ha, in 2012 – 2.05 million ha, in 2013. - 1.16 million ha, in 2014-3.14 million ha, in 2015 – 2.75 million ha, in 2016 – 2.51 million ha, in 2017-3.28 million ha, in 2018-7.4 million ha, in 2019 – 8.68 million ha.

According to the concept of intensive use and reproduction of forests, “the use of methods of accelerated reforestation with the use of planting material and seed stock of improved qualities [5]”, will allow to diversify in a positive direction the standard methods of traditional reforestation [6]. Ensuring the ratio of the area of reforestation and afforestation to the area of felled and dead forest stands at the level of 100% in 2021-2024, provided for by the forest reproduction subprogram of the state program of the Russian Federation “Development of Forestry” for 2013-2020 (as amended by the decree of the Government of the Russian Federation No. 393 of March 31, 2020), will require the use of product innovation in the form of “technical modernization of works in the field of forest seed production, planting material cultivation and reforestation based primarily on, Russian forest engineering” [7].

A quick Google Scholar search for “reforestation” generates more than 1 million views, which are guaranteed to place this topic in the category of actively and widely discussed [8]. Given the lack of consensus on an unambiguous definition of the terms “forest” and “reforestation”, R K Domroese et al. [9] consider the terminological issue to be quite important. The term “restoration of forest landscapes” (FLR – Forest Landscape Restoration), as noted in the work of S Mansourian [10], is quite widely interpreted by researchers. Most of the restoration of ecological potential on Earth is mainly the restoration of forest ecosystems [11], which depends on the order of technological operations of restoration process, and therefore they cannot be separated from forestry, more specifically, from afforestation and reforestation.

Another question is the purpose of reforestation. What to restore? Is it necessary to restore the degraded forest to its original state (for example, composition and structure), as proposed [12], or is it necessary to make an “attempt to restore the ecosystem functions of the forest” [9]? Faced with the uncertainty of climate change, restoring the “baseline” at some historical level will be difficult. Therefore, the use of a promising approach to the use of technology for the restoration of forest functions at the landscape level is more logical.

The area for which there are potential applications of forest landscape restoration technology on a global scale is estimated by the experts of the Bonn Challenge (Washington, USA) at more than 2 billion ha [13]. An important aspect of the study is the amount of Forest Reproductive Material (FRM) required for reforestation programs. Indeed, there are a number of major initiatives, commitments, and ongoing programs for artificial reforestation and afforestation around the world. Haase and Davis [14] estimate that approximately 18.3 billion seedlings should be planted each year by 2030. It should be noted here that this calculation is based on a very conservative target density of only 500 seedlings per ha, which is significantly lower than the more common planting density in reforestation programs, which is between 2,000 and 3,000 seedlings per ha.

To ensure the specified number of seedlings, it is necessary to produce seeds that are improved physiologically [15] and genetically. The technological process of improving the quality of seeds by separation should provide a given supply of conditioned seeds at the output, suitable for both seeding and storage. In particular, the seeds coat color is an important hereditary indicator for conducting genetic experiments. Until now, grading of seeds by color has been carried out by the organoleptic method. This method has a low accuracy due to the peculiarities of the human eye structure. The seed coat color is characterized by spectrometric properties in the visible optical region (VIS). To improve the quality of Scots pine seeds grading in the visible wavelength region (VIS-grading), it is advisable to use an
optoelectronic grader. The accuracy of getting seeds into the group on a spectrometric basis directly depends on the integration and alignment of the optoelectronic and mechatronic grader systems.

In an optoelectronic grader, three processes are carried out with respect to forest seeds: orientation, detection and calibration. Orientation provides a uniform supply of forest seeds one by one for subsequent detection. When designing orienting devices, it is necessary to take into account the theoretical positions of the flow of bulk objects from the hopper holes, robotic seed feeding and the use of air, water, electromagnetic media to change the kinetic energy reserve of the seed. The detection provides a fast digital analysis of forest seeds in time according to the spectrometric criterion [16] using optoelectronic sensors. At the same time, non-destructive testing of the shape, dimensions, as well as changes in seeds thermal properties are possible.

