Soil Research 54 (3) 354-359 (2016)

Applicability of the photogrammetry technique to determine the volume and the bulk density of small soil aggregates

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Running title

Photogrammetry technique on small soil aggregates

ABSTRACT

The aggregate density (ρ) is defined as the relationship between the mass and the volume occupied by an aggregate. Although most studies have been addressed to characterize ρ on large to medium soil aggregates sizes (>4 mm in diameter), little information is available for the smaller aggregates (<4 mm). The objective of this paper is to test the viability of the photogrammetry (PHM) technique to determine the volume and the subsequent ρ of small soil aggregates (ranging between 1 and 8 mm in diameter). The method uses a standard digital camera that photographs a rotating aggregate, and reconstructs its three-dimensional surface and the corresponding volume. To validate the method, the volume estimated with PHM on rough stones of different sizes (from 1 to 16 mm in diameter) was compared to the corresponding volume measured by the Archimedes' principle. The method was tested on soil aggregates from 1 to 8 mm in diameter, collected from two sites under conventional and conservation tillage treatments. The strong correlation (R^2 >0.99; p <0.0001) between the volumes estimated on rough stones with the PHM and Archimedes methods demonstrates that this technique can be satisfactorily used to estimate the volume and, consequently, the ρ of small soil aggregates. Results showed an increase of ρ with decreasing the aggregate size. A general trend of increase in ρ with the degree of soil disturbance by tillage was also observed.

Keywords: Soil clods; Aggregate surface; Tillage system

INTRODUCTION

The soil bulk density is defined as the mass of solids that occupy a unit volume of soil (Jury and Horton, 2004). This parameter is related to total soil porosity and is commonly used as a measure of soil quality, being related to the ease of root penetration into soil, water movement, or soil strength (Grossman and Reinsch, 2002). Values of bulk density depend on the texture, structure, degree of compaction, and shrink–swell characteristics of soil (Hillel, 1998). Under field conditions, in soils with a certain amount of clay (>15%, < 2 μm), the mineral particles (sand, silt and clay) tend to form structured units known as aggregates (Horn et al., 1994). According to Horn (1990), in humid climates, the bulk density values of these aggregates range between 1.45 and 1.65 g cm^{-3}. The formation of the soil structure due to shrinkage and swelling depends not only on the distribution of the pore space in the bulk soil but also on variations in the physical and chemical properties of single aggregates. At the same time, many physical and biological soil processes depend, besides on the organization of soil aggregates, on the internal microscale or aggregate structure (Horn, 1990; Blanco-Canqui et al., 2005a). For this reason, there is an increasing interest in knowing the properties of individual soil aggregates to understand the behavior of the whole soil and its response to management (Munkholm et al., 2007; Blanco-Canqui and Lal, 2008; Blanco-Moure et al., 2012). Although most studies have been addressed to characterize the ρ on large to medium soil aggregates sizes (> 4 mm in diameter) (among others, Benjamin and Cruse, 1985; Saleh, 1993; Lipiec et al., 2012; Surboy et al., 2012), practically nonexistent information for smaller aggregates (<4 mm) is so far available.

In agricultural soils, tillage affects soil aggregation and bulk density by breaking up root systems and large aggregates and exposing organic matter to decomposition and loss. To this respect, bulk density of soil aggregates has been measured in studies that evaluate the effect of different management practices on soil physical conditions (Materechera and Mkhabela, 2001; Munkholm and Schjønning, 2004; Blanco-Canqui et al., 2005b). However, ρ data from long-term conservation tillage systems are scarce and also variable despite the increasing interest in these alternative systems in most countries around the world (Friedrich et al., 2012).

