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RESEARCH ARTICLE

Reforestation pipeline: case for quality management of NIR-region grading of Scots pine seeds and FLR-algorithm for information processing

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Abstract
When controlling the process of improving the quality of seeds by separating on a spectrometric basis, the primary information about the state of Scots pine seeds is carried by the wavelengths of optical fluxes and their amplitudes. The algorithm for analyzing the required characteristics of small forest seeds in the infrared range is a corresponding sequence of logical terms that provide the ability to determine the specified seed parameters by a combination of spectral frequencies and light flux amplitudes taken from the corresponding photodetectors. At $\Delta C = 0.5$, the efficiency of the algorithm was 77.6 %, and at $\Delta C = 0.9$, respectively, 99.5 %. In this regard, the choice of ΔC is the result of a compromise between the cost of rejection of high-quality seeds and losses when using unrecognized low-quality seeds and it is made according to the results of relevant experiments.

Keywords
Forest landscape restoration; Scots pine, *Pinus sylvestris* L.; seed grading, NIR-region; fuzzy logic

Introduction

Bringing the Scots pine (*Pinus sylvestris* L.) seeds to the sowing condition – improvement of qualitative properties (Ivetic, Novikov, 2019; Afzal et al., 2020) in climatic projects (Andivia et al., 2021) of forest landscapes restoration (Novikova, 2022) – includes the grading task (Drapalyuk, Novikov, 2018; Kaliniewicz, Tylek, 2019), based on the optical features of the seed coat (Novikov et al., 2019; Bernardes et al., 2022). Scots pine (*P. sylvestris* L.) climatic types, as a rule, characterized by different spectrometric properties of seeds, demonstrate different mechanical qualities of wood (Rabko et al., 2021). Optical grading (Sokolov, Novikov, 2019) Scots pine (*P. sylvestris* L.) seeds to varying degrees affects the ontogenesis of juvenile crops on the field (Novikov et al., 2019; Petrishchev, 2021; Novikova et al., 2023a), container nursery (Nosnikau et al., 2020) and seed orchards (Dutkuner et al., 2008) can be the basis for seeds priming (Singh et al., 2020) during sowing (Kazakov et al., 2019) and part of a machine complex (Tsypouk et al., 2021) for reforestation. The optoelectronic (Sokolov et al., 2019) sensing elements that make up the core of the diagnostic system must have a certain accuracy in detecting (Novikov et al., 2021a) absorbed radiation, and must provide a timely signal to the mechatronic (Shafaei et al., 2020; Tylek et al., 2020) elements of the seed grader.

To solve this problem, an optoelectronic device was developed consisting of an optical emitter, photodetectors of reflected and transmission radiation, and an electronic information processing unit containing a microprocessor. To process the information received from photodetectors, fuzzy logic algorithms are implemented in the microprocessor, according to the results of which a control signal is generated, which enters the actuators of the calibration system. The actuators, in turn, form the appropriate trajectory of the seed movement, directing it to a given seed receiver.

Due to the fact that the carriers of the initial information about the quality of seeds are the wavelengths of optical streams and their amplitudes measured with certain errors, it is necessary to use fuzzy logic methods to synthesize an algorithm for processing such information. In this case, the algorithm for analyzing the characteristics of forest seeds will be a corresponding sequence of logical rules and terms described in detail below.

The aim of the study is to develop a fuzzy logic algorithm for grading Scots pine seeds, taking into account the intensity of absorption of optical radiation by the seed surface in the near infrared (NIR) region.

Materials and methods

The construction of the desired algorithm for information processing and quality management of grading Scots pine seeds in the infrared region was carried out by analogy with the VIS-grading algorithm (Novikov et al., 2021b), using the classical fuzzy logic sequence "Mamdani" (Tabakov et al., 2021; Mohammed, Hussain, 2021; Fayaz et al., 2019).

Firstly, the fuzzification of the membership function (MF) $\Xi_{P\alpha\beta}(z_\beta)$ from each (β = 1, 2, ..., ω) detectable variant of z_β (input signal from the photodetector of the grader system) was performed on the basis of (α = 1, 2, .., ψ) fuzzy production rules organized into sets $P_{\alpha\beta}$.

