SOIL AGGREGATE STABILITY INDEX ON AGRICULTURAL, PLANTATION, AND FOREST LANDS

Yayat Hidayat[1)]*, Dwi Putro Tejo Bakoro[1)], Wahyu Purwakusuma[1)], Mariana Sella Siregar[2)], dan Muhammad Haris Achyar Ramadhi[2)]

[1)] Department of Soil Science and Land Resources, Faculty of Agriculture IPB University, Bogor 16680
[2)] Alumni of Department of Soil Science and Land Resources, Faculty of Agriculture IPB University, Bogor 16680

ABSTRACT

The soil aggregate stability index is one of the critical indicators of soil physical quality, primarily related to the soil's ability to absorb water into the soil and the soil's resistance to rainwater splashing and surface flow erosion in the soil erosion process. The study aimed to determine the soil aggregate stability index class criteria using the dry and wet sieving methods on the OSK 10701 sieve type and to identify the stability of soil aggregates on agricultural land, plantations, and forests around the IPB Dramaga campus. The transformation of the soil aggregate stability class criteria from the conventional sieve to the OSK 10701 sieve types gave excellent results with a coefficient of determination (R^2) of 0.89. The soil aggregate stability index differs significantly between soil types and land uses. Podsolic Jasinga has a higher aggregate stability index than Podsolik Dramaga, Regosol Dramaga, and Latosol Dramaga in the upper layer (0-20 cm) and the lower layer (20-40 cm). Forests have a better aggregate stability index than conservation agricultural land, conventional agricultural land, rubber plantations, and oil palm plantations. The difference in stability index between land uses is closely related to soil organic matter contents. Although the soil is denser/more compact, the soil in oil palm and rubber plantations has a lower stability index and is classified as unstable.

Keywords: conservation agriculture, forest, oil palm plantation, rubber plantation, soil aggregate stability index

INTRODUCTION

Soil aggregate stability is one of the soil's most important physical proper-ties supporting the hydrological function (Moncada et al., 2015) of agricultural land, plantations, and forests. Aggregate stability measures the ability of soil aggregates to withstand external destructive forces when the soil is exposed to rainwater splashing, surface flow erosion, soil expansion, shrinkage processes, and soil tillage (Papadopoulos et al., 2009). Soil aggregate stability is a crucial indicator of soil quality, where aggregate stability is a manifestation of the physical, chemical, and biological properties (Doran et al., 1996). Aggregate stability is a physical property of the soil that manifests the resistance of soil aggregates to the effects of disintegration by water and mechanical manipulation.

Soil aggregate stability is generally measured using dry and wet sieving methods. Aggregate stability is calculated as the fraction of aggregates that survive after receiving external crushing pressure (Angers & Carter, 2020), with Mean Weight Diameter (MWD) as an indicator of soil aggregate stability. The greater the MWD, the greater the size of the soil aggregate agglomeration and the stronger the aggregate/soil structure stability (Crastignano & Stelluti, 1999). The stability of soil aggregates obtained from this method is greatly influenced by the sieving time and the size of the sieve hole diameter used (Baskoro & Manurung, 2005). Soil with low aggregate stability will immediately fragment into small aggregates/granules when soaked, raised, and lowered in water. At the same time, the soil with high aggregate stability will remain stable after the wet sieving process. Measurement of soil aggregate stability in the Soil and Water Conservation division uses two series of sieves, namely a) conventional sieve (sieve developed by Yoder, 1936 and De Boodt, 1959; in Kurnia et al., 2006) and b) OSK 10701 sieve (Ogawa Seiki Limited).

The stability of soil aggregates is greatly influenced by the type and amount of clay, the texture and structure of the soil, the amount of organic matter, and the type and amount of cations found in the adsorption complex. Soils that have developed in the final stage (senile stage) that have undergone the eluviation and illuviation of clay and humus usually have better aggregate stability than young soils (virile stage). Likewise, soils with a high level of sesquioxide have better soil aggregate stability.

Land use and management will affect the composition of soil aggregates and their stability, which in turn affects the structure and health of the soil (Li, 2023). Land use with dense vegetation, such as forests and agroforestry lands, can produce organic matter continuously so that the soil's organic matter content becomes higher than agricultural land. Management of agricultural and plantation land that always cleans up plant residues and weeds thrown out of agricultural land will have a lower organic matter content, causing the soil aggregate stability to be low.