The most common procedure to measure ρ is the clod method (Blake and Hartge, 1986). In this method, a dry clod of a known weight is coated with a water-repellent substance and the sample is weighed in water. Making use of Archimedes' principle, the volume of coated clod is calculated from the clod water displacement (Saleh, 1986; Grossman and Reinsch, 2002). However, this method, that is time-consuming, needs clods between 4 and 10 cm which should be sufficiently stable for handling (Palmer and Troeh, 1995). On the other hand, removing the coating is difficult, tedious and subject to error., Clod density can also be estimated by an easier, less time-consuming method, which consists of saturating the porosity of small clumps or aggregates with kerosene before measuring the buoyant force in this liquid (Monnier et al., 1973). This technique is suitable for samples with low macroporosity, at least 15% clay and a silty skeleton; it can thus be used on several dozen aggregates at the same time (2-5 g of soil), and thus a more representative sample than a single aggregate. Alternatively clod density has been measured by gamma-ray attenuation (Benjamin and Cruse, 1985) or with an automated three-dimensional laser scanning technology (Rossi et al., 2008). Although these techniques are non-destructive, the relatively high cost of these equipments precluded widespread use. More recently, Stewart et al. (2012) used the photogrammetry technique to estimate the bulk density of soil clods ranging in volume from 15 to 40 cm^3 (diameter between 30 and 40 mm). This method, which has been successfully employed to characterize the soil roughness (Taconet and Ciarletti, 2007, Taconet et al., 2010) and microrelief (Aguilar et al., 2009), uses a standard digital camera that photographs a rotating clod, which allows reconstruction of its three-dimensional surface, and subsequent calculation of its volume. However, although this method has been successfully tested on medium to large soil aggregates, its feasibility on small aggregates has not been still demonstrated.

Due to the lack of information concerning the bulk density of small soil aggregates, mainly because of the difficulties to measure the volume of so small units, new efforts should be done to adapt the current available methods to cover these necessities. The objective of this work is to test if the photogrammetry technique (PHM) can be used to estimate the volume and the subsequent bulk density of small soil aggregates, i.e. with diameter ranging between 1 and 8 mm. The method was validated with respect to the Archimedes method in rough stones with diameter ranging from 1 to 16 mm in diameter. Then it was subsequently used to measure the volume and the corresponding bulk density of the small soil aggregates collected from two different soils under different tillage systems.

MATERIAL AND METHODS

Experimental design

To determine the volume of soil aggregates, the samples are placed on a rotating imaging stand (Fig. 1a), which, similarly to Stewart et al. (2012), includes a calibration object of known volume. In our case, the calibration object was a wood cylinder of 6.04 mm diameter and 10 mm high, with a red ring painted in the middle of the cylinder (Fig. 1b). The ring was subsequently used to scale the digitized aggregate. A 2 mm-thick transparent methacrylate disc was placed between the aggregate and the cylinder, and the rotation of the imaging set was powered up with an electrical motor. To prevent imprecision in the aggregate volume measurement, the flattest face of the aggregate was placed against the methacrylate disc surface. A single-board microcontroller (Arduino), which connects the motor to the camera and a computer, allowed controlling the number of photos per rotation (Fig. 1a). The soil aggregate and the cylinder were photographed using a Nikon D80 camera of six megapixel with a 105-mm (Micro Nikkor 105 mm1:2.8 G) lens, and the photos were automatically sent and saved in the computer. Depending on the aggregate size, imaging stand was positioned between 0.20 and 0.40 m from the camera focal plane. A total of 30 and 40 images per rotation were taken for aggregates larger and smaller than 4 mm, respectively. The photo exposure time was about 3-4 seconds and the minimum diaphragm aperture was selected. This means a total of 6 minutes per aggregate.

The photos were joined together using the Agisoft PhotoScan software (Fig. 2a). This software uses common points between photos to create three-dimensional point clouds of x,y,z- and r,g,b-referenced vertices. The reconstructed aggregate was converted into .ply (polygon) format and then it was manipulated using the freeware program Meshlab (Fig. 2b). Within Meshlab, color selection filters and manual removal of extraneous vertices were used to isolate the aggregate point clouds. Poisson surface meshes were used to reconstruct the aggregate. This technique considers all the points at once, without resorting to heuristic spatial partitioning or blending, and is therefore highly resilient to data noise. This approach allows a hierarchy of locally supported basis functions, and therefore the solution reduces to a well conditioned sparse linear system (Kazhdan et al., 2006). Photogrammetry technique provides a cloud of points that need to specify arbitrary scale. Scaling of the soil aggregate required the following steps. Using a chromatic analysis, the points of the red ring drawn on the wood cylinder were detected and located. These points were fitted to a circle using the least squares method, and real dimensions of the diameter cylinder calculated. Once the aggregate was scaled, its surface and volume were numerically calculated. Since Poisson reconstruction provided a mesh made with a set of connected triangles, the aggregate surface was calculated as the sum of the areas of these triangles. To calculate the aggregate volume, the aggregate was adjusted to a cube, which was divided into 1000x1000x1000 small cubes. Making use of a discrete algorithm, the small cubes were successively occupied from the center to the wall of the aggregate, and the volume was calculated as the sum of the small cubes contained within the surface of the aggregate. The 1000x1000x1000 partition was selected from a preliminary analysis of the results convergence to obtain sufficient accuracy. This process, which could be simultaneously applied to different aggregates, took about 15 minutes per aggregate.