Secondly, aggregation of the set of production rules of the algorithm for information processing and quality management of grading Scots pine seeds in the infrared range was carried out with the setting in each (α = 1, 2, ..., ψ) rule for the statement "variant z_β belongs to the set of grading $P_{\alpha\beta}$" of the truth level of the antecedent pa from the condition of the minimum operation of the MF-conjunction $\Xi_{P\alpha\beta}(z_\beta)$:

$$p_\alpha = \min_{\substack{\alpha = 1,2,\dots,\psi \\ \beta = 1,2,\dots,\omega}} \begin{cases} \Xi_{P_{\alpha 1}}(z_1); \\ \Xi_{P_{\alpha 2}}(z_2); \\ \Xi_{P_{\alpha\beta}}(z_\beta); \\ \dots \\ \Xi_{P_{\alpha\omega}}(z_\omega). \end{cases}$$

Thirdly, the modification of the MF $\Xi_{Q\alpha}(q)$ of the output variant q (the signal of the control action on the elements of the mechatronic grader system) to the $\Xi_{Q'\alpha}(q)$ was made proceeding from the condition of the minimum operation of activating the consequent of (α = 1, 2, .., ψ) fuzzy production rules:

$$\Xi_{Q'_\alpha}(q) = \min_{\alpha = 1,2,\dots,\psi} \left[p_\alpha; \Xi_{Q_\alpha}(q)\right].$$

Fourthly, the accumulation of the activated set , the resulting MF was carried out using the maximum function that implements the operation of fuzzy disjunction for each (α = 1, 2, .., ψ) rule:

$$\Xi_\Sigma(q) = \max_{\alpha = 1,2,\dots,\psi} \begin{cases} \Xi_{Q'_1}(q); \\ \Xi_{Q'_2}(q); \\ \Xi_{Q'_\alpha}(q); \\ \dots \\ \Xi_{Q'_\psi}(q). \end{cases}$$

Fifthly, the defuzzification of the resulting set of to determine the output version of q (the signal of the control action on the elements of the mechatronic grader system) was implemented on the basis of the classical center of gravity method.

Results and discussion

Taking into account the above-mentioned inevitability of recording frequencies and amplitudes of optical flows with certain errors and, in accordance with this, the need to use fuzzy logic methods, we will consider the possibility of seed separation based on the above algorithm of fuzzy logic inference of Mamdani.

Let us consider the case of seed separation in the infrared region. The correspondence of the optical parameters of ordinary pine seeds to the characteristics of the optical beam is given in table 1 (in parentheses in the table are the designations of the output logical variables used in the implementation of the algorithm). For the possibility of implementing a formal logical construction of the algorithm, the tables additionally contain in parentheses the designations of the output logical variables used in the description of the algorithm: (C, C_1), when C is condition seeds, 1-V; C_1 is non condition seeds, 2-NVP and 3-NVE.

Table 1. Correspondence of seed parameters to the optical beam during separation in the NIR-region

Wavelength, nm	Radiation amplitude	Detection options
λ_1	A_0 % and more	Not Condition (C_1)
	less than A_0 %	Condition (C)
λ_2	A_0 % and more	Not Condition (C_1)
	less than A_0 %	Condition (C)
…		
λ_k	A_0 % and more	Not Condition (C_1)
	less than A_0 %	Condition (C)
λ_{k+1}	A_0 % and more	Condition (C)
	less than A_0 %	Not Condition (C_1)
…		
λ_{N+1}	A_0 % and more	Condition (C)
	less than A_0 %	Not Condition (C_1)
λ_N	A_0 % and more	Condition (C)
	less than A_0 %	Not Condition (C_1)

Let us consider the conclusion of the seed separation algorithm based on the qualitative composition. Due to the fact that in real operating conditions, variables λ, A can be determined only with a certain error: $\Delta\lambda = \pm\varepsilon$ nm, $\Delta A = \pm\rho$ %, to describe them, it is necessary to involve the apparatus of fuzzy logic.

