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POSSIBILITIES OF USING FIJIIMAGEJ2, WIPFRAG AND BASEGRAIN PROGRAMS FOR MORPHOMETRIC AND GRANULOMETRIC SOIL ANALYSIS

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KEYWORDS

digital image processing, granulomorphometric soil analysis, soil structure.

ABSTRACT

The process of determining the granulometric sludge of soil is represented by the dominant method of dry sieving on sieves. The procedural complexity of this method and the inability to quickly assess soil structure directly in the field led to the search for alternative methods of determination. The article summarizes the features and effectiveness of using three image analysis software packages FijiImageJ2, WipFrag v.3.3.14.0 and BASEGRAIN v.2.2.0.4 in the procedure for determining the morphological parameters of soil aggregates. In the studies used the processing of digital images of both the soil surface and the layer of identified fractions after sieving using the publicly available manual of these programs. Individual plugin functions of the programs for its application for soil analysis were determined. The possibility of using the FijiImageJ2 program to assess the microrelief of the soil layer of the corresponding fractions was determined. The effectiveness of WipFrag v.3.3.14.0 and BASEGRAIN v.2.2.0.4 programs for processing images of a layer of soil aggregates in the interval 2–>10 mm fractions was introduced. For the same programs, the possibility of forming additional indicators of the size of soil aggregates by such parameters as Feret diameters and the separation length criterion (D) was established.

INTRODUCTION

The issue of determining the structural composition of the soil is one of the fundamental parameters for assessing the formation of its main modes and agronomic properties (Rabot et al., 2018; Vogel et al., 2021). Based on modern concepts, soil structure is understood as the spatial organization of all soil matter, which is characterized by a set of morphometric, geometric and energy features and is determined by the composition, quantitative ratio and interaction of soil components (Erktan et al., 2020). Across all types of the soil structure and from an agronomic perspective, the most favorable soil structure is the crumbly soil structure, i.e. the aggregate of 0.25-7 mm and in some cases even up to 10 mm. But in the drier regions the aggregates of 0.25 to 2-3 mm are the most favorable from the aspect of soil fertility (Jugović et al., 2020: da Luz et al., 2022).

Soil structure indicators are basic various variations of national methodological standards in the field of soil science. The dominant methodology for their determination involves the use of a system of fractional sieves with the subsequent calculation of the percentage of the obtained soil particles of a certain size fraction in weight terms (Romero-Ruiz et al., 2019; Fomin et al., 2021). For this block of methods, a number of comments have been identified over a rather long period of existence. It was not possible to assess the degree of variation in the size of soil aggregates for sieve fractions (Yudina et al., 2018; Fomin et al., 2021). Shortcomings have also been noted in terms of assessing the microrelief of the soil surface by the placement of soil aggregates of different sizes (da Luz et al., 2022).

Another block of methods for determining the soil structure involves the use of visualization approaches based on the use of specialized soil surface scanning systems or vertical soil profile sections with subsequent digital image processing using certain programs (Thomsen et al., 2015; Tuchtenhagen et al., 2018; Franco et al., 2019; Lin et al., 2022). This methodology has now acquired a number of technological variations from simple analysis of scanned images of the soil surface to sweet 3-4 D visualization of the resulting scanned image (Mele et al., 2021; Gerke et al., 2022) and the use of tomographic and fluoroscopic technology

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(Nohara & Mukunoki, 2021). Despite some innovativeness, these techniques are quite expensive and complex and require the use of special equipment, specific software products, and sophisticated skills (Gerke et al., 2022).

The third group of methods includes the direct processing of the obtained photo images of the soil surface with the selection of effective programs for their analysis (Aitkenhead et al., 2016; Tobiszewski &Vakh, 2023). This direction is the least time-consuming and requires only the selection of an effective program and the development of an appropriate methodological algorithm for processing and analyzing the obtained images (Suchan & Azam, 2021; Tobiszewski &Vakh, 2023). Research in this area is quite relevant, since the problem of effective morphometric analysis of the soil surface based on conventional fluoroscopic images is a controversial issue both due to the heterogeneity of opinions on the effectiveness of using such classical image processing programs as ImageJ (Passoni et al., 2014) and by identifying effective tactics for adapting alternative programs to improve this process (Hu et al., 2019).

As a result, it should be noted that the use of the dry sieving method to assess the particle size distribution of soil limits the application of the method directly in the field, which makes it difficult to assess the soil surface for structural structure, aggregate looseness, and microprofile. These indicators are important for assessing tillage systems, the general condition of the soil and its agrophysical properties under different technological options. In view of this, the purpose of the research was to investigate the possibility of programs FijiImageJ2, WipFrag and BASEGRAIN in enhancing methods for assessing for morphometric and granulometric soil analysis.

MATERIAL AND METHODS

Study Site. This research was performed in 2023 at Vinnytsia National Agrarian University (49°11′ N, 28°22′ E) using samples of dark gray forest soils categorized as Luvic Greyic Phaeozem soils according to IUSS Working Group (2015). Height above sea level: 325 m. The area has a temperate continental climate. The maximum and minimum temperatures were 18.3 °C in July and 15.8 °C in May, respectively. Mean annual relative humidity was 77% and mean annual precipitation was 480-596 mm.

Two approaches to possible adaptation of programs for studying soil granulometry were used in the research. The first one involved obtaining photographic images of the soil surface made in 10 repetitions directly in the field. The second involved obtaining photographic images of the soil surface formed by the output of the sieves of the corresponding fractions, including repetitions in accordance with the dry sieving technique in the laboratory.

Digital image preparation. The images were captured using a Canon EOS 750D Kit 18-135mm IS STM DSLR camera with an additional Canon EF 100mm f/2.8 Macro lens with a UV filter. The process of photographing was carried out in an orthogonal projection to the soil surface and soil fractional layer using a standard scale ruler under artificial shading according to Gilliot et al. (2017), Xingming et al. (2021), Liu et al. (2022). The area of the images was 0.25 m^2 of soil surface for the field images and 0.025 m^2 of the surface of the corresponding fractional yield and sieves for the laboratory images. As a result, the ratio of the accounting perimeter for field and laboratory conditions was 1:10 (according to Gilliot et al. (2017). To avoid possible effects of positional micro-profiling of images (Giesko et al., 2007), the camera positioning was changed in 4 positions with a shift in relation to different sides that formed the perimeter of the image area. The focusing distance for all photographic variants was 50 cm for field conditions and 25 cm for laboratory conditions.