Method validation and testing

This method was validated by comparing the volume of rough stones measured by the Archimedes' principle to the corresponding values estimated with the PHM technique. A total of 16 rough stones of different sizes (1-4, 4-8 and 8-16 mm in diameter) were dried, weighed and immersed in distilled water. The stones were placed in a small receptacle immersed in water, and the volume was calculated according to the Archimedes' principle. The water temperature was taken and the water density corrected. Next, the same stones were placed in the rotating imaging stand and the stones volume were estimated according to the above described procedure.

The PHM method was subsequently used to estimate the volume of soil aggregates and evaluate the sensitivity of this method to detect differences in bulk density of aggregates from soils under different tillage systems. Soil samples (0-5 cm depth) were collected from two different sites, Peñaflor and Torres de Alcanadre, located in the Zaragoza province (NE Spain). Details on soil characteristics and management for each site are given in Blanco-Moure et al. (2012). Briefly, in Peñaflor, the soil sampling was carried out in research plots from a long-term tillage experiment at the dryland research farm of the Estación Experimental de Aula Dei (Consejo Superior de Investigaciones Científicas). Three tillage treatments were compared under the traditional cereal-fallow rotation in the area: conventional tillage with mouldboard ploughing (CT), reduced tillage with chiselling (RT) and no tillage (NT). A randomized complete block design with three replicates per tillage treatment was used (López and Arrúe, 1995). A composite sample came from each of the 3 tillage plots per treatment (CT, RT and NT) was performed. At the Torres de Alcanadre site (hereafter, Torres), the study was conducted under on-farm conditions (fields of collaborating farmers) where adjacent fields of NT and CT were compared under a continuous cereal cropping. In this case, an undisturbed soil under native vegetation (NAT) close to the NT and CT fields was included in the study. Both soils were medium-textured soils (loam at Peñaflor and sandy loam at Torres), alkaline (pH>8) and with low organic carbon content (OC<20 g kg^{-1}) (Table 1). Soil samplings were made in three different zones within each field (CT, NT and NAT). Three soil samples were collected and mixed to make a composite sample. Once in the laboratory, soil samples were air dried at room temperature (≈20 °C) and sieved to obtain aggregates of three different size classes (8-4, 4-2 and 2-1 mm in diameter). Six aggregate per tillage treatment and size class were selected, weighed and subsequently placed on the rotating imaging stand to measure their volumes and surface areas. The bulk density of the aggregate was calculated as the quotient between the weight and its corresponding volume.

The soil aggregate shape was characterized with the dimensionless index

$$E = \frac{4\pi\left(\sqrt[3]{\frac{3V}{4\pi}}\right)^2}{S} \tag{1}$$

where V and S are the volume and surface of the soil aggregate, respectively. This index, that indicates how close is the aggregate form to a sphere, ranges between 0 (plane) and 1 (sphere). For instance, the E value for a sphere, dodecahedra, cube, or plan surface is 1.0, 0.91, 0.81 or 0.0, respectively. Within each study site, statistical comparisons among treatments were made using one-way ANOVA, assuming a randomized experiment.

For the general characterization of soils, particle size distribution was obtained by laser diffraction analysis (Coulter LS230), organic carbon (OC) and $CaCO_3$ contents by dry combustion with a LECO analyser, and electrical conductivity and pH by standard methods (Page et al., 1982).

RESULTS AND DISCUSSION

The strong correlation (Fig. 3) observed between the volume of the stones measured with the Archimedes' principle and that determined with the PHM technique indicates that, in contrast to the reference clod method, only applicable to medium-large soil aggregates (4-10 cm diameter), this relative inexpensive method is sensitive enough to estimate the volume of soil aggregates with sizes ranging between 1 and 8 mm in diameter.