In this case, all the logical variables listed in table 1 can be described, based on their physical meaning , by the MF presented in Figs 1–5. Here , in order to avoid complicating calculations, it is advisable to use "triangular" functions (Fig. 1):

$$\mu(\lambda_i) = \begin{cases} 0, if\ \lambda < a_i, \\ \dfrac{\lambda - a_i}{\lambda_i - a_i}, if\ \ a_i < \lambda \le \lambda_i, \lambda_i = a_i + \varepsilon = b_i - \varepsilon \\ \dfrac{b_i - \lambda}{b_i - \lambda_{i+1}}, if\ \ \lambda_i < \lambda \le b_i, \\ 0, if \lambda > b_i \end{cases}$$

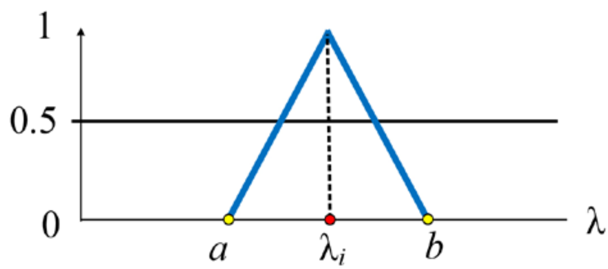

Figure 1. Triangular MF

or "Gaussian" functions with a large spread of parameters of the optoelectronic separating device (Fig. 2):

$$\mu(\lambda_i) = \ \exp\left[-\frac{(x-a)^2}{2b^2}\right];$$
$$3b_i = \varepsilon, a_i = \lambda_i.$$

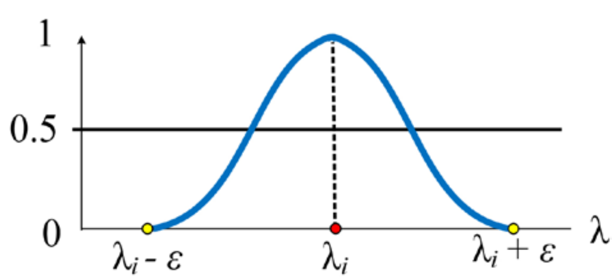

Figure 2. Gaussian MF

To describe the membership functions that characterize the process of seed detection in the infrared range for the 1....*k*-th wavelength (table 1), based on its physical meaning, you can use the "threshold" functions of the form (Fig. 3):

$$\mu(A, A_0) = \begin{cases} 0, if\ A \leq a_0 \\ \dfrac{A - a_0}{A_0 - a_0}, if\ \ a_0 < A \leq A_0, A_0 = a_0 + \rho \\ 1, if A > A_0 \end{cases}$$

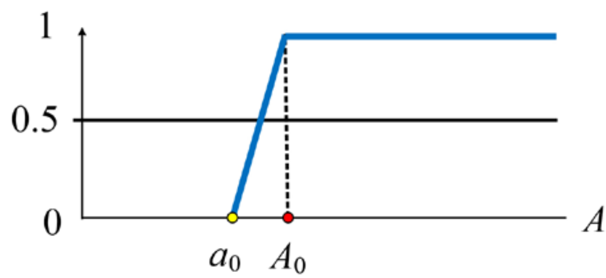

Figure 3. Threshold MF

Otherwise, one may apply those with a large spread of the parameters of the diagnostic system of the separating device, “more blurred” functions of the form (Fig. 4):

$$(A, A_0) = \begin{cases} 0, if\ A \leq A_0 \\ \left(1 + \left(\dfrac{A - A_0}{0.1A_0}\right)^{-2}\right)^{-1}, if\ \ A_0 < A \leq 100 \end{cases}$$

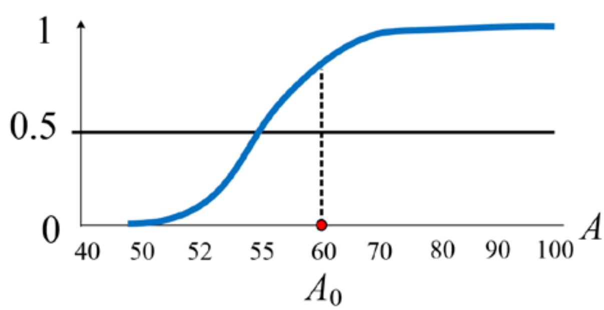

Figure 4. “Blurred” threshold MF (A_0=60)

$$\mu(A, A_0) = \begin{cases} 1, if\ A \leq A_0 \\ \dfrac{a_0 - A}{a_0 - A_0}, if\ \ A_0 < A \leq a_0, A_0 = a_0 - \rho \\ 0, if A > a_0 \end{cases}$$

Accordingly, to describe the membership functions that characterize the detection process for the (k+1) ... N-th wavelength (table 1), you can use "inverse threshold" functions of the form (Fig. 5):