An optical beam with a given wavelength (in our case, 700 nm) generated by a light source is focused at an angle of 45 degrees on the seed. The beam diffusely reflected from the seed is focused on the photodetector. According to the amplitude \( A \) of the optical beam, the control system outputs a control signal for seed calibration. The optoelectronic system includes an optical radiation generation unit, a reflected radiation receiver unit, and closely interacts at the analog signal level with an electronic control unit [16]. The electronic control unit includes a multiplexer, Analog-to-Digital Converter (ADC), and microprocessor. The electronic control unit receives optical measurement signals from the photodetectors, summarizes them in the multiplexer, and transmits them via the ADC [17] to the microprocessor. The microprocessor processes the signals using fuzzy logic methods and transmits the control signal to the actuators of the mechatronic calibration system. Depending on the grading algorithm, the actuators change the trajectory of a single seed, directing it to the appropriate seed receiver.

In the real process of Scots pine seeds VIS-grading, it is necessary to take into account the probabilistic deviations of random values of wavelength \( \lambda \) and amplitude \( A \). Therefore, the aim of the study is to develop a VIS-grading fuzzy logic algorithm, and evaluation of its effectiveness.

2. Material and methods
A seedlot \((m = 1 \text{ kg})\) of Scots pine, obtained from cones collected in 2019 in a natural tree stand (Pavlovsky district, Voronezh Region, Russia), was taken from the breeding and seed-growing center. Pretreatment (extraction from cones, desquamation, cleaning and gravity sorting) of seeds was carried out according to the standard method on the equipment of BCC AB (Sweden). 5 samples \((m = 50 \text{ g})\) were randomly selected from the seedlot, in each of which three spectrometric groups of 100 seeds were visually selected: dark (D), light-dark (LD) and light (L). Previously, for seeds of similar color groups from the same stand, the values of the amplitude \( A \) and reflection coefficient \( R \) of the light beam [18], presented in table 1, were established for a wavelength of 700 nm using a VIS spectrometer.

| Spectrometric group | Wavelength, nm | Radiation amplitude \( A \) | Reflection coefficient \( R \) |
|---------------------|----------------|----------------------------|----------------------------|
| (D)                 | 700            | 55-65 %                    | 0.1549-0.0706              |
| (LD)                | 700            | 35-50 %                    | 0.5229-0.3468              |
| (L)                 | 700            | 18-30 %                    | 0.3010-0.1871              |

Table 1. Detection criteria for the Scots pine seeds VIS-grading.

Then, based on the fuzzy logic theory of Mamdani, we derived a VIS-grading algorithm for loading it into the optoelectronic grader microprocessor, using the following steps [19-20]:

1) fuzzification – the stage of "introducing fuzziness", the process of obtaining the value of the membership function \( \mu_{A_i}(x_j) \) of the fuzzy set \( A_i \), corresponding to the value of the \( j \)-th input variable \( x_j \) in the premise of the \( i \)-th fuzzy production rule \((i = 1, 2, ..., m; j = 1, 2, ..., n)\);

2) aggregation – the process of determining the degree of truth of a condition (antecedent) \( A_i \) in each \( i \)-th rule \((i = 1, 2, ..., m)\). The algorithm of Mamdani fuzzy inference the degree of truth of the antecedent, \( A_i \) the \( i \)-th rule is determined by operations min-conjunction for all fuzzy statements "\( x_j \) is \( A_{ij} \): \( A_i = \min (\mu_{A_{i1}}(x_1), \mu_{A_{i2}}(x_2), ..., \mu_{A_{im}}(x_m) ; f(i = 1, 2, ..., m; j = 1, 2, ..., n)\);"
3) activation – the process of determining the modified membership functions \( \mu_{Bi}(y) \) of the output variable \( y \) in the conclusion (consequent) of each \( i \)-th rule. In the Mamdani algorithm, the modification of the functions \( \mu_a(y) \) of the output variable \( y \) is carried out on the basis of min-activation: \( \mu_{Bi}(y) = \min (\mu_i, \mu_{Bi}(y)) \) \((i = 1, 2, ..., m)\); 