The average ρ value of soil aggregates determined with the PHM technique ranged between 1.50 and 1.92 g cm^{-3} (Fig. 4.). These results are comparable to those reported in the literature for other soils (Schafer and Singer; 1976; Blanco-Canqui et al., 2005a; Stewart et al., 2012) and varied not only with soil management or tillage treatment but also with the aggregate size. Although the differences among aggregate sizes were not always statistically significant, an increase in ρ with decreasing aggregate size was observed in all cases (Fig. 4). The higher density of small aggregates is also reported in previous studies (Park and Smucker, 2005; Blanco-Canqui et al., 2005a), suggesting that they have lower macroporosity after higher cohesion and more contact points than large aggregates. Soil management had a significant effect on ρ (Fig. 4) with a general trend of increase in ρ with the degree of soil alteration (i.e. NAT<NT<RT<CT). These results are in agreement with previous data of tensile strength of aggregates from these same soils (Blanco-Moure et al., 2012) and indicate that the highest ρ of CT aggregates responds to tillage operations. Tillage disrupts soil aggregates, depleting soil OC, and causes rapid post-tillage consolidation. In contrast, in NT and, especially, in NAT soils, the lower ρ is due to a higher biological activity, promoted by the minimal or no soil disturbance which results in higher porosity and OC content (Blanco-Moure et al., 2012). No large differences were found between Peñaflor and Torres, as expected due to the similar soil texture (medium textures) and OC content (averages of 11.7 and 12.0 g kg^{-1} for the agricultural soils of Peñaflor and Torres, respectively). Considering together the two sites and all treatments, we found that 74% of the total variation in ρ was explained by the aggregate size (d, diameter in mm) and the aggregate-associated OC (g kg^{-1}) as follows

$$\rho = 2.33 + 0.298/d - 0.702 \log \mathrm{OC} \qquad (r^2=0.744;\ P<0.0001) \qquad (2)$$

This relationship (Fig. 5) agrees well with that previously obtained for tensile strength of these same soils (Blanco-Moure et al., 2012), confirming the validity and applicability of the PHM method.

The E index averaged 0.864, ranging from 0.750 to 0.926. This indicates that aggregate shape varied between a dodecahedra and a cube form. The smallest aggregates showed a more spherical shape than the larger ones. No significant differences in E among tillage treatments were observed in Torres. However, the E index calculated in the aggregates from Peñaflor was significantly lower under NT (Fig. 6). Overall, the standard deviation calculated for the E index was lower than 6%, which indicates that the aggregate shape was quite homogeneous.

CONCLUSION

This paper demonstrates the viability of the photogrammetry technique (PHM) to determine the volume of small soil aggregates, with size ranging from 1 to 8 mm in diameter. The method was validated by comparing the volume measured in stones by the Archimedes' principle to the corresponding values estimated with the PHM technique. Next, the method was used to estimate the bulk density of soil aggregates under different tillage treatments. The results demonstrated, likewise, that the PHM method was sufficiently sensitive to detect changes in the aggregate bulk density in response to soil management and tillage.

Acknowledgements

The authors are grateful to Rubén Martín, M. Josefa Salvador and Ricardo Gracia for their help in various technical aspects of this study. The fellowship within this work has been supported by the Ministerio de Ciencia e Innovación of Spain (BES-2011-076839).

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Figure captions

Fig. 1. Rotating imaging stand (a) and wood cylinder, methacrylate disc and soil aggregate set (b).

Fig. 2. Agisoft PhotoScan software (a) and Poisson surface mesh form Meshlab software (b).

Fig. 3. Relationship between the stone volumes measured with the Archimedes' principle and the PHM technique.

Fig. 4. Bulk density of soil aggregates of different size classes as affected by soil management (CT, conventional tillage; RT reduced tillage; NT, no-tillage; NAT, natural soil) collected in Torres de Alcanadre (a) and Peñaflor (b) fields. Different lowercase letters indicate significant differences among tillage treatments for the same aggregate size class ($p < 0.05$). Different uppercase letters indicate significant differences among aggregate size classes for the same tillage treatment ($p < 0.05$). Vertical bar within each column denotes the standard deviation.

Fig. 5. Relationship between measured and predicted bulk density of soil aggregates (*ρ*) using Eq. 2. Data come from soils under different tillage and management systems (cultivated soils under conventional and conservation tillage and natural soil). Vertical bar within each column denotes the standard deviation.

Fig. 6. Aggregate shape index (*E*) calculated for the different size soil aggregates as affected by soil management (CT, conventional tillage; RT reduced tillage; NT, no-tillage; NAT, natural soil) collected in the Torres de Alcanadre (a) and Peñaflor (b) fields. For the same aggregate

size, different letters indicate significant differences at $p<0.05$. Vertical bar within each column denotes the standard deviation.