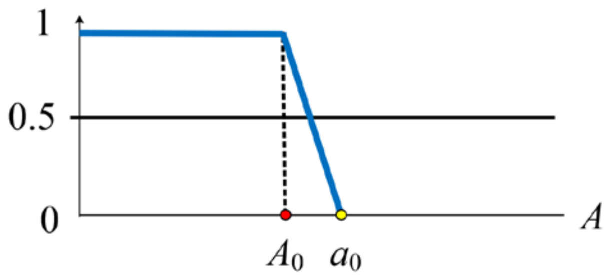

Figure 5. Inverse MF

In a different way, one may use them with a large variation in the parameters of the diagnostic system of the separating device:

$$\mu(A, A_0) = \begin{cases} 1, if\ A \leq A_0 \\ \left(1 - \left(1 + \dfrac{A - A_0}{0.1A_0}\right)^{-2}\right)^{-1}, if\ A_0 < A \leq 100 \end{cases}$$

Setting the MF-functions of all variables allows you to go directly to the construction of the separation algorithm in the infrared wavelength range (according to the qualitative composition). To do this, we use the structure of logical inference further according to the Mamdani scheme (Mamdani, 1974). When executing the Mamdani fuzzy inference algorithm, the base of production rules is generally represented by a multi-in, single-out (MISO) structure, which generally looks like (Mohammed, Hussain, 2021):

Rule *1*: IF x_1 is A_{11} AND x_2 is A_{12} AND..AND x_n is A_{1n}, THEN y is B_1;
Rule *2*: IF x_1 is A_{21} AND x_2 is A_{22} AND..AND x_n is A_{2n}, THEN y is B_2;
…
Rule *i*: IF x_1 is A_{i1} AND x_2 is A_{i2} AND.. AND x_n is A_{in}, THEN y is B_i;
…
Rule *m*: IF x_1 is A_{ml} AND x_2 is A_{m2} AND.. AND x_m is A_{mn}, THEN y is B_m,

when $x_1, x_2,.., x_n$ are n input variables of a Fuzzy Production System (FPS); A_{ij} is the ij-th term of the j-th input variable xj in the i-th rule, represented by a fuzzy set with the corresponding membership function $\mu_{Aij}(x_j)$(i = 1,2, ..,m; j = 1,2,..,n); y is an output variable of FPS; B_i is the term of the output variable y in the i-th rule, represented by a fuzzy set with the corresponding membership function $\mu_{Bi}(y)$ (i = 1,2,..,m).

The first stage of the Mamdani algorithm was implemented above in the synthesis of the FP of logical variables (Figs 1-5). Based on the analysis of the states of the output variable C (C_1) shown in table 1, the implementation of steps 2-4 (see M&M Sections) leads to the construction of the following fuzzy logic analyzing algorithm, the block diagram of which is shown in Fig. 6:4

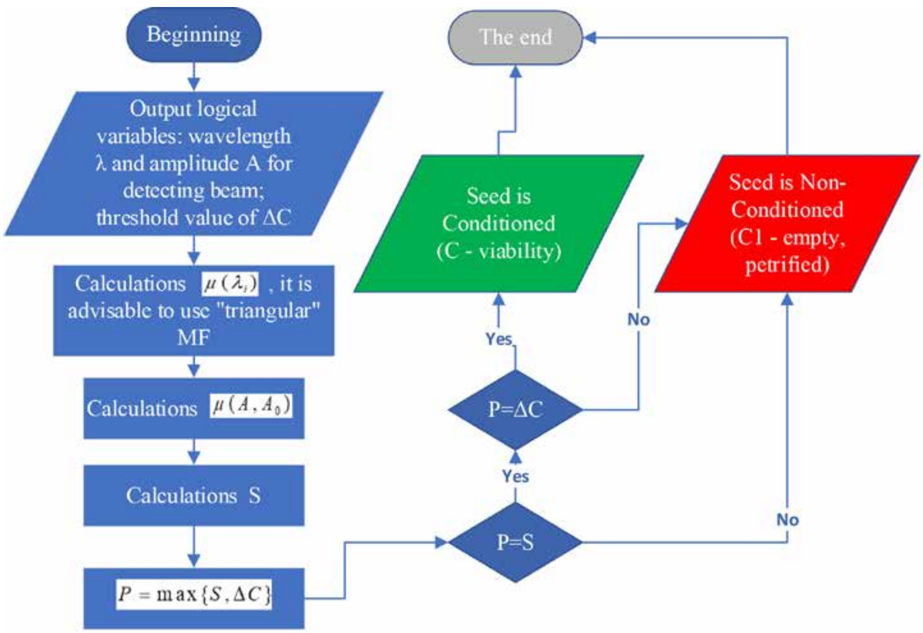

Figure 6. Block diagram of the analyzing algorithm for quality control of the separation of Scots pine seeds in the infrared wavelength region

