

How Germination Changes During Individual Seed RGB-Space Differentiation: The Case of *Pinus sylvestris* L. cv. Negorelskaya

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Article

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Abstract

To watch the growth of 1200 *P. sylvestris* cv. Negorelskaya trees from seeds to young or even old stage is a big grant project. We want to make a «seed–culture» passport. Each individual seed ($N = 1200$) was weighed, and image acquisition via a flatbed scanner in the VIS wavelength region and seeded into an individual 120 cm^3 cell of a 40-cell container. On day 30, container-grown germination was evaluated according to the following dichotomous criterion: 1 – germinated ($n_1 = 942$), 0 – did not germinate ($n_0 = 258$), and 0-group and 1-group datasets were formed. The RGB space color of the individual seed epidermis between the 0- and the 1-group were compared via the Kolmogorov–Smirnov criterion D. The lower individual weight of the seed in the 0-group compared with the 1-group was not accidental ($p = 0.0045$). Additionally, in the 0 group, the median values of R, G, and B brightness of pixels from individual seeds are not accidental ($p = 0.0000381$) compared with those of the 1 group. Therefore, in this experiment, seeds that reflected most of the light from the epidermis showed a lower germination when placed in the container.

1. Introduction

The success of forest plantations, like protective forest strips ^{1,2} or field shelterbelts ³, or seed orchards ^{4,5}, depends on how well the trees used can handle biotic (living) and abiotic (non-living) environmental factors. In turn, these characteristics are determined at the genetic level and determine the quality ⁶ of Forest Reproductive Material (FRM). As rightly noted, Clara Tattoni et al. ⁷ from the DAGRI: “*Accurate estimates of forest seed production are central for a wide range of ecological studies*”⁷. The productivity of forest crops can be improved through breeding tests.

The main purpose of the entire funded study was to track, evaluate, and analyze the individual reproduction cycles of 1,200 plants of *Pinus sylvestris* L. cv. Negorelskaya. We have created a «seed-culture» technological passport, starting from the datasets of the spectral and germination properties of each seed.

A *P. sylvestris* cv. Negorelskaya is a breeding cultivar ⁸ characterized by intensive growth and early abundant seed production (up to 15%). All other things being equal, it's going to come down to the seeds quality ^{9,10}. The better the seeds ¹¹, the better the plants. And the seedlings quality ¹² is closely linked to its seeds physical properties: seeds weights (or mass), seeds size ¹³, seeds color – seed visible features ^{13–16}, seed infrared features ^{17–19}, seed immersion features ²⁰, seed irradiation features ²¹, seed conditioned features ²². All these studies were conducted on group seed samples. For example, weight was determined for 1,000 seeds, color characteristics were evaluated for 100 seeds, and seed germination was calculated for another 100 seeds.

The individual mass of each seed and its individual visual spectral characteristics (seed coat color ^{23–26}, seed epidermis color, or pericarp color ¹⁷) are important indicators of seeds quality. The first result,

according to Professor John A. Stanturf, is quite well known. The second result is interesting and may have some significance for quick seed sorting²⁷. Seeds quality criteria²⁸ are also taken into account when designing seeds hoppers²⁹, feeders³⁰, graders^{31–33}, and analyzers^{34,35}, their electronic³⁶ and optoelectronic³⁷ components. Also, the success of a bunch of different seeding techniques, like aerial seeding^{38,39} on hard-to-cultivate sites, depends on how good the seed is.

Rational assessment of the effectiveness of reforestation technology^{40,41} by *P. sylvestris* L. cv. Negorelskaya when moving seeds to the experimental site according to the climatic gradient, "*dependence of accumulated precipitation on accumulated degree days*"⁴², used in this study, is based on the hypothesis of the influence of spectrometric seed parameters on germination rates on day 30^{43,44} in containers of an automatized forest nursery.

The accuracy of nondestructive^{33,37,45} detection of forest seeds via electromagnetic waves from different regions increases with the individual evaluation of each single seed^{16,18,19,46–48}, which is affected by the focal distance⁴⁹ from the sensor to the point of reflection of the electromagnetic beam from the surface of the seed coat⁵⁰. Moreover, depending on the type and nature of exposure to electromagnetic radiation, the biophysical^{37,51} parameters of the seed may be correlated with different properties and indicators of a single seed: biochemical content of lipids^{52,53}, starch⁵⁴, protein⁵⁵, trace elements⁵⁶, etc., as well as physiological germination.

The accuracy of detection also depends on the quality of the seed (size, shape, heterogeneity) and the characteristics of the detector. Esteve Agelet et al. (2014) conclude from a systematic search for 168 references for single seed identification that "*although no measurement mode (reflectance, transmittance) have led to the best reported calibrations, when dealing with heterogeneous seeds reflection is the best working mode*"⁵⁷. In most studies of forest single seeds, expensive devices are used to create and detect electromagnetic radiation (VIS, NIR) reflected from cameras with prolonged exposure. Some researchers use rather expensive USB cameras with autofocus⁵⁸, which are independent of the exhibition. However, the use of an inexpensive scanner⁵⁹ or a smartphone may be sufficient for the predictive evaluation of seedlots.

To quantify the color of the seed coat in the VIS region of visible light wavelengths, Red–Green–Blue (RGB-space) is often used, for example, in Yuval Nehoshtan et al.⁵⁸, Jaromir Przybyło and Mirosław Jabłoński⁶⁰, which consists of estimating the medium color density (from 0–250) of an RGB image, as in Antonio Dell'Aquila⁶¹, or estimating the color density of each of the three color channels (R, G, or B), as in Érika Beatriz de Lima Castro et al.⁶², and Ruoyu Zhang et al.⁶³.