4) accumulation – the process of determining the resulting membership function \( \mu_{Bi}(y) \) of the output variable \( y \) by combining (max-disjunction) modified fuzzy sets \( B_i \) for each \( i \)-th rule \((i = 1, 2, ..., m)\). In the Mamdani algorithm, the process of combining the membership functions \( \mu_{Bi}(y) \) of the output variable \( y \) for each \( i \)-th rule of the NPS is performed using the max-disjunction operation: \( \mu_{Bi}(y) = \max (\mu_{Bi}(y); \mu_{Bi+1}(y); \mu_{Bi+2}(y); ...; \mu_{Bm}(y)) \) \((i = 1, 2, ..., m)\); 

5) defuzzification – the stage of “bringing to clarity” or the process of determining a clear value of the output variable \( y \).

Having loaded the VIS-grading algorithm into the microprocessor of the laboratory installation, a grading cycle was performed for 5 samples \((n = 1500)\) of Scots pine seeds into three spectrometric groups. After each grading cycle, the efficiency \( E(\%) \) of grading seeds of the corresponding spectrometric group was visually determined.

3. Results and discussion

The synthesis of a fuzzy logic algorithm for seed analysis is illustrated by the example of Scots pine seeds VIS-grading. In general, the algorithm composition results that determine the correspondence of the seed parameters to the characteristics of the optical beam are shown in table 2.

To implement the formal logical construction of the VIS-grading algorithm, table 2 reflects the principle of correspondence of the spectrometric characteristics of seeds to their qualitative phenotype: if, at the wavelength of the reflected optical beam \( \lambda_i \), the amplitude of this flow is within \((A_{k} - A_{k+1})\%\), where \( A\% \) is the percentage of the reflected beam, then the quality of grading of the seed will correspond to some attribute (or D, or LD, or L) used as an output logical variable. The physical meaning of these features is given in table 1.

For the possibility of implementing a formal logical construction of the algorithm, the designations of the output logical variables used in the description of the algorithm are additionally given in parentheses [1]: \((D, LD, L)\), where D is the spectrometric group III-T, \( R = 0.1549-0.0706 \); LD is the spectrometric group II-CT, \( R = 0.5229-0.3468 \); L-spectrometric group I-C, \( R = 0.3010-0.1871 \), for the visible region 650-715 nm.

### Table 2. Output logical variables of the VIS-grading algorithm for Scots pine seeds to construct fuzzy set accessary functions \( \mu(x) \).

| Wavelength, nm | Radiation amplitude | Detection seed spectrometric group |
|----------------|---------------------|-----------------------------------|
| \( \lambda_{ni} \) | \( A_1 - A_2 \) % | (D) |
| \( \lambda_{ni-2} \) | \( A_3 - A_4 \) % | (LD) |
| \( \lambda_{ni-3} \) | \( A_5 - A_6 \) % | (L) |

The construction of the VIS-grading algorithm was performed as follows. As an accessory function \((AF) \mu(\lambda_i)\) for a fuzzy set of wavelength values is advisable to use “triangular” (or Gaussian) AF, and as an accessory function \( \mu(A_1, A_2, A_3) \) for a fuzzy set of amplitude values, based on the data in table 2, “trapezoidal” AF (figure 1):

**Figure 1.** Trapezoidal accessory function to form a fuzzy set for detecting seeds by the optical beam amplitude.
\[
\mu(A, A_i, A_{i+1}) = \begin{cases} 
0, & \text{if } A < a_i, \\
\frac{A-a_i}{A_i-a_i}, & \text{if } a_i < A \leq A_i, \\
1, & \text{if } A_i < A \leq A_{i+1}, \\
\frac{a_{i+1}-A}{a_{i+1}-a_{i+1}}, & \text{if } A_{i+1} < A \leq a_{i+1}, \\
0, & \text{if } A > a_{i+1}, 
\end{cases}
\]

Using further the structure of the Mamdani fuzzy logic output and the data in table 2, we obtain the VIS-grading algorithm, the block diagram of which is shown in figure 2.