Table 1. Selected properties of the studied soils in the 0-5 cm depth (CT, conventional tillage; RT, reduced tillage; NT, no tillage; NAT, natural soil).

Site	Treatment	pH (H_2O, 1:2.5)	EC (1:5)[a] dS m^{-1}	Sand	Silt	Clay	$CaCO_3$	Organic carbon
				g kg^{-1}				
Peñaflor	CT	8.4	0.23	287	463	250	462	10.7
	RT	8.4	0.19	318	439	243	466	11.1
	NT	8.3	0.31	313	451	236	473	13.3
Torres de Alcanadre	CT	8.4	0.15	584	281	135	235	10.5
	NT	8.2	0.25	615	269	116	223	13.4
	NAT	8.4	0.15	695	215	90	233	16.8

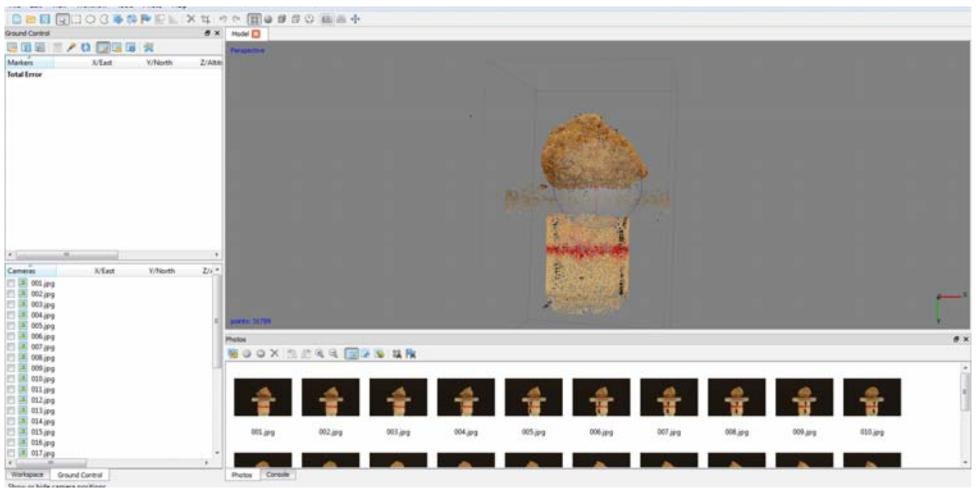
[a] EC, electrical conductivity.

a **b**

Camera
Aggregate
Arduino
Motor
Aggregate
Methacrylate disc
Red ring
6.04 mm
Wood cylinder

Figure 1.

a



b

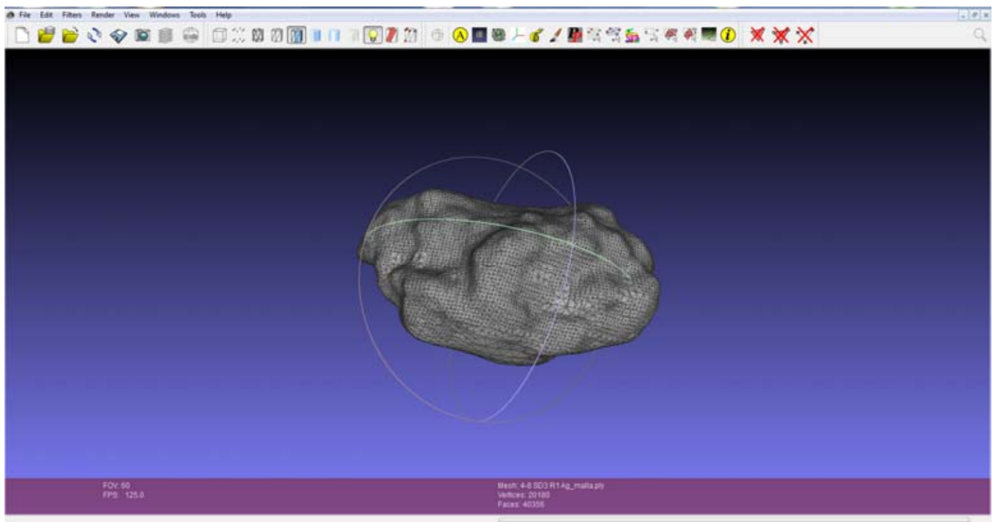


Figure 2.