An express semantic analysis of keywords in the LENS system for seed research^{14,27,64–67} on the basis of their images, organized according to an ORCID query by Clissia B. da Silva, returns the "*germination*"

descriptor in a third of the cases. This finding is convincing enough to reveal a connection between the spectral characteristics of the seed epidermis and germination.

The purpose of this paper was to evaluate the degree of relationship in the RGB space between the color of the seed coat of *P. sylvestris* L. cv. Negoretskaya and the seed quality determined by germination in the cells of an nursery container.

2. Results

In this section, we demonstrate the results of 30-day germination of individual seeds (N = 1200) of *Pinus sylvestris* L. cv. Negorelskaya, depending on the individual RGB parameters of the color of the seed coat. All the considered RGB parameters (measured and normalized) differed significantly between the zero (1-group) and zero (0-group) germination groups (Table 1).

Table 1

Variability of the measured and specific RGB color parameters of the seed coats of individual *Pinus sylvestris* L. cv. Negorelskaya seeds in groups with nonzero (1-group) and zero (0-group) container-based germination for 30 days after seeding.

Patameter's Title	«1» - germination group (N = 942); mean ±SD CV%	«0» - germination group (N = 258); mean ±SD CV%	«1» vs. «0» P value mean's different	Kolmogorov–Smirnov D
Seed individual mass (m), g	0.006098 0.001672 27.42	0.005673 0.001961 34.57	0.0045	0.1226
Pixel brightness of the R-channel	86.42 23.81 27.55	109.10 31.33 28.71	< 0.0001	0.3540
Pixel brightness of the G-channel	75.96 16.68 21.96	92.60 23.30 25.16	< 0.0001	0.3372
Pixel brightness of the B-channel	69.51 12.31 17.71	81.28 18.02 22.17	< 0.0001	0.3017
Specific pixel brightness of the R-channel $r = R/(R + G + B)$	0.3690 0.0247 6.68	0.3820 0.0239 6.25	< 0.0001	0.3031
Specific pixel brightness of the G-channel $g = G/(R + G + B)$	0.3278 0.0062 1.89	0.3275 0.0055 1.67	0.0429	0.0973
Specific pixel brightness of the B-channel $b = B/(R + G + B)$	0.3031 0.0225 7.41	0.2905 0.0218 7.53	< 0.0001	0.3024

The mass parameter of an individual seed in both germination groups has a distribution at the tails that deviates slightly from the Gauss curve (Fig. 1, b); therefore, to evaluate the null hypothesis that there are no differences between the distributions of values in the groups, we apply the nonparametric Kolmogorov–Smirnov D criterion. In both groups of seeds (with zero and nonzero germination), there is a moderate tendency toward low values of the individual weight parameter, since the medians (Me [Q1; Q3]) of the parameter values for the group are zero (5.5 mg [4.5; 7]) and nonzero (6.0 mg [5; 7]) germination is focused slightly to the left of the mean value (Fig. 1, a) and determines a slight left-sided asymmetry. The interquartile range of the IQR (Q3–Q1) parameter characterizes the nonzero germination group (2.0 versus 2.5 mg) as more robust to outliers. Moreover, the groups are characterized by an increased level (see the CV parameter in Table 1) of individual weight factor variability, and 27.9% of the seeds in group 1 (Fig. 1, c) and 22.1% of the seeds in group 0 (Fig. 1, d) have a mass of 6 mg. Nevertheless, it is statistically shown (Fig. 1) that the lower values of the individual seed weight from group 0 than those from group 1 are not accidental at a confidence level of $p = 0.0045$.

The pixel brightness parameter R in the image of an individual seed in both germination groups has a distribution at the tails that deviates slightly from the Gauss curve (Fig. 2, b); therefore, to evaluate the null hypothesis of the absence of differences between the distribution of values in the groups, we apply the nonparametric Kolmogorov–Smirnov criterion D. In the group of seeds with zero germination, there is a strong approximation of the median to the average value, namely, 109.5 [80.0; 134.3] to 109.1, but still on the right, which implies a minimal shift toward the prevalence of high values of R. In the group of seeds with nonzero germination, there is a moderate tendency of the R-parameter to low values, since the median of 80 [69; 99] parameter values is positioned on the left, in the middle between the mean value (Fig. 2, a) and Q1, which characterizes a moderate left–sided asymmetry. The IQRs of the R parameter values characterize the nonzero germination group (30.0 vs. 54.3) as more resistant to outliers. At the same time, both groups are characterized by an increased level (see the CV parameter in the R-row in Table 1) of variability in the pixel brightness factor of the seed epidermis image in R-space; 24% of the seeds in the 1-group (Fig. 2, c) have an R-brightness of 70, 12% of the seeds in the 0-group (Fig. 2, d) – R-brightness of 130. Nevertheless, it was statistically shown (Fig. 2) that the greater R-brightness of the epidermis of the 0-group seeds was not accidental ($p < 0.0001$).