$$IF\ (\mu(\lambda_1)\cap\mu(A,A_0))\cap(\mu(\lambda_2)\cap\mu(A,A_0))\cap\ldots\cap(\mu(\lambda_k)\cap\mu(A,A_0))\cap(\mu(\lambda_{k+1})\cap\bar{\mu}(A,A_0))\cap$$
$$\cap\ldots\cap(\bar{\mu}(\lambda_{N-1})\cap\mu(A,A_0))\cap(\mu(\lambda_N)\cap\bar{\mu}(A,A_0)), THEN\ \boldsymbol{S}. \quad (1)$$

Here, when implementing the operation of a fuzzy-logical conjunction, for which there are currently several definitions, the Mamdani (Zade) variant is used:

$$\mu(\lambda_i)\cap\mu(A,A_0) = min\{\mu(\lambda_i)\cap\mu(A,A_0)\}. \quad (2)$$

After calculating the algorithm (1) using the operation (2), the value of the variable *S* is calculated, which is then defuzzified by the right modal value together with the specified threshold value of ΔC:

$$\mu(\lambda_i)\cap\mu(A,A_0) = min\{\mu(\lambda_i)\cap\mu(A,A_0)\}.$$

According to the results of defuzzification, at P = S, a decision is made on the state C_1 – "Not Conditioned", at P = ΔC, respectively, C – "Conditioned". A numerical simulation of the algorithm (1), confirming its computational efficiency, is given below.

The peculiarity of this algorithm, as shown by the results of the numerical experiment, is the dependence of its efficiency on the selected threshold ΔC:

– at low values (about 0.5), the proportion of unrecognized low-quality seeds increases;

– at values close to 1, the efficiency is reduced due to the rejection of high-quality seeds because of errors in determining the wavelength of the received radiation and the amplitude of the light.

The evaluation of the grading algorithm (see Fig. 6) efficiency included in the reforestation algorithm (Novikova, 2022a, 2022b) is considered by the example of the analysis of the Scots pine (*P. sylvestris* L.) seeds, the spectral study results of which are shown in table 2.

Table 2. Detection options for the separation of Scots pine seeds by the spectrometric feature in the infrared wavelength region

Wavelength, nm	Radiation amplitude	Detection options
970	60 % and more	Not Condition (C_1)
	less than 60 %	Condition (C)
1196	60 % and more	Not Condition (C_1)
	less than 60 %	Condition (C)
1390	60 % and more	Condition (C)
	less than 60 %	Not Condition (C_1)
1878	60 % and more	Condition (C)
	less than 60 %	Not Condition (C_1)

The results of the experiments conducted on seed samples (n = 1000) showed that the efficiency of the separation of Scots pine seeds in the infrared range using the developed algorithm significantly depends on the selected threshold value of the ΔC output variable.

Conclusion

A stochastic model for controlling the grading process of Scots pine (*P. sylvestris* L.) seeds in the infrared wavelength range, taking into account the probabilistic deviations of random values of wavelengths and the amplitude of the optical flow, is the basis for the synthesis of the analyzing algorithm.

So, at ΔC = 0.5, the efficiency of the algorithm was 77.6%, and at ΔC = 0.9, respectively, 99.5 %. In this regard, the choice of ΔC is the result of a compromise between the cost of rejection of high-quality seeds and losses when using unrecognized low-quality seeds and it is made according to the results of the appropriate experiments.

Let us note that these results of the algorithm implementation are valid within the boundaries of seeds from this location. The universalization of the NIR classification algorithm for the Scots pine (*P. sylvestris* L.) seeds for any provenance and its practical use will occur as a result of the accumulation of a sufficiently large amount of data (Novikova et al., 2023b) on the seeds spectrometric features.

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