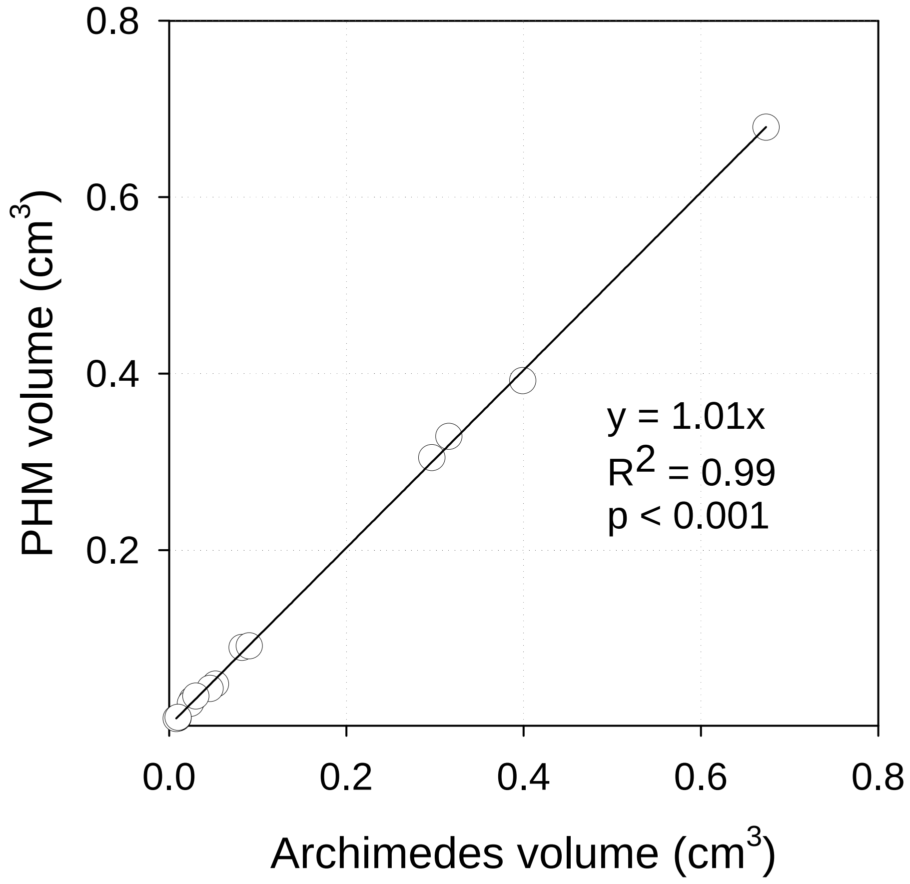
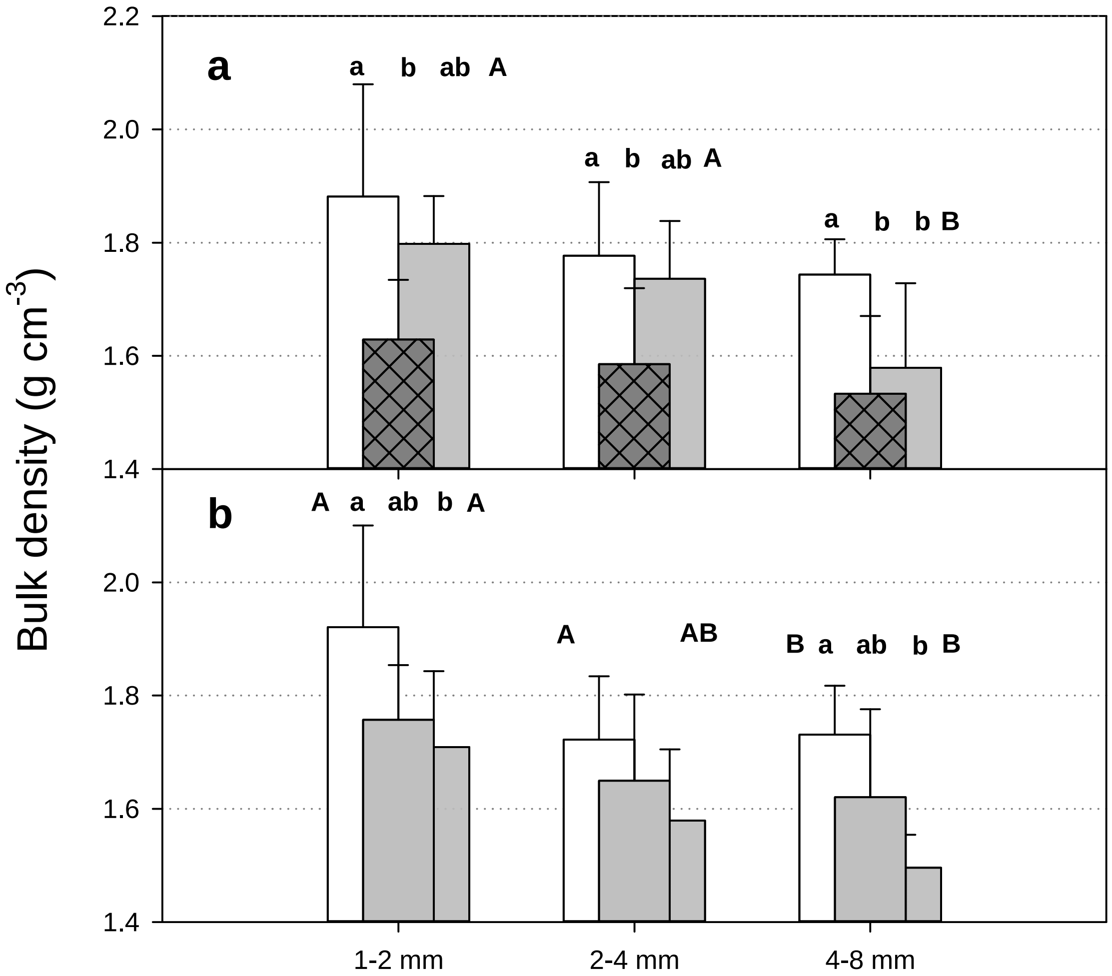