The distributions of the values of the G-brightness parameter of pixels in the image of an individual seed in the germination 1-group are moderate, and in the 0-group, they deviate significantly from the Gauss curve (Fig. 3, b); therefore, the nonparametric Kolmogorov–Smirnov criterion D was used to evaluate the null hypothesis about the absence of differences between the distributions of values in the groups. In the 0-group of seeds, as well as in the R-brightness (see Fig. 2, a), there is a strong approximation from the median 91 [71.75; 111.3] to the average value of 92.6, but on the left, which implies a minimal shift toward the prevalence of lower values of G-brightness (Fig. 3, a). In the 1-group of seeds, there is a moderate tendency of the G-parameter to low values (as in the R-brightness), since the median 72 [65; 83] is focused on the left, almost in the middle between the mean value of 75.95 (Fig. 3, a) and Q1, which characterizes a moderate left-sided asymmetry. The interquartile range (IQR) of the distribution of G-

parameter values characterizes the 1-group (18.0 vs. 39.55 for the 0-group) as more robust to outliers. Moreover, Group 1 is characterized by an average (21.96%), and Group 0 is characterized by an increased level (see the CV parameter in the G row in Table 1) of variability in the pixel brightness factor of the image of the epidermis of the seed in G space. Notably, 17.8% of the seeds in the 1-group (Fig. 3, c) presented a G-brightness of 70, and 10.9% of the seeds in the 0-group (Fig. 3, d) presented a G-brightness of 70. Nevertheless, it is statistically shown (Fig. 3) that higher values of G-brightness in the epidermis of seeds from the 0-group are not noticeable at a confidence level of $p < 0.0001$.

The distributions of the pixel brightness parameter B in the image of an individual seed in germination group 1 are moderate, and in group 0, they deviate significantly from the Gauss curve (Fig. 4, b); therefore, the nonparametric Kolmogorov–Smirnov D criterion was used to evaluate the null hypothesis that there are no differences between the distributions of values in the groups. In the 0-group of seeds, there is a moderate location of the median of 76.5 [66; 97] to the left of the mean value of 81.3, which suggests a moderate tendency toward the prevalence of lower values of B-brightness (Fig. 4, a). In the mean group 1, there is a moderate tendency of the B parameter to have low values (as in the R and G luminosities), since the median 67 [61; 75] is focused on the left, almost in the middle between the mean value of 69.5 (Fig. 4, a) and Q1, which characterizes moderate left–sided asymmetry. The interquartile range (IQR) of the distribution of the values of the B parameter characterizes the 1-group (14 versus 31 in the 0-group) as more robust to outliers. In this case, group 1 and group 0 are characterized by the average (17.76 and 22.17%, respectively) level (see the CV parameter in the B-row in Table 1) variability of the pixel brightness factor of the image of the epidermis of the seed in the B-space. Notably, 22.6% of the seeds in group 1 (Fig. 4, c) have a B-brightness of 65, and 17.1% of the seeds in group 0 (Fig. 4, d) have a B-brightness of 65. Nevertheless, it is statistically shown (Fig. 4) that the higher values of B-brightness in the epidermis of the seeds from the 0-group are not random at a confidence level of $p < 0.0001$.

Thus, for the 1 200 breeding seeds included in this study, it is statistically significant ($p < 0.0001$) that brighter seeds reflecting most of the light rays from the epidermis will have lower container germination. Visually, this can be represented as a palette on a black background of the median RGB brightness values for the two germination groups (Fig. 5).

3. Discussion

We discuss the results of applying physical pixel brightness indices and their derivatives, normalized reflection indices, for potential evaluation of seed productivity: how they can be interpreted from the point of view of previous studies and working hypotheses. Note that the results and their significance should be interpreted within the framework of the experimental conditions.

Image acquisition method as an interpretation criterion

First, we note that obtaining an image of the epidermis of seeds should strive for the optimum, at which the cost of using devices would not exceed the productive efficiency of plants. In other words, the lowest resolution of the seed image and the minimum time of its exposure and processing, at which it is

possible to detect statistically significant differences between the dichotomous groups of seed germination, would be preferable when choosing a phenotyping method in the future.

The second fundamentally important factor is the R&D focus: one set of instruments and instruments is needed for scientific purposes, and another is needed for production conditions.

The third factor determining the choice of statistical apparatus and the accuracy of the results is the level of certification of the sample: group – when a sample of seeds from 10 to 1000 or more pieces is selected as a single sample; individual – when a group of individual seeds is used as a single sample, each of which has a technological passport ⁶⁸, including morphometric and biophysical parameters and replenished as the seed germinates and the culture obtained from it grows early.

In this study, we used a budget flatbed scanner available in almost every laboratory with a minimum image resolution of 300 dpi and obtained significant differences ($p < 0.05$) in the distribution of RGB spectral indices for germinating and nongerminating seeds of *Pinus sylvestris* L. cv. Negorelskaya, which is the continuation of research toward reducing the resolution of the scanner (for example, up to 150 dpi to search for the lowest possible resolution for identification).

As in Yuval Nehoshtan et al. ⁵⁸, a color bodyless machine vision camera with an IDS UI-3884LE-C-HQ-AF liquid lens with a resolution of 6.41 megapixels (3088 × 2076 pixels), on the one hand, significantly increases the cost of seed detection, and on the other hand, it allows the assembly of an engineering and technically automated system with a controlled camera. For example, Guoqing Feng et al. reported that the accuracy of the dichotomous classification of wheat grains by health (healthy/infected with a fusarium) based on VIS images in the RGB space can reach 97% ⁶⁹, and Bernardes et al. ⁵⁹ reported an accuracy of 99% when the Epson Perfection V800 flatbed scanner was used.