1. If \( \mu(\lambda_{N+1}) \cap \mu(A, A_i, A_2) \), that \((D)\).
2. If \( \mu(\lambda_{N+2}) \cap \mu(A, A_1, A_3) \), that \((LD)\).
3. If \( \mu(\lambda_{N+3}) \cap \mu(A, A_3, A_6) \), that \((L)\).

**Figure 2.** Block diagram of the analyzing algorithm for VIS-grading quality control of Scots pine seeds.

Here, when implementing the operation of fuzzy-logical disjunction [19,21], the Mamdani (Zade) variant is also used:

\[
\mu(\lambda_i) \cup \mu(A, A_0) = \max\{\mu(\lambda_i), \mu(A, A_0)\}.
\]

After determining the numerical values of the output variables \((D)\), \((LD)\), \((L)\), the final conclusion about whether \(P\) belongs to a particular seed spectrometric group is made on the basis of the right modal defuzzification algorithm:

\[
P = \max\{D, LD, L\},
\]

The evaluation of the effectiveness of the obtained VIS-grading algorithm (2) using the accessory function shown in figure 1 was considered on the example of Scots pine seeds VIS-grading, the results of which according to the technique described above, as well as in [16], are shown in table 3.

According to table 1, when programming the grader microprocessor, the following values were assigned to the logical variable \(A\): \(A_0=60, A_1=55, A_2=65, A_3=35, A_4=50, A_5=18, A_6=30\). The values of the measurement errors of the wavelength \(\varepsilon\) and the amplitude \(\rho\) of the optical beam were determined by the parameters of the detecting system’s sensors and were chosen equal, respectively: \(\varepsilon = 4\ \text{nm}, \rho = 3\%\).
Table 3. Experimental degree (in %) of Scots pine seeds samples grading for spectrometric groups using the developed VIS-grading algorithm.

| Sample number | Spectrometric groups |
|---------------|----------------------|
|               | (D)  | (LD) | (L)  |
| 1             | 100  | 99   | 100  |
| 2             | 98   | 100  | 99   |
| 3             | 97   | 98   | 98   |
| 4             | 99   | 99   | 100  |
| 5             | 99   | 99   | 98   |
| Mean ±SD      | 98.60±1.02 | 99.00±0.63 | 98.87±0.85 |

The results of experiments conducted on samples of Scots pine seeds (n = 1500) showed that the grading efficiency using VIS-grading algorithm is 98.9%. The highest degree of grading is observed in the (LD) spectrometric group of seeds and is characterized by the smallest variation of the variant, the lowest – in the (D) spectrometric group, which is explained by the features of diffuse reflection and large values of the absorption of the optical flux by the dark seed.

Many researchers divided the seeds of Scots pine by the color of the seed coat, studying the color dynamics depending on the location in the cone, on the tree, the germination of seedlings and the growth of seedlings in the field, but the separation method was not automated and was carried out organoleptically. Therefore, it is extremely difficult to adequately compare the results obtained with previously known ones. However, it can be argued that the qualitative phenotype of Scots pine-the color of the seeds, has a certain influence on the genotype of future seedlings. It is necessary to continue studying the spectrometric properties of seeds in the visible range on the basis of creating a data bank and conducting a meta-analysis on the effect of VIS-grading of seeds on the genetic quality of seedlings throughout the growing area.

4. Conclusion

Automated VIS-grading has a long-term perspective for conducting breeding and genetic experiments. This will significantly reduce the time spent and increase the accuracy of color classification compared to the organoleptic technique. The fuzzy logic VIS-grading algorithm demonstrates an efficiency of 98.9% for seeds of a specific trees and a specific provenance. It is possible to further improve the accuracy and quality of the algorithm by improving the design of the grader’s optoelectronic elements.