0.8
0.6
0.4
0.2
PHM volume (cm3)
y = 1.01x
R2 = 0.99
p < 0.001
0.0
0.2
0.4
0.6
0.8
Archimedes volume (cm3)

Figure 3.



2.2
2.0
1.8
1.6
1.4
a
a b ab A
a b ab A
a b b B
b
A a ab b A
A
AB
B a ab b B
Bulk density (g cm-3)
1-2 mm
2-4 mm
4-8 mm

Figure 4.

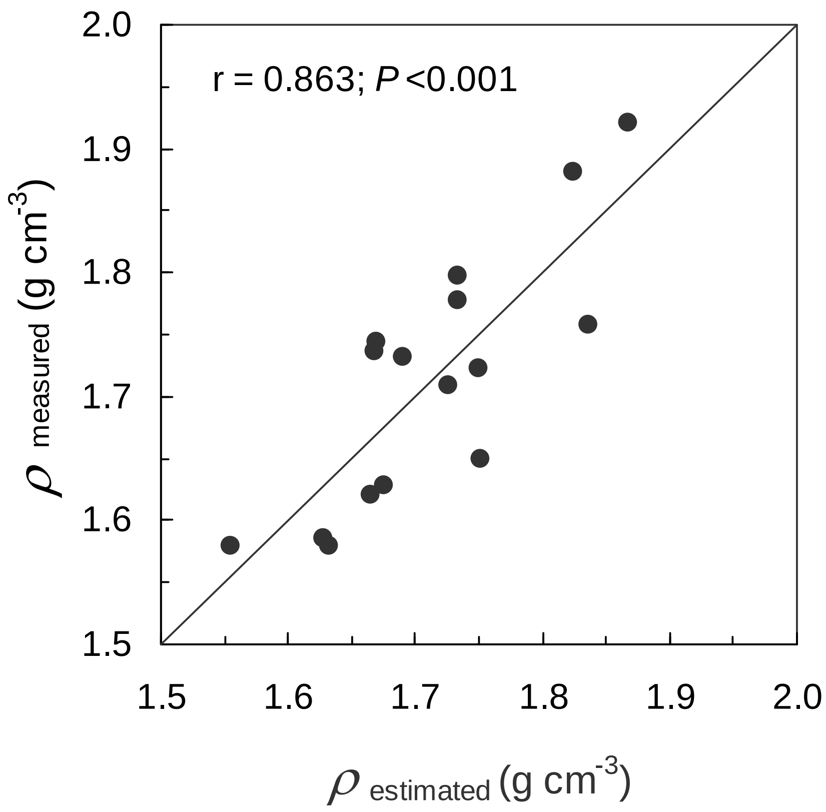

r = 0.863; P <0.001
2.0
1.9
1.8
1.7
1.6
1.5
1.5
1.6
1.7
1.8
1.9
2.0
ρ measured (g cm-3)
ρ estimated (g cm-3)

Figure 5.