RGB index as an interpretation criterion

The following was accepted as the null hypothesis: the RGB index values in two dichotomous germination groups (0-germination and 1-germination) had a sufficiently high probability of being distributed equally. However, for all the RGB indices in this study, it is statistically significant ($p < 0.001$) that the high values of the indices in the 0-group compared with those in the 1-group are not accidental. This means that the biophysical criterion—the color of the seed epidermis—has great potential for predicting the physiological parameters of germination (that is, the manifestation of the phenotype).

R. Zhang et al. ⁶³ reported a regression relationship $R^2 = 0.7148$ ($p = 0.01$) for cotton seeds between the normalized parameters of color characteristics $R/(R + G + B)$, $G/(R + G + B)$, $(R - G - B)/(R + G)$, and germination. Xu Yan et al. ⁷⁰ developed software to simulate the sorting of seeds of five species in real time via the color ratios in RGB-space, which demonstrated a fairly high correlation when the purity of a seed batch was predicted.

In the future, projects and collaborations based on these data descriptors are possible, for example, with a group of scientists led by C.B. Mastrangelo ⁵⁹, who will be aimed at developing informatization of forest management systems and will combine the ambitious goal of tracing and ensuring the ability to effectively manage the process of restoring forest landscapes “from seeds to forest crops” on the example of Scots pine (*P. sylvestris* L.). In the future, we plan to expand research “from seeds to forest crops” to other types of woody plants.

4. Materials and methods

4.1. Seed collection

Three samples (n = 400) of dewinged seeds were selected by quartering ³⁰ from a seedlot of Scots pine (*Pinus sylvestris* L. cv. Negorelskaya) collected in 2023 from a location (53.577939, 27.056128, 180 m asl).

The authors confidently state that *Pinus sylvestris* L. cv. Negorelskaya is a cultivar. Detailed information on cultivar breeding was provided by Rabko et al. ⁸. The information about this is confirmed by the certificate for variety No. 0003707 and the breeder's certificate No. 0005065, with priority dated 28.03.2008, issued to the author S.U. Rabko and colleagues by the Ministry of Agriculture and Food of the Republic of Belarus.

The issue of italicizing the epithet Negorelskaya is quite debatable. On the one hand, the International Code of Nomenclature of Cultivated Plants (ICNCP) recommends against italicizing epithets below the species level. On the other hand, there are studies that provide fairly acceptable arguments for the use of italics throughout the taxonomic description (for example, Marco Thines et al. (2020) <https://imafungus.biomedcentral.com/articles/10.1186/s43008-020-00048-6#Sec12>). Therefore, the epithet Negorelskaya is written without italics.

Currently, seeds of Scots pine (*P. sylvestris* L. cv. Negorelskaya) for germination experiments in the gradation function ⁷¹ of the accumulated annual precipitation (mm) depending on the accumulated degree days ⁷² of the region. The current experiment is no exception: 1200 varietal seeds were removed from the collection site (1731 degree days, 722 mm) to the experimental site (2326 degree days; 786 mm).

4.2. Datasets creation

The library of forest reproductive material (FRM-Library) ⁷³, which is based on Pravdin's conjecture ^{11,24}, is expanding and being filled with data on individual parameters and indicators of each single seed of *P. sylvestris* L. cv. Negorelskaya.

Dataset blocks used in this study are presented in detail additional PDF file (Figure A1, Appendix A) and include:

- Seed morphometric block (from Dataset 1), included seed individual mass;
- Seed VIS-spectrometric block (from Dataset 2);
- Seed germination block (from Dataset 3).

4.3. Seed image processing

Scanning, according to the proposed method of the author T.P. Novikova ⁶⁸ (Patent application RU 2024137297, 2024-12-12), was performed for 40 seeds, placing them on flatbed scanner glass with a white background ¹⁶ in the order of future sowing in containers.

We preconfigured the field size of the 40-seed scan by clicking the [Preview] button in the scan window of the scanner interface (Brother DCP). The scan paper size was cut to 280*145 mm. For the subsequent study of spectrometric properties and to ensure a sufficient level of subsequent segmentation of the image of the dorsal and ventral projections of the seeds of Scots pine (*P. sylvestris* L. cv. Negorelskaya) with a square of 124 × 124 pixels, for example, as in Rodrigo K. Bernardes and coauthors ⁵⁹, a sufficient level of randomization, as well as minimization of the noise of the CCD scanner matrix, provided for the location of the seeds of Scots pine (*P. sylvestris* L. cv. Negorelskaya) at a distance of at least 20 mm from the edge of the tablet in the order corresponding to the order of subsequent sowing of seeds in side-ingot containers.

The scanning resolution was set to 300 dpi, the scanning mode was color, and the brightness was set to the default value. Moreover, the paper size in the pixels was set to 1718*3309 pixels. Next, the [Scan] button was pressed, and the scan timing was determined via a smart stopwatch background, the value of which was entered into the Excel table. For the period of sample scanning, the time from the appearance of the "Data Transfer" window to the appearance of a thumbnail of the scanned seed image in the left menu of the ABBYY Fine Reader program was assumed. The resulting seed scan was saved in uncompressed TIFF format with a file name of the form dI(1–40)@300 = Scan, where d(v) is the conditional dorsal (ventral) orientation of the seed relative to the scanner glass; I (II, III) is the number of random samples of seeds from the seedlot; 1–40 is the unique seed cipher in the current study; @300 (600,1200) is the scanning resolution, with dots per inch; and = Scan is the color of the reflective substrate of the scanner or colored paper.