This study aims to a) determine the criteria of soil aggregate stability index classes for the OSK 10701 sieve and b) identify the soil aggregate stability index in several types of soil and land use around the IPB Dramaga campus.

MATERIALS AND METHODS

Time and Location of the Study

Our study was conducted with meticulous attention to detail and thoroughness. It spanned from April to July 2021 and from June 2022 to January 2023, covering a range of locations including the Cikabayan Education Garden, IPB Dramaga Campus, Dramaga Research Forest, and PTPN VIII Oil Palm Plantation, Division IV of Cigelung, Bogor Regency. Soil analysis was conducted at the Soil and Water Physics and Conservation Laboratory and the Land

*) Penulis Korespondensi: Telp. +6281314535163; Email: yahida@apps.ipb.ac.id DOI: http://dx.doi.org/10.29244/jitl.27.2.56-62

Physical Resources Laboratory of the Department of Soil Science and Land Resources, Faculty of Agriculture, Bogor Agricultural University. This comprehensive approach ensures the reliability and robustness of our findings.

Materials and Equipment

The materials used include soil aggregate samples, intact soil samples, disturbed soil samples in various land uses, distilled water, deionized water, distilled water, Potassium Bichromate ($K_2Cr_2O_7$) 1 N, Sulfuric Acid (H_2SO_4), Ferroin indicator 0.025 M, Iron(II) Sulfate ($FeSO_4.7H_2O$) 1 N, Hydrogen Peroxide (H_2O_2) 30%, Hydrochloric Acid (HCl), and Sodium Pyrophosphate ($Na_2H_2P_2O_7$) 0.025 mol. The equipment used in the research was soil sieves with a diameter of 20.5 cm (7 series of conventional sieves) and a diameter of 15 cm (6 series of DIK-2010 OSK 10701 series sieves), hoes, jars, plastic clips, soil pounding hammers, cups, volumetric pipettes, burettes, Erlenmeyers, heaters, and ovens as well as other laboratory equipment.

Dry and wet sieving methods were used to determine the stability of soil aggregates using two types of sieves, namely seven conventional sieve series and 6 DIK-2010 OSK 10701 sieve series. The seven conventional sieve series are 20.5 cm diameter sieves with sieve holes of 7.9 mm, 4.76 mm, 2.83 mm, 2 mm, 1 mm, 0.5 mm, and 0.297. The six OSK 10701 sieve series are 15 cm in diameter with sieve holes of 2.83 mm, 2 mm, 1 mm, 0.5 mm, 0.25 mm, and 0.11 mm. The soil used in dry sieving is 500 gr for conventional sieves and 250 gr for OSK 10701 sieves.

Dry sieving simulates the effect of mechanical stress on the resistance of soil aggregates. In a conventional sieve series, 500 grams of soil aggregates are placed on a series of 7.9 mm, 4.76 mm, 2.83 mm, 2 mm, and 0 mm sieves. All soil aggregates are broken until they pass through the 7.9 mm sieve, and then all sieves are shaken manually 5 times. The amount of soil retained on each sieve is weighed and then transferred proportionally according to the size of the aggregate to be used in wet sieving, as much as 100 grams. Each soil sample is dripped with distilled water with a burette from a height of 30 cm to field capacity, then incubated for 24 hours at a stable temperature. The process of dripping distilled water from a height of 30 cm is a simulation of the impact of raindrops on soil aggregates in the field.

Wet sieving simulates the conditions of surface flow immersion and inundation conditions in the field, using sieve sizes of 4.76 mm, 2.83 mm, 2 mm, 1 mm, 0.42 mm, 0.3 mm, and 0.15 mm. One hundred grams of dry sieving aggregate that has been incubated is placed on each sieve, then sieved for 5 minutes at a puddle height of 2.5 cm with several swings of 50 swings per minute. The same treatment was carried out on the OSK 10701 sieve series using sieve holes of 2.83 mm, 2 mm, 1 mm, 0.5 mm, and 0 mm for dry sieving and sieve holes of 2.83 mm, 2 mm, 1 mm, 0.5 mm, 0.25 mm, and 0.11 mm for wet sieving.

The weight of the aggregate retained on each sieve (w) is weighed, then the mean weight diameter (MWD) between the two sieves (x) is calculated:

$$MWD = \frac{\sum_{i=1}^{N} wi.\bar{x}i}{\sum_{i=1}^{n} wi}$$

The difference between dry sieving MWD and wet sieving MWD is identified as the soil aggregate instability index, so the soil aggregate stability index (ASI) is calculated as:

$$ASI = \frac{1}{indeks\ instabilitas} \times 100$$

The soil aggregate stability index is classified according to the Center for Agricultural Land Resources Research and Development (2006) classification, as presented in Table 1.