Programs used in this study. The following programs were used to process the images: FijiImageJ2, WipFrag (v.3.3.14.0) and BASEGRAIN (v.2.2.0.4). All images generated by the field and laboratory methods were processed after its preliminary 8-bit transformation with the same contrast level adjusted manually. To identify the size of soil structural aggregates within the image, a standard mechanism for setting the pixel ratio of the line length in accordance with the ruler scale on the image and its pixel display was used. The programs used had certain differences in these preparatory operations, which are detailed in the available manuals (Abramoff et al., 2004; Tosun, 2018; Detert & Weitbrecht, 2013; Passoni et al., 2014; Gogoase Nistoran et al., 2019; Nanda & Pal, 2020; Shehu et al., 2022; WipFrag 3.0, 2023). For the BASEGRAIN program (v.2.2.0.4), the system for processing field and laboratory images used a manual option for selecting the optimal configuration of parameters in accordance with four consecutive standardized steps of image segmentation in the program frame (Detert & Weitbrecht, 2013). Its detailed and consistent adaptation for images of soil aggregates is described in the research results in this article. For image processing, the WipFrag program (v.3.3.14.0) used an in-software segmentation system, which is detailed in the available program manual (WipFrag 3.0, 2023). The morphoparametric data of image processing were obtained from the visualization data of the results generated in the form of graphs with data dynamics for the WipFrag program (v.3.3.14.0) and an additional in-software file in Exel format for the BASEGRAIN program (v.2.2.0.4). The principle of individual morphometric identification of soil aggregates in the software packages used due to their complex shape was based on the automatic determination of such parameters as the Feret diameter (synonymous with the Fere diameter) (Pabst & Gregorová (2007)). This parameter is used to determine the size of particles of a complex projection configuration with the formation of two diameters: vertical (maximal (b)) and horizontal (minimal (c)) and their corresponding ratio, the separation length criterion (D) (Figure 1 Equation 1 (according to Church et al. (1987)).

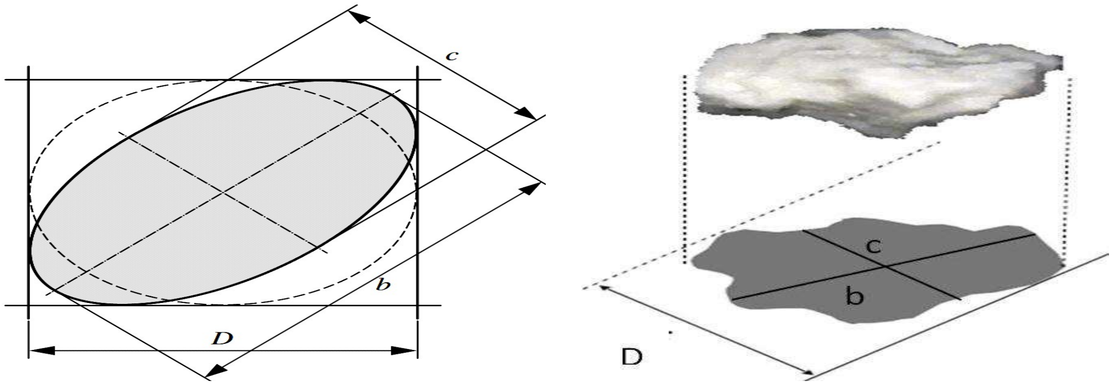

FIGURE 1. Definition sketch for lengths D, b, and c (According to Stähly et al. (2017)).

$$D = b \times \left(\frac{1}{\sqrt{2}} \times \left[1 + \left(\frac{c}{b} \right)^2 \right]^{0.5} \right) \quad (1)$$

In which:

b - vertical (maximal) Feret diameter, mm;

c - horizontal (minimal) Feret diameter, mm,

D - separation length criterion, mm.

Formation of sieve soil fractions. To compare the effectiveness of the use of appropriate image processing programs in the soil particle size distribution system, we processed photographic images of the corresponding sieve outputs obtained by the standard method of dry sieve sieving (State Standard of Ukraine..., 2005). Samples for sieving were selected in a randomized replication from the areas of previous photographing in the field conditions for its surface from a layer of 5 cm depth. The soil sample was sieved using meshes of 10 mm, 7 mm, 5 mm, 3 mm, 2 mm, 1 mm, 0.5 mm, and 0.25 mm. The sieve set had a tray for collecting the fraction < 0.25 mm. The soil was divided into fractions: > 10 mm; 10-7 mm; 7-5 mm; 5-3 mm; 3-2 mm; 2-1 mm; 1-0.5 mm; 0.5-0.25 mm; < 0.25 mm. The corresponding single-type software processing was applied to the photographic images of the full spectrum of the specified grid outputs with the actualization of the most statistically appropriate interval for the identification of morphoparameters of soil aggregates, taking into account the specification of the applied programs.

Statistical processing. The indicators of variation statistics were determined using the generally accepted calculation method as outlined in Stoyan & Unland (2022). These analyses were performed with the statistical software Statistica 10 (StatSoft – Dell Software Company, USA).

RESULTS AND DISCUSSION

General features and cautions of soil aggregate analysis. The complexity of analyzing soil aggregates in the images was determined by two components. The first of them was black colour with a narrow range of shade gradation in a monochrome converted image (Jena et al., 2013; Holm et al., 2020). The second component is caused by surface irregularities of soil aggregates with pronounced microrelief, which complicates the application of the thresholding function for 8-bit images (Fig. 2). With a decrease in the size of the soil aggregate fraction from >10 mm to 3-2 mm, the signs of microrelief became less noticeable with a decrease in the variation of soil aggregate sizes, which was also noted in other publications. (Yudina & Kuzyakov, 2019; Gerke et al., 2021; Xingming et al., 2021; Liu et al., 2022; Yudina et al., 2022).