The resulting file (image) has the following numbering of each individual seed. After a sample of 40 seeds corresponding to the future location in side-ingot containers was scanned, the resolution and size of the paper were changed to 600 dots per inch and 3436*6619 pixels, respectively. Moreover, the timing was determined for a resolution of 600 dpi, and the data were entered into the corresponding cell of the Excel table. After the scan was saved, the resolution and paper size were changed to 1200 dpi and 6873*13238 pixels, respectively.

4.4. Seed germination processing

The seeds (three samples of four hundred seeds each) were sown manually on June 23, 2023, into each of the 40 cells with a volume of 120 cm³ in HIKO V-120 SideSlit containers (size 352*216*110 mm, 526 seedlings per square meter; BCC AB, Sweden). Each container was prefilled with an acid reaction peat substrate, and the seed was placed in the center of the cell at a depth of 0.5–1 cm. The location of the seeds for subsequent identification was carried out in accordance with Figure A.7, *a* (supplementary) indicating the initial reference cell from the outside with a special marker as in Figure A.7, *b* (supplementary). After sowing 40 seeds, each container was filled with mulch in the form of perlite and placed on a pallet for transportation to the greenhouse. Each sample of 400 seeds was placed in 10 containers. Thirty^{42 43} days after seeding, the individual germination of each seed was calculated (0 – not germinated; 1 – germinated).

4.5. Data analysis

The pixel intensities of red, green and blue spectral visible channels (reflected at 700.0, 546.1 and 435.8 nm wavelengths, respectively⁷⁴) of the segmented individual seed image were analyzed via ImageJ ver. 1.46r open source software, such as P.D. Abeytilakathna et al.⁷⁵.

For each seed in the zero and nonzero germination groups, the following RGB ratios were calculated via the Prism program, version 8.4.3:

The distribution of indices and normalized RGB indices of segmented images of individual seeds in groups with nonzero and zero germination was visualized via the "box and whiskers" diagram in Prism, version 8.4.3. Moreover, the box size represents the interquartile range (IQR), with whiskers indicating the 10th–90th percentiles. The index distribution was visualized via a frequency diagram, and the degree of normality of the distribution was visualized via a QQ plot.

The level of variability of the individual seed weight parameters and RGB indicators of the seed coat was estimated on the basis of the values of the CV variation coefficient^{76,77}: very low (less than 7%); low (7–15%); medium (16–25%); increased (26–35%); high (36–50%); and very high (more than 50%).

To assess the significance of the differences between the distributions of the RGB indices in the zero and nonzero germination groups, the nonparametric Kolmogorov–Smirnov test D at $\alpha = 0.05$ was used.

5. Conclusions

The lower individual seed weight in the 0-group than in the 1-group was not accidental ($p = 0.0045$). Additionally, in the 0-group, the median values of R, G, and B pixel brightness of individual seeds are not accidental ($p < 0.0001$) compared with those of the 1-group. Thus, for the 1,200 breeding seeds involved in this study, it is statistically significant to state that they are brighter (reflecting most of the light rays from the epidermis) and that the seeds will have a smaller container-grown germination.

Declarations

Supplementary Information: The online version contains supplementary material available at <https://doi.org/10.1038/s...>

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Data availability statement: The seeds used in this study were collected in 2023 a forest seed orchard (Latitude 53.577939; Longitude 27.056128, Altitude 180 m a.s.l.; Negorelsky Experimental Forestry Center of Belarusian State Technological University, Minsk region, Belarus Republic).

The original morphometric data—Dataset 1—of *Pinus sylvestris* L. cv. The individual Negorelskaya seeds (N = 1200) presented in the study are openly available in Mendeley Data at DOI: <https://doi.org/10.17632/8g258nbgmf.1>. The original VIS image data of *Pinus sylvestris* L. cv. The individual Negorelskaya seeds (N = 1200) presented in the study are openly available in Mendeley Data at DOI: <https://doi.org/10.17632/dt78jhyw2j.2>. The original germination data—Dataset 3—of *Pinus sylvestris* L. cv. The individual Negorelskaya seeds (N = 1200) presented in the study are openly available in Mendeley Data at DOI: <https://doi.org/10.17632/hrs3fgc8tt.1>.

Competing interests: The authors declare no competing interests.