Table 1. The classification of soil aggregate stability index

Soil Aggregate Stability Index	Classification
>200	Very very stable
80-200	Very stable
66-80	Stable
50-66	Slightly stable
40-50	Less stable
<40	Unstable

RESULTS AND DISCUSSION

Soil Aggregate Stability Index Class Criteria

Soil aggregates are secondary grains of various soil particles united by organic substances, clays, and silica. These aggregates are grouped into large aggregates (> 2000 µ), macro aggregates (250 µ > aggregates < 2000 µ), and micro aggregates (< 250 µ). Due to flocculation, clay particles usually aggregate into fine-sized microaggregates (Six et al., 2004). The aggregates form larger aggregates due to the cementation of weather-resistant organic matter (humus). Macroaggregates consist of clay complexes, polyvalent cations, and organic molecules, where clay is bound to organic molecules by polyvalent cations. Large aggregates are formed due to the agglomeration of smaller aggregates either due to the cementation of organic matter, fungal mycelium bonds, or bonds by plant hair roots. Macroaggregates generally have higher organic matter content, are less sensitive to soil erosion, and can form larger pores to create better aeration and infiltration rates (Niewczas and Witkowska-Walczak, 2003).

The soil aggregate stability index indicates soil aggregates' resistance to external influences such as mechanical pressure during soil processing, splashes of raindrops, and surface flow erosion when it rains. The larger the soil aggregate, the weaker the bond tends to be, so the aggregate is easily destroyed to form smaller aggregates. Differences in aggregate size and sieves used in determining aggregate stability cause differences in the aggregate stability index obtained (Table 2).

Table 2. Results of measuring the soil aggregate stability index around the IPB campus Dramaga uses conventional sieve and OSK 10701 sieve types

No.	Conventional sieve (sieve hole 7.9 mm)		OSK 10701 sieve (sieve hole 2.83 mm)	
	Soil aggregate stability index	Classification*	Soil aggregate stability index	Classification*
1	45.4	Less stable	263.1	Very very stable
2	33.3	Unstable	179.6	Very stable
3	46.2	Less stable	235.5	Very very stable
4	34.4	Unstable	170.5	Very stable
5	50.3	Slight stable	255.8	Very very stable
6	35.0	Unstable	196.2	Very stable
7	46.1	Less stable	238.9	Very very stable
8	33.5	Unstable	179.7	Very stable
9	42.5	Less stable	222.0	Very very stable
10	32.0	Unstable	176.2	Very stable
11	45.6	Less stable	224.5	Very very stable
12	31.7	Unstable	167.7	Very stable
13	37.0	Unstable	210.1	Very very stable
14	26.7	Unstable	126.3	Very stable
15	39.8	Unstable	202.9	Very very stable
16	27.7	Unstable	124.0	Very stable
17	38.6	Unstable	190.6	Very stable
18	28.0	Unstable	126.8	Very stable
19	31.6	Unstable	199.1	Very stable
20	30.0	Unstable	156.8	Very stable
21	32.8	Unstable	189.8	Very stable
22	30.2	Unstable	152.5	Very stable
23	44.7	Less stable	231.1	Very very stable
24	31.8	Unstable	165.0	Very stable
25	47.3	Less stable	245.2	Very very stable
26	31.7	Unstable	175.0	Very stable
average	**36.7**	**Unstable**	**192.5**	**Very stable**

*) classification of the Center for Agricultural Land Resources Research and Development (2006)