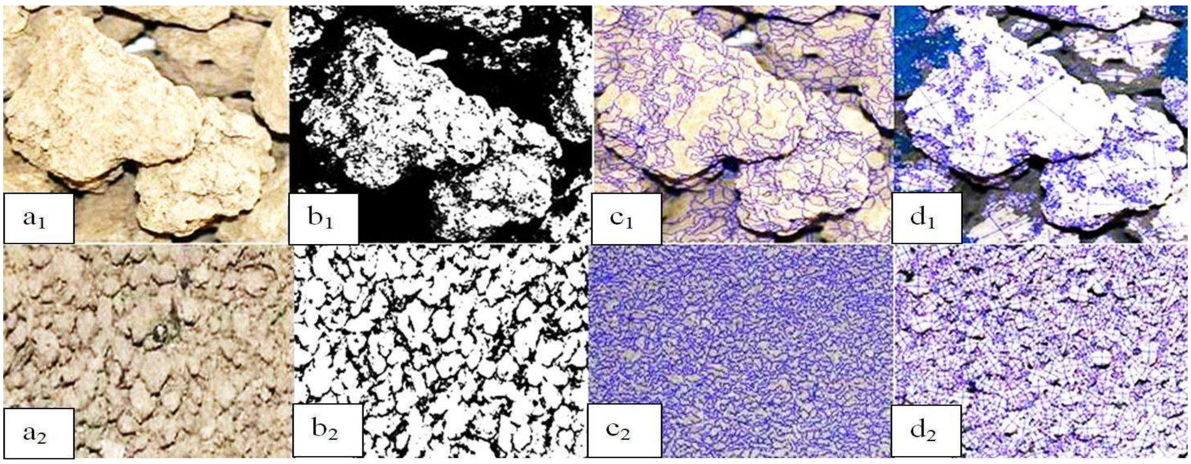

FIGURE 2. Expression of complex microrelief of soil aggregates in the process of skeletonization and morphometry of images using an automated image processing system for the same area of the photo (top row for fraction >10 mm, bottom row for fraction 3-2 mm: a_1,a_2 - original image; b_1,b_2 - processed in FijiImageJ2; c_1,c_2 - processed in WipFrag v.3.3.14.0; d_1,d_2 - processed in BASEGRAIN v.2.2.0.4).

Determination of the granulometric composition of the soil by dry sieving of the sample on sieves gave the determination of the proportion of different fractions only in the ratio of the masses of each of them to the total mass of the sample. The use of the FijiImageJ2, WipFrag and BASEGRAIN programs in this regard made it possible to expand the range of indicators that allowed us to analyze the variation in the size of aggregates according to the proposed criterion D by the ratio of the corresponding Feret diameters. Based on the regularities of the morphometry of soil aggregates in the analysis (Vargas-Ubera et al., 2007; Hussain et al., 2020), it was found that their sphericity (proximity of the values of the maximum and minimum Feret diameters) gradually increases with a decrease in fractional size from the fraction >10 mm to the fraction 2.0-3.0 mm. The angularity of the aggregates (the complexity of the aggregate outlines in the corresponding quarter, which is formed by the axes of Feret diameters (Valsangkar, 1992)) also had similar dynamics. The identified features prove the need to use Feret diameters by processing images of the corresponding soil fraction obtained from the results of laboratory sieving. For the laboratory practice of granulometric analysis of soils, the possibility of incomplete separation and the presence of fractions that do not fit the sieve interval were noted. Thus, aggregates smaller than 3 mm in size may remain in the 5-3 mm fraction interval (Yudina et al., 2018). For these reasons, criterion D calculated using image processing is more useful given the round meshes of the laboratory sieves that do not fully correlate with the observed angularity of soil aggregates.

Application of the FijiImageJ2 program. The study used the recommended standard image processing algorithm for analyzing microscopy parts and objects (Abramoff et al., 2004). Among the 9 options for processing the transformed 8-bit image (in the 'Auto Local Threshold' command option), the one with the most complete filling (black on a white background) of the soil aggregate profiles with the most complete delineation of their tangent boundaries was selected (Figure 3 $c_{1\text{-}2}$). This approach made it possible to clearly diffract the elements of the image substructure and reduce the already mentioned microrelief features of the aggregate structure (Figure 3).

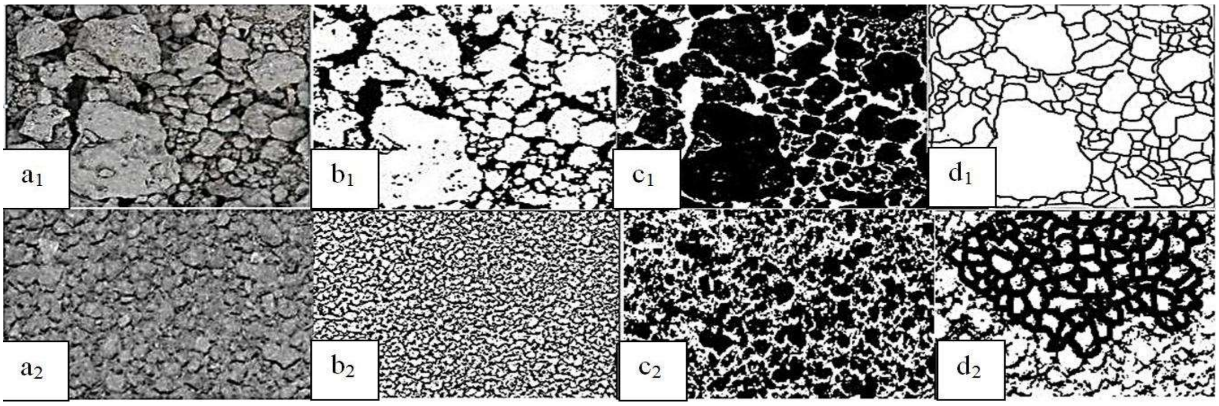

FIGURE 3. Sequential analysis of soil images using the FijiImageJ2 software frame (top row for fraction >10 mm, bottom row for fraction 3-2 mm: a_1,a_2 - original image; b_1,b_2, c_1,c_2 - processed using the Threshold option (8-bit transformation sequentially on black and white backgrounds); d_1,d_2 - processed in the system of manual outlining of soil aggregates ('Color picker'/'Paintbrush tool').

The use of FijiImageJ2 program in assessing the morphometry of soil aggregates was showed a number of limitations in application. First, the clear skeletonization of the image during its thresholding for images of coarse soil fractions (mass of separated soil on 10 mm sieves) reduced the value of the plane perimeter of soil aggregates. This phenomenon is commonly referred to as the plane-perimeter reduction effect (Jena et al., 2013). For images of the soil layer of small fractions (starting with the soil mass on sieves with 5 mm holes), this effect became even more noticeable, which distorted the reliability of the obtained morphometric data of soil aggregates (Figure 3c_2). A possible option to avoid such effects was to use manual outlining of the contours of soil aggregates using the 'Color picker' (Figure 3d_1) and 'Paintbrush tool' options (Figure 3d_2). However, this variant of image analysis required precise copying of the contours of the outline of soil aggregates, the elimination gaps and a lot of time. In addition, this approach was technically challenging for images of small soil fractions - the accuracy of the outline was reduced by at least an order of magnitude (Figure 3d_2). The use of FijiImageJ2 program in soil sieve fractions 0.25-2 mm was problematic due to the conflict of image microstructure resolution. For this interval, a decrease in the clarity of identification of aggregate boundaries was noted against the background of a decrease in the depth of field. This made it impossible to clearly identify the boundaries of the aggregates. Similar conclusions were drawn in the studies by Jena et al. (2013) and Holm et al. (2020) regarding the possibilities of morphological resolution in digital image analysis. In addition, was noted that aggregates < ~20 px hardly detectable at all (Detert & Weitbrecht, 2013), which is confirmed by Graham et al. (2005) who found a limit of 23 px. Based on the resolution of our images (px/mm), fraction identification in FijiImageJ2 was possible starting from aggregate sizes of 2 mm. For fractions smaller than this threshold, it is advisable to obtain micrographs with an appropriate level of hardware magnification for more efficient use of the FijiImageJ2 program. These conclusions was supported by the studies of Passoni et al. (2014) and Hussain et al. (2020) on the identification of particles and small micropores in the scanning microscopy image procedure.