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Figures

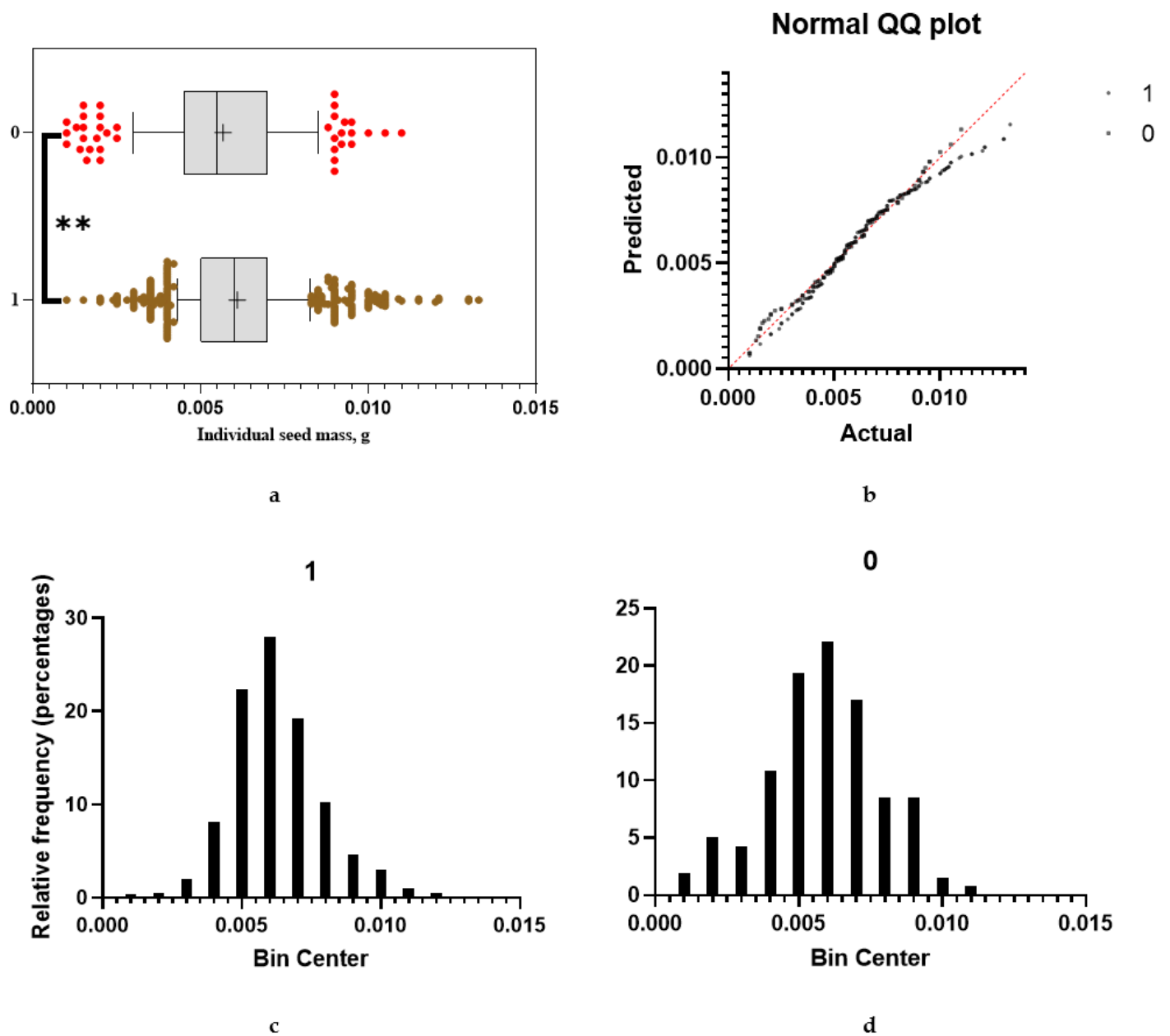


Figure 1

Mass of an individual seed of *Pinus sylvestris* L. cv. Negorelskaya: (a) boxplots of values in groups of nonzero (1) and zero (0) germination in containers on the 30th day after sowing (** the null hypothesis of group equality is rejected by the nonparametric Kolmogorov–Smirnov criterion $D = 0.1226$ at $p = 0.0045$); (b) QQplot; (c) distribution of values in the nonzero germination group; (d) distribution of values in the zero-germination group.