References

[1] Keenan R J, Reams G A, Achard F, de Freitas J V., Grainger A and Lindquist E 2015 Dynamics of global forest area: Results from the FAO Global Forest Resources Assessment 2015. Forest Ecol. Manag. 352 9 http://dx.doi.org/10.1016/j.foreco.2015.06.014
[2] FAO 2020 Global Forest Resources Assessment 2020 (Rome: Food and Agriculture Organization of the United Nations) p 184 https://doi.org/10.4060/ca9825en
[3] ITAR-TASS 2013 Prosecutor General’s Office: 800 thousand hectares of forest are illegally cut down in the Russian Federation per year, available at: https://rg.ru/2013/10/29/les-anons.html
[4] EMISS 2020 Forest land area covered by fires Federal Forestry Agency of the Russian Federation, available at: https://fedstat.ru/indicator/38496?id=38496
[5] SPBNIILH 2015 Concept of intensive use and reproduction of forests, available at: http://www.spb-niilh.ru/pdf/Rosleshoz_booklet.pdf
[6] Morkovina S S, Drapalyuk M V and Baranova E V 2015 Innovative technologies in forest culture: reality and prospects. Forestry Engineering Journal 5 316 http://dx.doi.org/10.12737/14181
[7] Burtsev D S 2014 Prospects for the innovative products creating in the reforestation. Proceedings of the St. Petersburg Scientific Research Institute of Forestry 3 6 [in Russian]
[8] Ivetić V and Novikov A I 2019 The role of forest reproductive material quality in forest restoration. Forestry Engineering Journal 9 56 http://dx.doi.org/10.34220/issn.2222-
[9] Kasten Dumroese R, Palik B J and Stanturf J A 2015 Forest restoration is forward thinking. *J. Forest.* 113 430. http://dx.doi.org/10.5849/jof.15-049

[10] Mansourian S 2018 In the eye of the beholder: Reconciling interpretations of forest landscape restoration. *Land Degrad. Dev.* 29 2888. http://dx.doi.org/10.1002/ldr.3014

[11] Löf M, Madsen P, Metslaid M, Witzell J and Jacobs D F 2019 Restoring forests: regeneration and ecosystem function for the future. *New Forest.* 50 139. http://dx.doi.org/10.1007/s11056-019-09713-0

[12] FAO Forest Restoration and Rehabilitation, available at: http://www.fao.org/sustainable-forest-management/toolbox/modules/forest-restoration-and-rehabilitation/basic-knowledge/en/

[13] IUCN A guide to the Restoration Opportunities Assessment Methodology (ROAM): Assessing forest landscape restoration opportunities at the national or sub-national level (Gland, Switzerland: International Union for Conservation of Nature and Natural Resources) available at: https://portals.iucn.org/library/sites/library/files/documents/2014-030.pdf

[14] 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 69. http://dx.doi.org/10.21750/refor.4.06.45

[15] Erickson V J and Halford A 2020 Seed planning, sourcing, and procurement restoration ecology. *Restor. Ecol.* 28 216. http://dx.doi.org/10.1111/rec.13199

[16] Novikov A, Lisitsyn V, Tigabu M, Tylek P and Chuchupal S 2021 Detection of Scots pine single seed in optoelectronic system of mobile grader: mathematical modeling. *Forests.* 12 240. http://dx.doi.org/10.3390/f12020240

[17] Sokolov S V, Kamenskij V V, Novikov A I and Ivetić V 2019 How to increase the analog-to-digital converter speed in optoelectronic systems of the seed quality rapid analyzer. *Inventions.* 4 61. http://dx.doi.org/10.3390/inventions4040061

[18] Novikov A I 2019 Visible wave spectrometric features of Scots pine seeds: the basis for designing a rapid analyzer. *IOP Conf. Ser. Earth. Environ. Sci.* 226 012064. http://dx.doi.org/10.1088/1755-1315/226/1/012064.

[19] Averkin A N, Batyrshin I Z, Blishun A F, Silov V B and Tarasov V B 1986 *Fuzzy sets in management models and artificial intelligence* (Moscow: Nauka) pp 347 [in Russian]

[20] Gorodetsky A E, Erofeev A A and Zhukov A Y 2000 Fuzzy control technology in optoelectronic systems. *Proceedings of the International Conference "Intelligent Systems and Information Technologies in Control"* (Pskov, Russia) [in Russian]

[21] Ulyanov S V, Tyatyushkina O Y and Kolbenko E V 2011 Fuzzy models of intelligent industrial controllers and control systems. *Electronic Journal “System Analysis in Science and Education.”* 2 23 [in Russian]