It was determined to be expedient to obtain 3D diagrams using FijiImageJ2 software to assess the microrelief of the soil surface both in field images and in images of the layer of the corresponding fraction of sieves (Fig. 4a, b).

These diagrams were built on the basis of graphical visualization of the depth of field of the image in the red, green, and blue spectra with the appropriate segmentation of the photo surface image. This method has been used in systemic photogrammetry methods to assess soil surface features (Suchan & Azam, 2021; Liu et al., 2022). In this case, it was used to visualize the microrelief of the surface of a photo image. The use of these graphs was appropriate for visualizing the variation of soil aggregates in the image plane, taking into account the scattering of the spectrum with different aggregate size. Such results are consistent with the studies of Hu et al. (2019) and confirm the statement that the variation component of the morphometric parameters of soil aggregates decreases with a decrease in the fractional size of the analyzed soil mass.

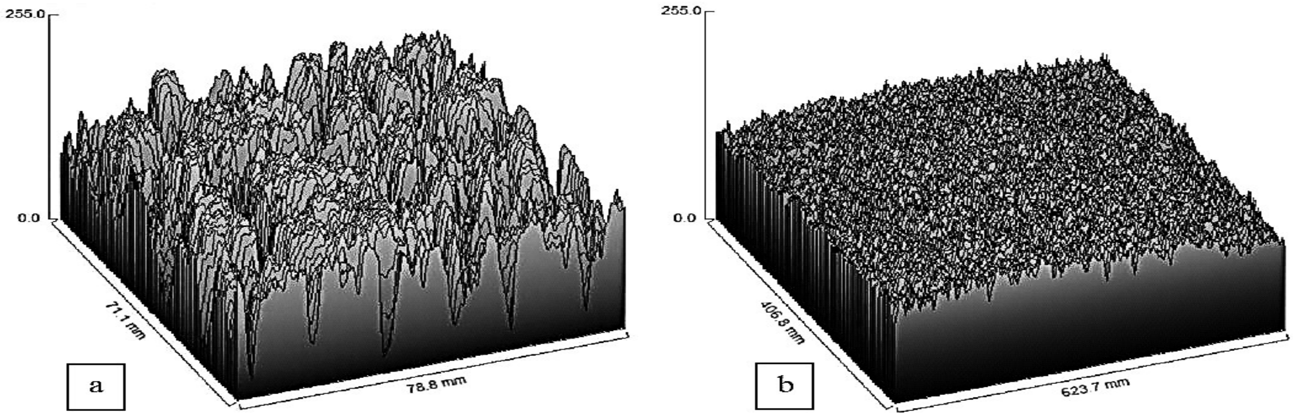

FIGURE 4. The surface of morphometric irregularities of the image of the soil layer of different fractional sieve output at the lower threshold level of image processing of 255 units (a - fraction >10 mm, b - fraction 3-2 mm).

This variant of the FijiImageJ2 program was deepened by the 'View5D' plug-in (Fig. 5). This plugin allowed us to obtain a profilogram of the soil surface image based on the principles of analyzing the spectral composition of the image. Due to artificial shading during the formation of photo images and the use of the orthogonality method when placing the photographic lens, the height position of the aggregates in the image plane coincided with the spectral segmentation of the image. As a result, a clear plot of the height difference of soil aggregates in the vertical and horizontal directions was obtained.

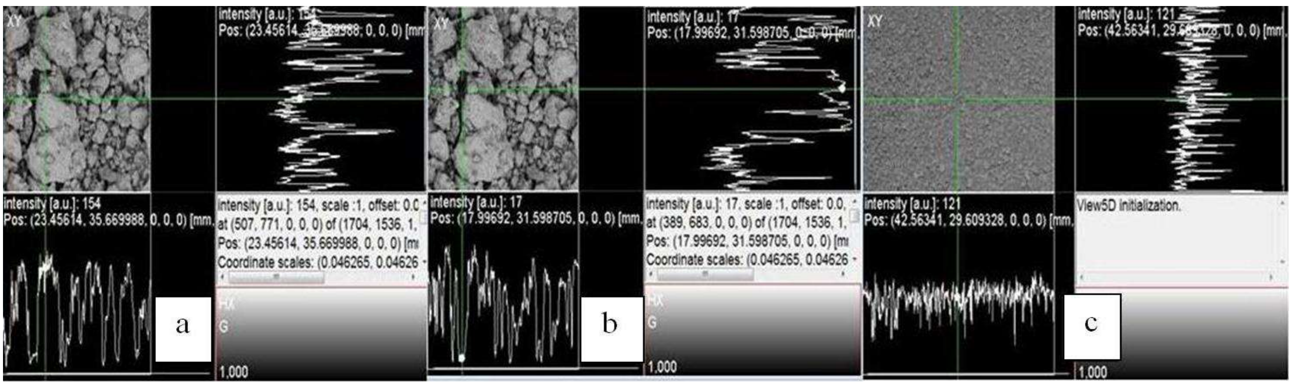

FIGURE 5 Application of the 'View5D' plugin for visualization of the micro-profile of soil layer of different fractional sieve output (a, b - fraction >10 mm (for a - visualization point in the highest aggregate position, for b - point in the lowest height position, c - fraction 3-2 mm).

This method simplified the analysis of surface microrelief based on the use of special laser and X-ray scanning systems (Gilliot et al., 2017; Xingming et al., 2021). However, the plugin is limited in terms of forming a database of micro-profile curves with the ability to import them.

Application of the WipFrag program. The study of the effectiveness of the program for fine image segmentation has already been carried out previously in the application to the fractional composition of seeds based on their image in the format of a densely placed layer (Tsytsiura, 2021), where it was concluded that it could be further adapted to agronomic practice. This program was used for the first time to study soil structure from images in accordance with a publicly available manual (WipFrag 3.0, 2023). The digital results of Application of the WipFrag program to analyze the soil structure are shown in Figure 6.