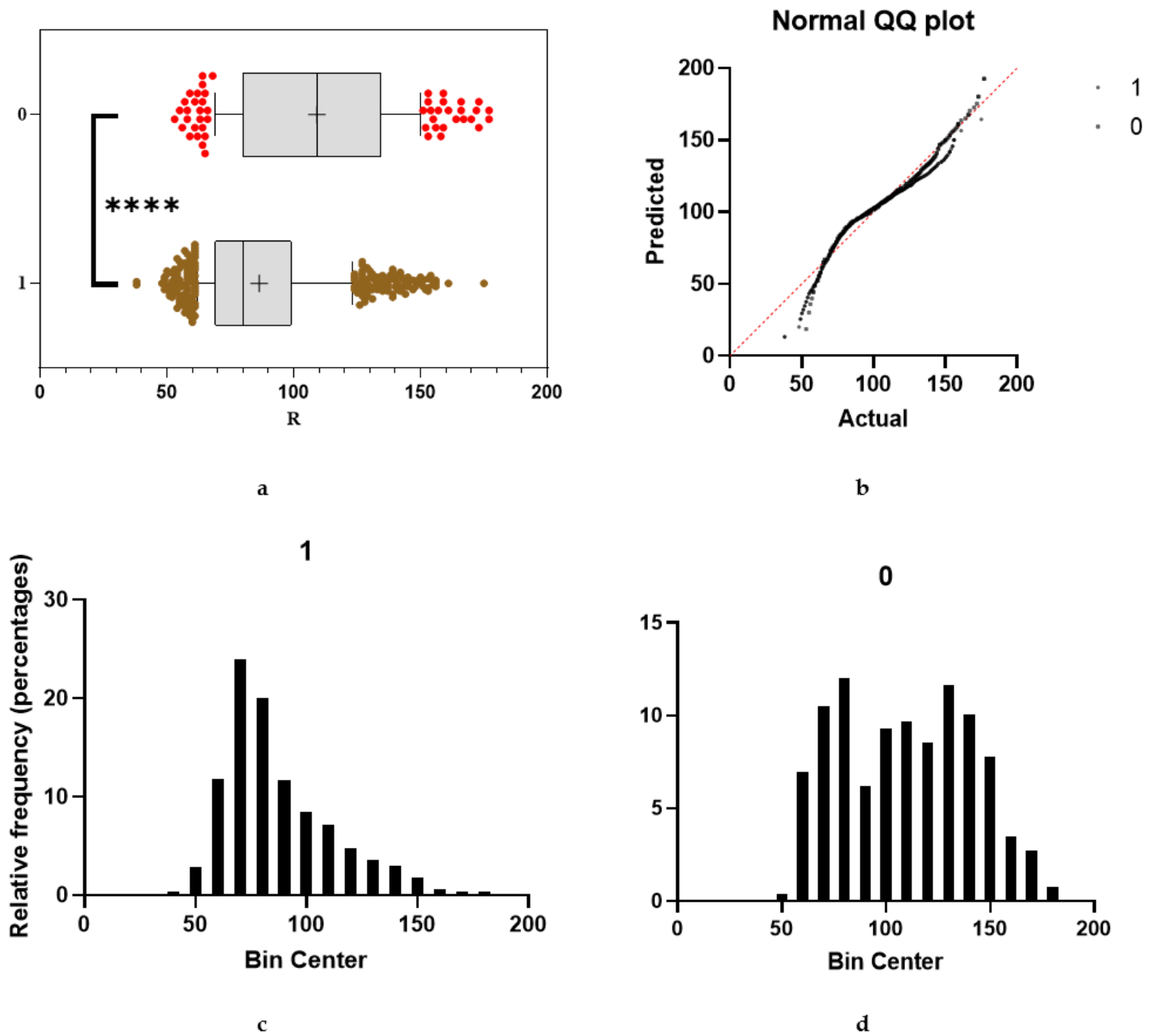


Figure 2

The R-parameter to pixel brightness in the image of an individual seed of *Pinus sylvestris* L. cv. Negorelskaya: (a) boxplots of values in groups of nonzero (1) and zero (0) germination in containers on the 30th day after sowing (**** null-the hypothesis of group equality is rejected by the nonparametric Kolmogorov–Smirnov criterion $D = 0.3540$ at $p < 0.0001$; (b) QQ-Plot; (c) distribution of values in the nonzero germination group (1-group); (d) distribution of values in the zero germination group (0-group).