The analysis of variance showed that the stability of soil aggregates produced by the two types of sieves was significantly different. The soil aggregate stability index produced on the OSK 10701 sieve was much higher (±4.2-5.2 times) than the aggregate stability index obtained on the conventional sieve. A smaller aggregate diameter (2.83 mm) on the OSK 10701 sieve indicates that the soil aggregate is relatively resistant to disturbance. Most of the aggregate is a micro and macro aggregate formed due to flocculation and cementation of organic materials. In contrast, the larger aggregate (large aggregate) on the conventional sieve (diameter <7.91 mm) is the result of aggregation of smaller soil aggregates (micro and macro) so that the aggregate tends to be easily destroyed if it experiences external disturbance (due to water immersion and scouring in the wet sieving process). Referring to the criteria of soil aggregate stability index (Center for Agricultural Land Resources, 2006), different average soil aggregate stability index classes were obtained for the same type of soil, namely unstable on a conventional sieve and very stable on an OSK 1070 sieve. The results obtained are contradictory to each other. Therefore, it is necessary to determine the standard criteria for the OSK 10701 sieve type so that the stability index obtained is the same as the conventional sieve type. The classification criteria for the soil aggregate stability index for the OSK 10701 sieve type can be made by projecting the aggregate stability index produced by the conventional sieve into the OSK 10701 sieve criteria (Figure 1).

The Criteria of the aggregate stability index for the OSK 10701 sieve can be seen in Table 3. These criteria are expected to be used as new criteria for the OSK 10701 sieve, considering the high use of the OSK 10701 sieve in the Soil and Water Conservation Laboratory, Department of Soil Science and Land Resources, Faculty of Agriculture, Bogor Agricultural University.

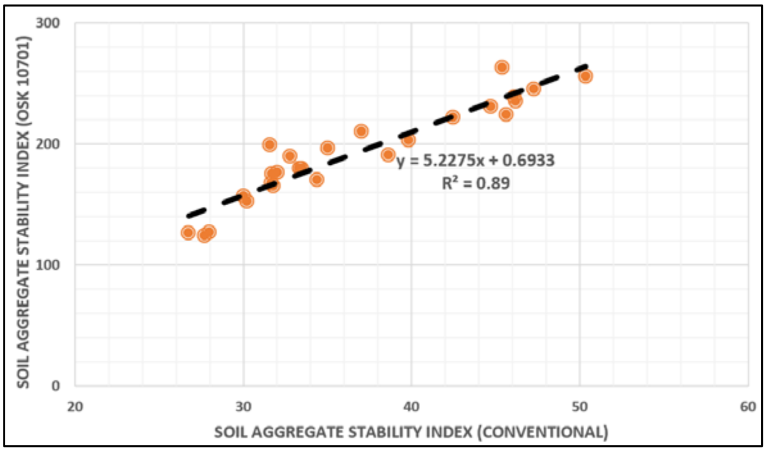

Figure 1. The soil aggregate stability index of the conventional sieve type is projected to OSK 10701 sieve.

Table 3. Criteria the class of soil aggregate stability index for conventional and OSK 10701 sieve types

Class of Soil Aggregate Stability Index	Soil Aggregate Stability Index (Conventional Sieve)	Soil Aggregate Stability Index (OSK 10701 Sieve)
Very very stable	>200	> 1050
Very stable	80-200	420 > x ≤ 1050
Stable	66-80	350 > x ≤420
Slightly stable	50-66	260 > x ≤350
Less stable	40-50	210 >x ≤260
Unstable	<40	<210

Soil Aggregate Stability Index on Several Types of Soil and Land Use

Soil Type

Soil aggregate is an important property that indicates soil health through its relationship with water infiltration and soil erosion resistance (Lal, 2016). Aggregation is the physical arrangement of soil particles bound by several chemical and biological binding agents (Lynch & Bragg, 1985). Chemical binding agents are usually Fe and Al complexes with or without organic binders (Edwards & Bremner, 1967).

The analysis of variance showed that the soil aggregate stability index of several types of soil around Dramaga and Jasinga were significantly different (Table 4). Podsolic Jasinga is an acidic soil rich in Fe and Al sesquioxides, so it has the highest soil aggregate stability index with a value of 109.02 (layer 0-20 cm) and 79.80 (layer 20-40 cm). The stability index of Podsolic Dramaga soil is 91.60 (in the 0-20 cm layer) and 59.75 (20-40 cm), Regosol Dramaga 76.59 (0-20 cm) and 49.45 (20-40 cm), and Latosol Dramaga soil 55.42 (0-20 cm) and 42.87 (20-40 cm).

Stable water-resistant aggregates in the wet sieving process play a significant role in determining the stability of soil aggregates. Podsolic Jasinga has large aggregates (> 2000 µ - 8000 µ) with stable water resistance of ± 72% in the 0-20 cm layer and ± 61.7% in the 20-40 cm layer, with a stability index classified as very stable (0-20 cm) and stable 20-40 cm. Podsolic Jasinga is classified as a medium-good physical quality soil based on the soil aggregate stability index. On the other hand, the large aggregates of Dramaga Latosol soil during wet sieving partially break to form macro aggregates (> 250 µ - 2000 µ) with a proportion of 23.9% in the 0-20 cm layer and 39.2% in the 20-40 cm layer; and micro aggregates (< 250 µ) of 12.2% in the 0-20 cm layer and 14.6% in the 20-40 cm layer (Figure 2).