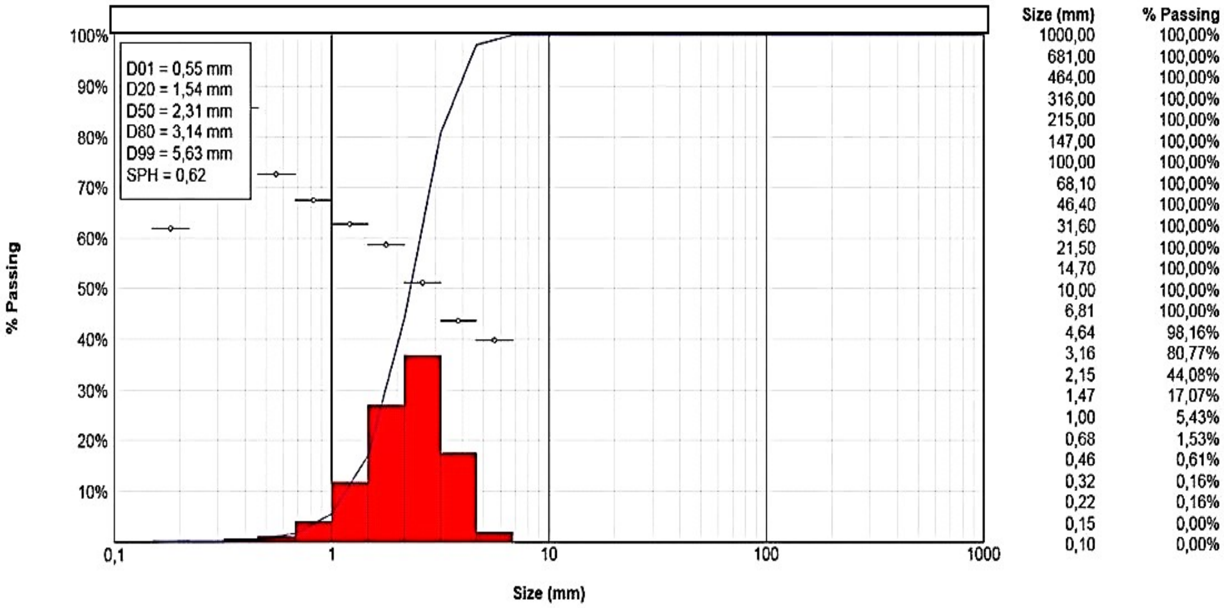

FIGURE 6. The results of using the WipFrag program to analyze the image of the soil layer of the 3-2 mm fractional sieve output.

The program is focused mainly on the fractional analysis of rocks obtained as a result of blasting, crushing and weight separation (Tosun, 2018; Nanda & Pal, 2020). Given that the formation of segmentation of stony materials is characterized by the formation of a simpler micro-profile compared to clay and soil substrates, one should expect high-quality outline segmentation of structural aggregates with a complex amorphous micro-profile structure (Shehu et al., 2022). The fine-grained structure, which approximates the corresponding geometric shapes, is better identified by the size of the aggregates (Yudina et al., 2022). These generalizations were confirmed in the course of applying this program. It was found that the segmentation of morphometric structures of the soil layer in the image had a minimal coincidence effect on samples of fractions with maximum size variation (output from a fractional sieve of 10 mm). The quality of segmentation and the reliability of measurements increased as the fraction of the soil sample decreased to the level of 3-2 mm. The subsequent decrease in the fractional size of 2-1 mm again negatively affected the quality of segmentation. For fractions <1 mm, the process of image segmentation based on the low resolution of the photo image again turned into a contour-chaotic character. Based on this, it is methodologically expedient to use the WipFrag program to assess the variation in soil morphometry for soil aggregates of 2-7 mm in size. These conclusions was confirmed by the data of Figure 6 and studies on the granulometric analysis of media of different fractional sizes (Valsangkar, 1992; Fredlund et al., 2011; Ciric et al., 2012; Gerke et al., 2021), including changes in the geometry of soil aggregates with a decrease in their size (Yudina et al., 2022).

To increase the reliability of the measurement results, it is necessary to ensure sufficient image clarity to guarantee the identification of the contour boundaries of soil aggregates without the formation of double structures (brown-red structures Fig. 7b).

These inaccuracies in image skeletonization for the soil layer of the >10 mm fraction had a higher frequency than for the 3-2 mm fraction. That is, the process itself for the latter fraction was an order of magnitude higher in terms of the reliability of the results obtained.

Application of the BASEGRAIN program. The program is widely used for the identification and morphometry of deluvial and colluvial pebble deposits in the riverbeds (Gogoase Nistoran et al., 2019) and in general for the morphometry of river sediments, sedimentary rocks of different fractional sizes in geology and geomorphology (Chen et al., 2022). The study of this program concerning soil fractional variation is carried out for the first time. There were some peculiarities in the process of its experimental adaptation to the analysis of the particle size distribution of the soil.

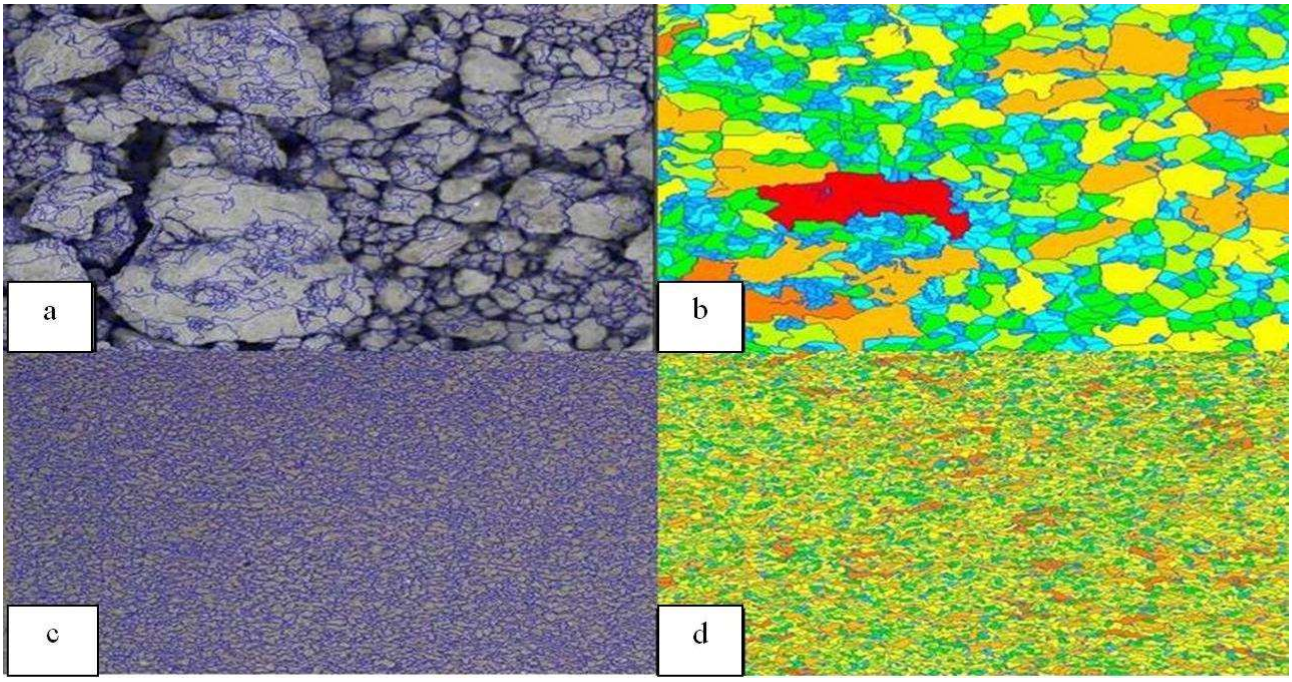

FIGURE 7. Application of the WipFrag program to analyze the image of the soil layer of different fractional sieve yields (a, b - fraction >10 mm, c, d - fraction 3-2 mm). Positions a, c - skeletonized image of the respective fractions, b, d - color filling of skeletonized contours).