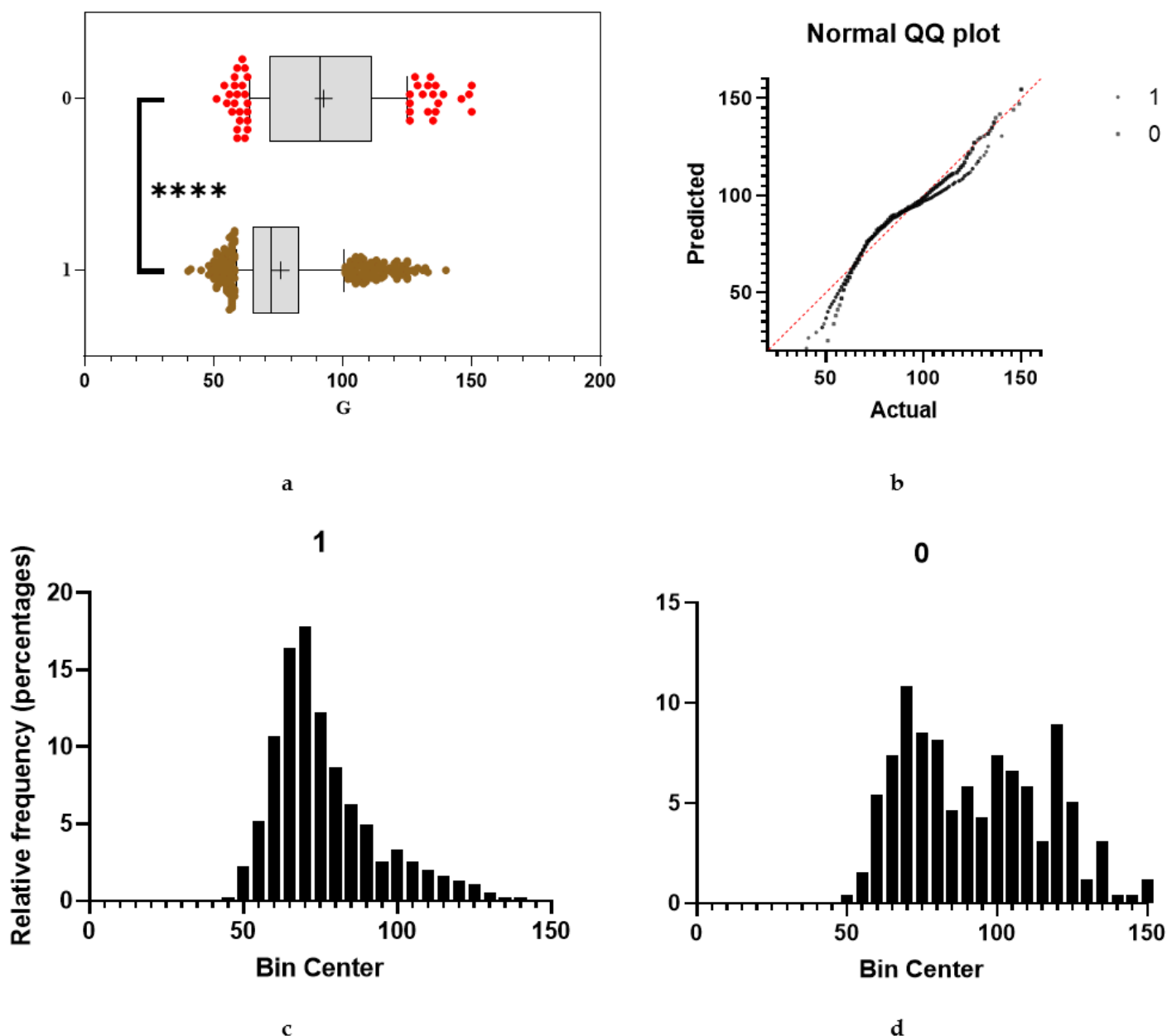


Figure 3

The G-parameter is the pixel brightness in images of individual seeds of *Pinus sylvestris* L. cv. Negorelskaya: (a) boxplots of values in groups of nonzero (1) and zero (0) germination in containers on the 30th day after sowing (**** the null hypothesis of group equality is rejected by the nonparametric Kolmogorov–Smirnov criterion $D = 0.3372$ at $p < 0.0001$); (b) QQ plot; (c) distribution of values in the nonzero germination group; (d) distribution of values in the zero germination group.

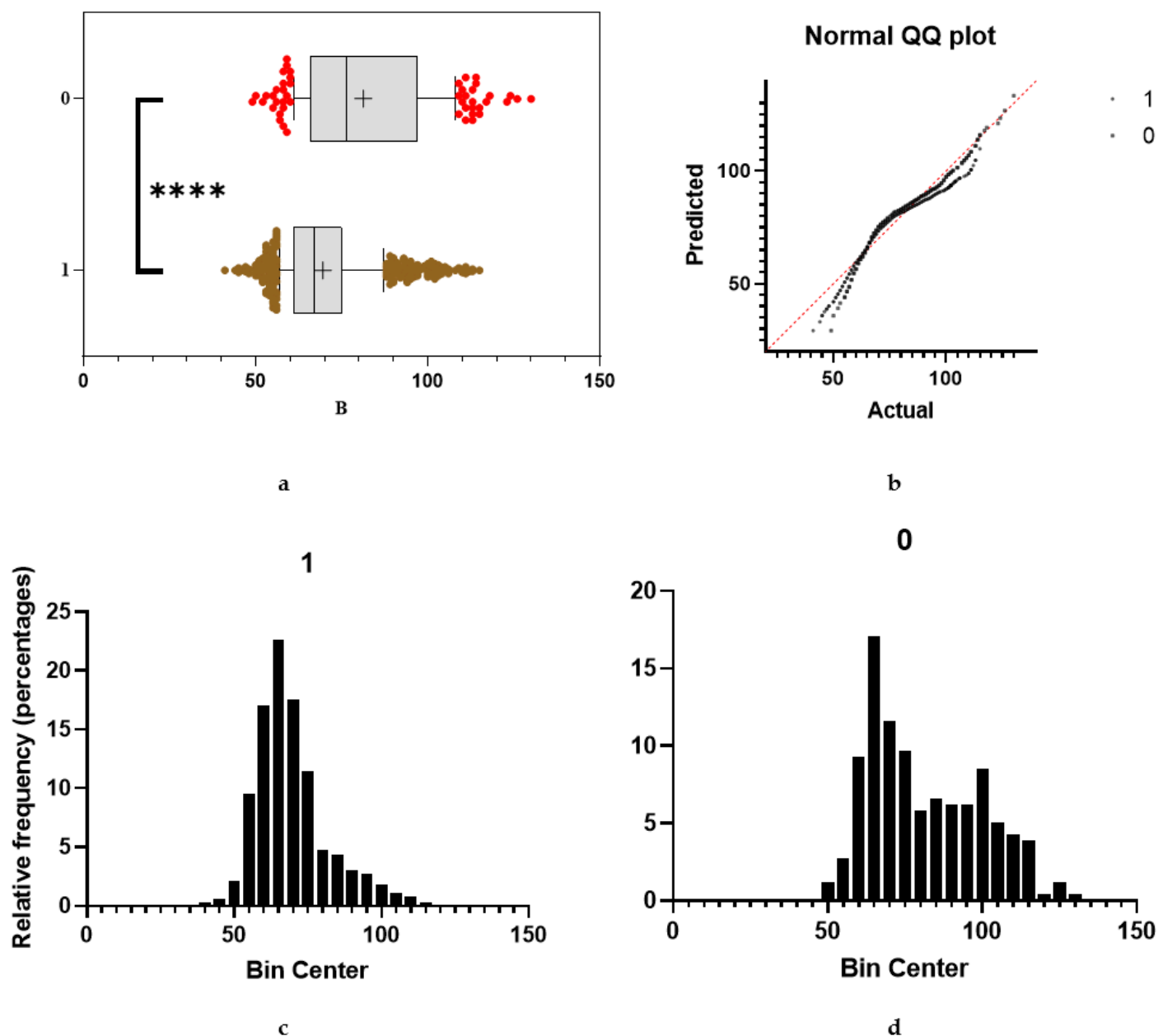


Figure 4

B-parameter of pixel brightness in images of individual *Pinus sylvestris* L. c. negorelskaya seeds: (a) boxplots of values in groups of nonzero (1) and zero (0) germination in containers on the 30th day after sowing (**** the null hypothesis of group equality is rejected by the nonparametric Kolmogorov–Smirnov criterion $D = 0.3017$ at $p < 0.0001$); (b) QQ-plot; (c) distribution of values in the nonzero germination group; (d) distribution of values in the zero germination group.



a

b

Figure 5

Palette of median RGB values of pixel brightness in images of individual *Pinus sylvestris* L. cv. Negorelskaya seeds: (a) for 1-group (R80 G72 B67); for 0-group (R110 G91 B77).

Supplementary Files

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