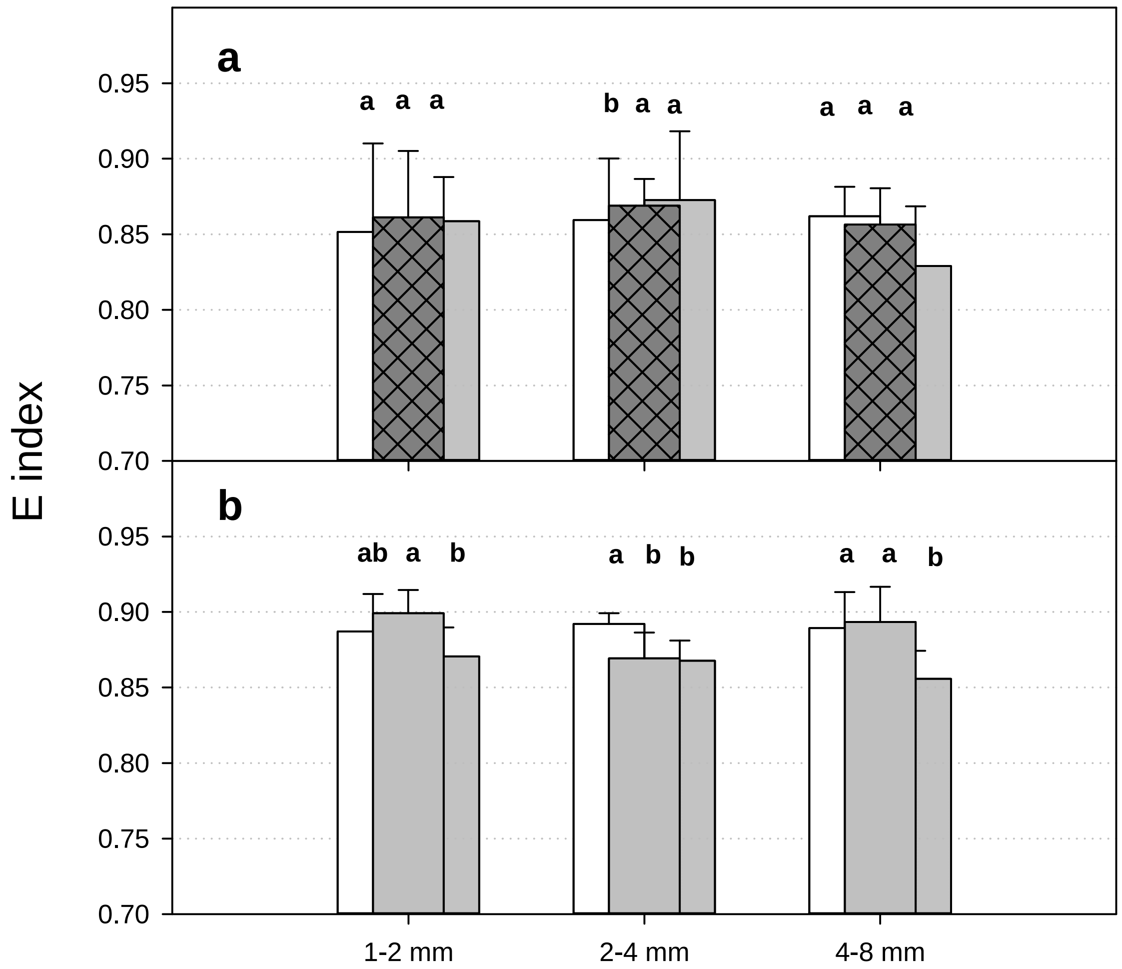

a
b
E index
0.95
0.90
0.85
0.80
0.75
0.70
a a a
b a a
a a a
ab a b
a b b
a a b
1-2 mm
2-4 mm
4-8 mm

Figure 6.