For factions sieve output of 10-7 mm and >10 mm, where there is a high variability in the morphometry of soil aggregates and the presence of microrelief on large aggregates, the analysis can be carried out in two successive variants. The first one involves adjusting the parameter of steps 1-5 of the program plugins (according to the step-by-step program manual Detert & Weitbrecht (2013)). This maintains the same level of the smallest soil particle size and increasing the level of the maximum particle size in the image. This is regulated by the size of the analyzed segmentation in Step 1 and Step 4 with the maximum increase in the percentage of curvature (Step 1) of the analyzed image plane coverage (up to 30º (Step 4)). As a result, we will have the analyzed coverage as shown in Figure 8 (position a-b).

The second involves a gradual reduction of the smallest soil particle size (step 4) while maximizing the fragmentation of the minimum selected area (step 1). In this case, gradual segmentation of aggregates by Feret diameters should be applied. This ensures the formation of two levels of identification of their sizes.

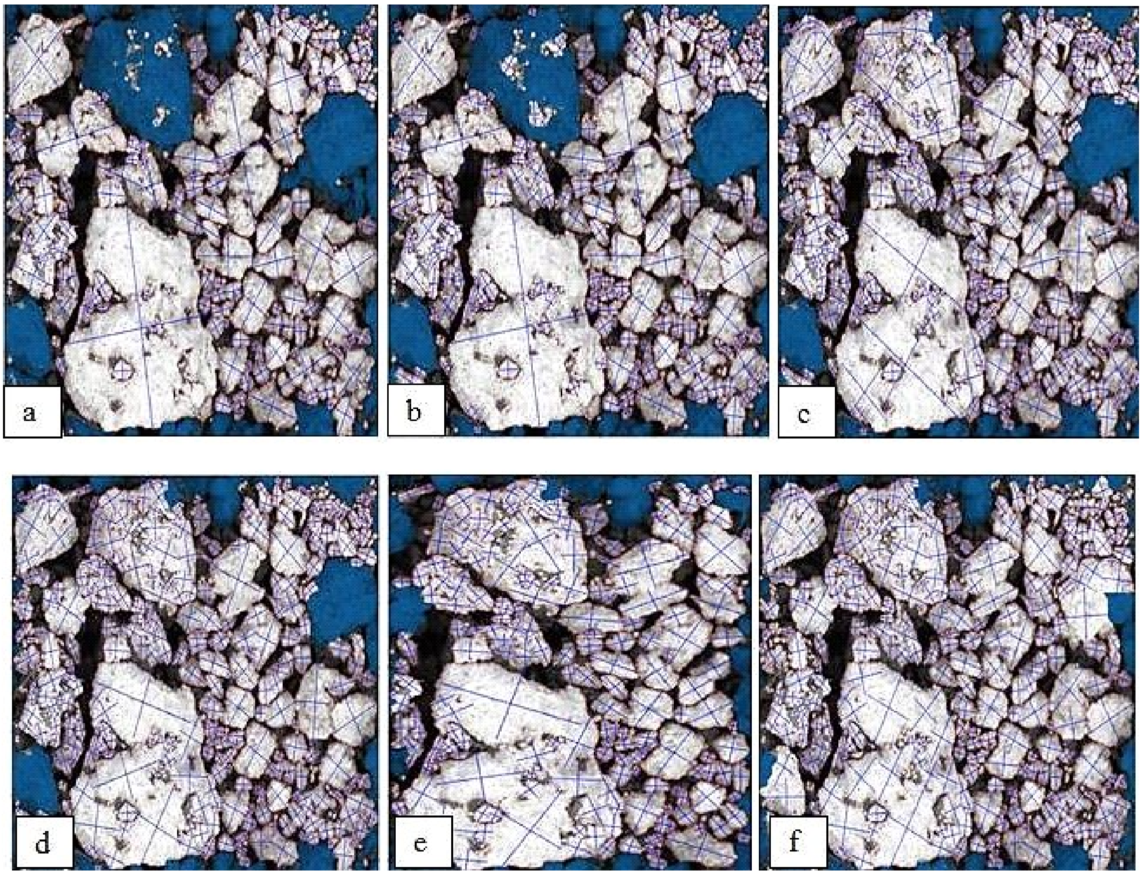

FIGURE 8. Various options for using the BASEGRAIN program to analyze the image of a soil layer with a fractional sieve yield of >10 mm (see text for explanation) (a, b - maximum increase of aggregates curvature (for Step 1) and up to 30º analyzed image plane coverage (for Step 4); c - reduction of the smallest soil particle size (for Step 4) and maximizing the fragmentation of the minimum selected area (for Step 1); d-f - intensification of segmentation in Steps 1, 3, and 4).

As a result, the structural and substructural dimensions for one soil aggregate are identified (due to the axes of Frett diameters b and c) (Figure 8c). The gradual intensification of segmentation in steps 1, 3, and 4 led to an increase in the substructural analysis of soil aggregates and the maximum possible coverage of the image plane (Figure 8d-f).

In the first approach of the program settings to the stage of the actual analysis in the image plane, soil aggregates that were not taken into account in the assessment remained unaccounted for (Figure 8a (aggregates are colored blue)). Taking into account the established features of the formation of the morphometry of soil aggregates while reducing the size of the sieve output fraction, the use of the BASEGRAIN program was methodologically more effective. The main task of the program settings was to clearly identify the selected smallest soil aggregate and to adjust the program in steps 1-5 so that the discreteness of the selected zone of the smallest aggregate forms a coherent and clear structure by Feret diameters. For example, the application of the program for the analysis of the soil fraction of 3-2 mm is shown in Figure 9 (positions a-f).

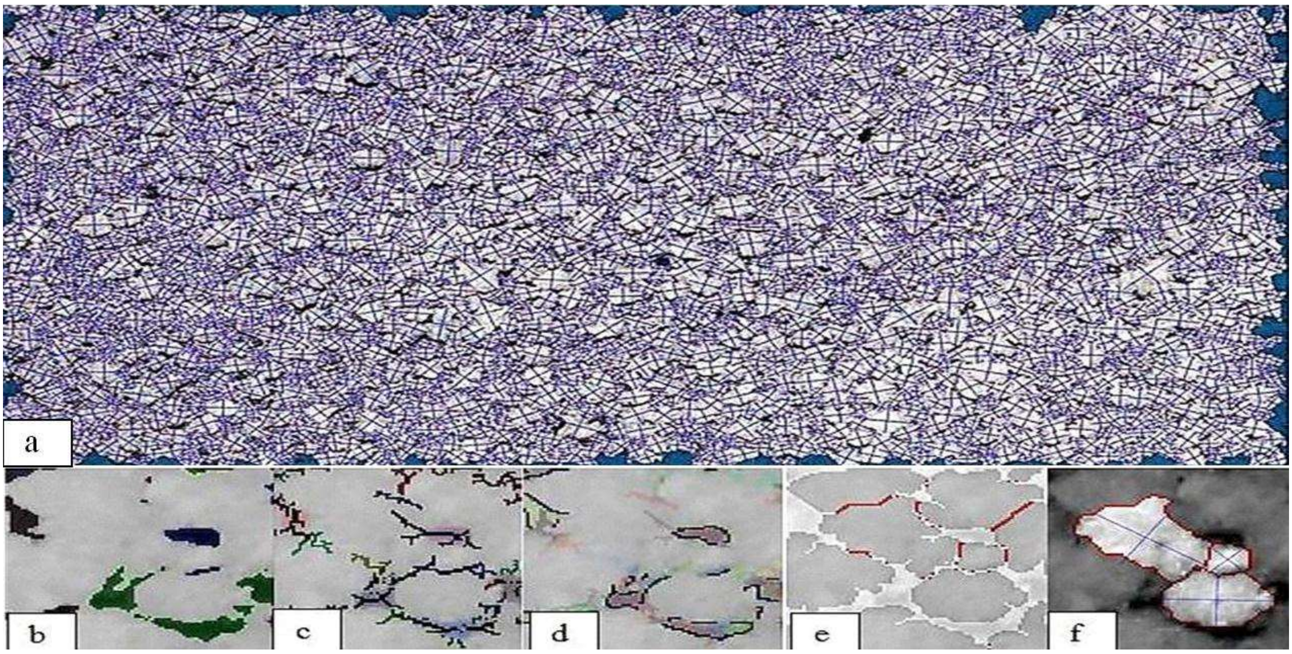

FIGURE 9. Various options for using the BASEGRAIN program to analyze the image of the soil layer of the 3-2 mm fractional sieve output (a - general view of the program window after analysis; b-f - sequential window of results at steps 1-5 of setting the analysis parameters).

The mentioned variability of analysis paths is not noted in the basic publications on the practical application of the BASEGRAIN program (Detert & Weitbrecht, 2013) because it is focused primarily on polished smooth stony structures of sedimentary riverbed rocks. However, by combining the adjustment of the items of program Steps 1-5 with a certain disregard for the marked optima, given the primary specificity of the program. It can be adapted to analyze the structural properties of soil and other materials of more complex indicators, as confirmed in the studies of Harvey et al. (2022) and Garefalakis et al. (2023). The possibility of its application to assess the structural loosening of the soil after different periods of post-harvest green manure using oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers. as a valuable phytomeliorant and phytoremediant (Tsytsiura, 2020)) was investigated (Fig. 10). As in the case of FijiImageJ2 and WipFrag programs, BASEGRAIN program was used for the analysis of soil layer with a sieve yield of 2-1 mm and <1.0 mm. There were methodological difficulties associated with the clarity of aggregate segmentation in the image plane due to the fine dispersion, image resolution, and the presence of impurities of the dust fraction (0.25-0.50 mm).

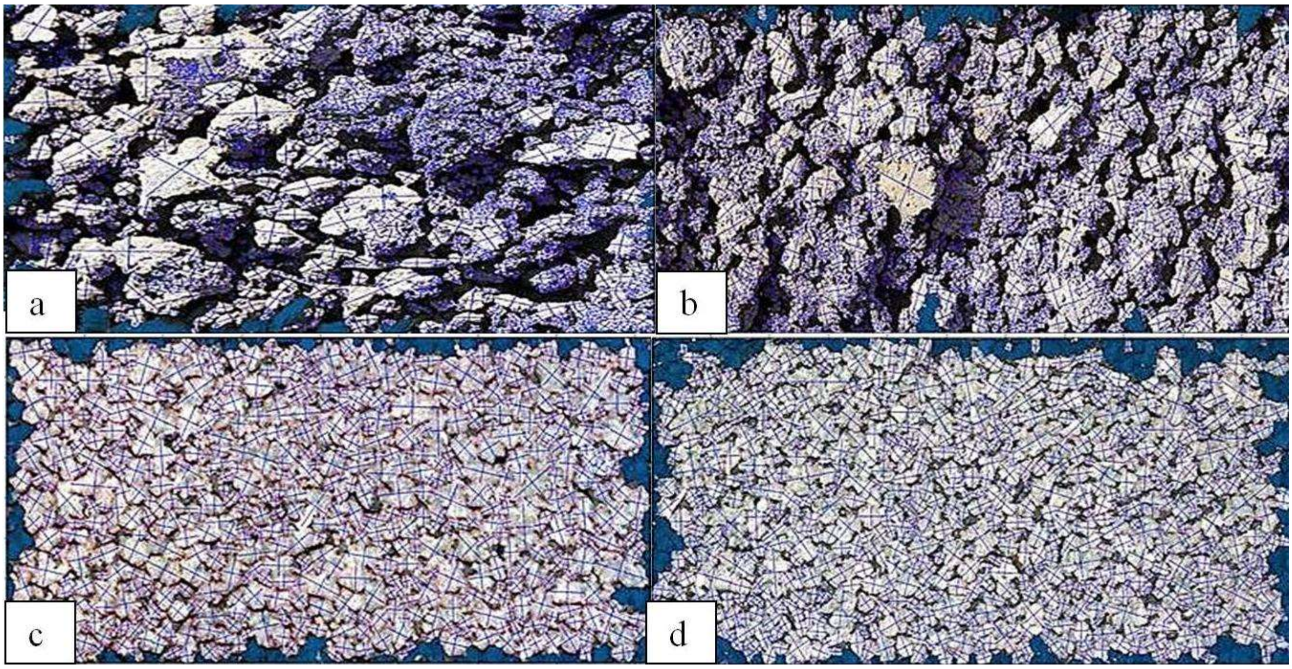

FIGURE 10. Different variants of direct field application of BASEGRAIN program for soil surface image analysis (a - soil after sunflower without green manure; b-f - after corn without green manure; c - variant with post-harvest green manure with oil radish (*Raphanus sativus* L. var. *oleiformis* Pers.) for 3 years; d - variant with post-harvest green manure with oilseed radish for 5 years).

These factors make it impossible to achieve effective identification of soil particles with an area less than 20-23 px (Graham et al. 2005: Detert & Weitbrecht, 2013). This character of the permissible methodological interval of fractions in the analysis of meso- and microstructure of soil based on the analysis of photo images had been noted in other studies (Yudina et al., 2018; van der Meer & van Mourik, 2019; Fomin et al., 2021, 2023; Garefalakis et al., 2023).

The effectiveness of the BASEGRAIN program was tested by calculating individual indicators for soil samples obtained by dry sieving with a mesh diameter of 2, 3 mm (Figure 11). Due to the use of this program, the formation of an additional mathematical and statistical base of indicators was achieved.

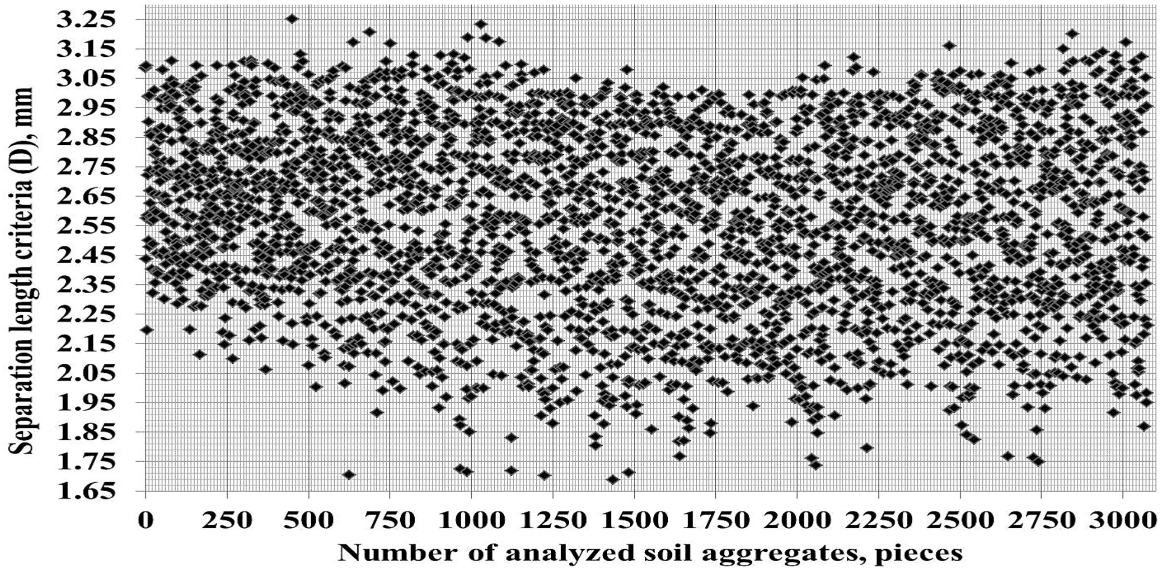

FIGURE 11. Distribution of soil aggregates according to the separation criterion (D) based on the results of the generated data block when processing the photo image of the soil layer of the fractional sieve output of 3-2 mm by the BASEGRAIN program (summary data set for 3075 (N) soil aggregates for 10 fields of processed images).

The results also indicate certain disadvantages of using sieves with classical round holes for particle size analysis of soil. This is mentioned in the studies of Stähly et al. (2017) and Garefalakis et al. (2023). Thus, in the output of the 3-2 mm sieve, soil aggregates larger than 3 mm and smaller than 2 mm were detected using the BASEGRAIN program. A negative asymmetry was found with a shift in the distribution to the interval >3.0 mm while maintaining the average value of D (2.856 mm) (Table 1). This confirmed the conclusions about the complex morphological configuration of soil aggregates with a complex formation of vertical and horizontal Ferret diameters. Due to the presence of shapes with a pronounced asymmetry of the b and c axes (according to Equation 1), soil particles with a diameter of more than 3.0 mm can, under intensive separation of the sieve system, fall into the output of the 3-2 mm fraction.

By analogy, the same features were noted for the 3-5 and 5-7 mm fractions. This confirmed the conclusions of Valsangkar (1992), Ciric et al. (2012), Yudina et al. (2018), Hussain et al. (2020) and Fomin et al. (2023) regarding the preservation of the polymorphometry of soil aggregates during their sequential fractional crushing.

TABLE 1. Statistical evaluation of the interval identification of soil aggregates for the output of the 3-2 mm sieve in the BASEGRAIN program frame (average for 10 repetitions at 4 image acquisition positions).

Interval of criterion D	Number of soil aggregates	Statistical evaluation within an interval			
		average	st. dev.	coefficient of variation C_v (%)	dispesion
1.6-1.8	14	1.698	0.218	12.839	0.095
1.8-2.0	29	1.851	0.205	11.075	0.115
2.0-2.2	84	2.155	0.287	13.318	0.109
2.2-2.4	281	2.307	0.309	13.394	0.118
2.4-2.6	409	2.518	0.407	16.164	0.156
2.6-2.8	532	2.684	0.402	14.978	0.148
2.8-3.0	585	2.907	0.425	14.620	0.135
3.0-3.2	548	3.095	0.417	13.473	0.124
3.2-3.4	508	3.309	0.384	11.605	0.112
3.4-3.6	83	3.510	0.311	8.860	0.091
3.6-3.8	3	3.704	0.095	2.565	0.104
For array	3075	2.856	0.345	12.080	0.119

CONCLUSIONS

The use of software packages FijiImageJ2, WipFrag (v.3.3.14.0) and BASEGRAIN (v.2.2.0.4) significantly expands the possible base of morphometric and granulometric data that can be obtained using the standard method by obtaining an interval of soil aggregate fractions by sieving on sieves of different hole diameters. The use of the 'View5D' plug-in of the FijiImageJ2 software package made it possible to determine the microrelief of the soil surface in the photo image in a given direction, which from an instrumental point of view would have required the use of a soil profiler or other special devices and the additional costs associated with it. The use of WipFrag (v.3.3.14.0) and BASEGRAIN (v.2.2.0.4) software allowed to identify soil aggregates by individual morphometric parameters (ratio of certain boundary fractions with graphical representation, Feret diameter, separation length criterion (D)), which ensured the formation of an individualized data set that significantly expands the possibilities of their statistical analysis and subsequent scientific interpretation in the practice of soil science.

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