The soil aggregate stability index differs significantly between land uses. Forests have the highest soil aggregate stability index compared to other land uses, followed by conservation agriculture, conventional agriculture, rubber plantations, and oil palm plantations (Table 5).

Table 4. Soil aggregate stability index of several soil types

Soil Type	n	0-20 cm		20-40	
		SASI	Classification	SASI	Classification
Podsolic Jasinga	3	109.02**a***	very stable	79.80**a***	stable
Podsolic Dramaga	3	91.60**a**	very stable	59.75**ab**	slightly stable
Regosol Dramaga	3	76.59**ab**	stable	49.45**bc**	less stable
Latosol Dramaga	22	55.42**b**	slightly stable	42.87**c**	less stable

SASI: Soil Aggregate Stability Index

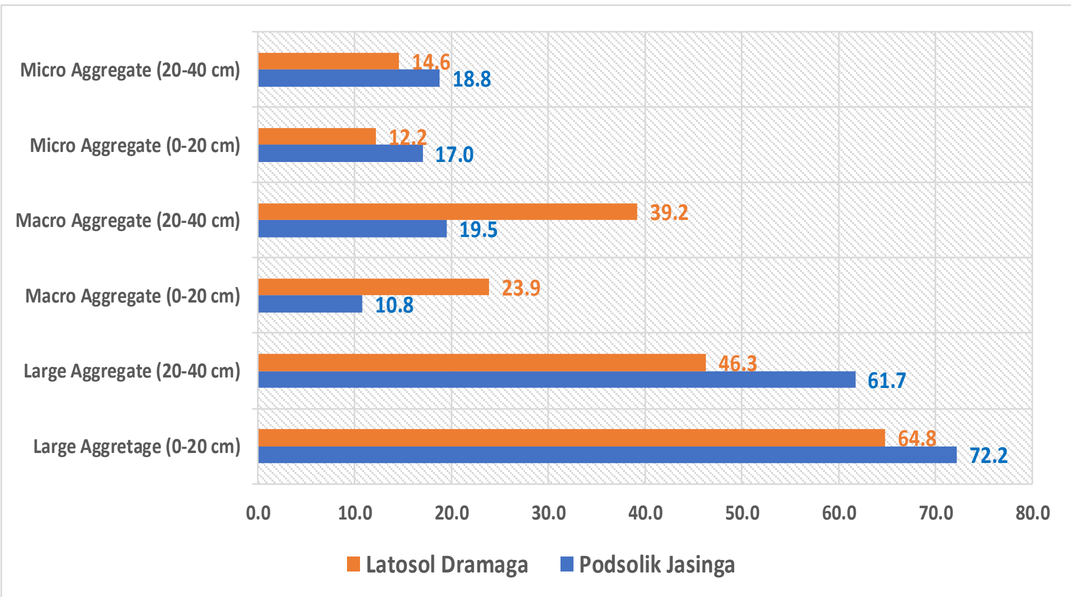

Figure 2. Percentage of large aggregates, macro aggregates, and micro aggregates in wet sieving for Podsolic Jasinga and Latosol Dramaga soils

Table 5. Soil aggregate stability index of Latosol Dramaga in several types of land use

Landuse Type	n	0-20 cm		20-40	
		SASI	Classification	SASI	Classification
Forest	3	95.58**a***	Very stable	57.87**a***	Slightly stable
Conservation Agriculture	6	57.03**b**	Slightly stable	47.58**ab**	Less Stable
Conventional Agriculture	6	43.12**bc**	Less Stable	39.44**bc**	Unstable
Rubber Plantation	3	34.53**c**	Unstable	31.43**c**	Unstable
Oil Palm Plantation	4	32.77**c**	Unstable	32.50**c**	Unstable

SASI: Soil Aggregate Stability Index

Forests are vegetation systems dominated by trees with relatively high vegetation density, and organic matter is produced continuously to accumulate organic matter in the surface soil layer. Because it has a higher organic matter content, plantation forests have a soil aggregate stability index value of 95.58 (very stable) in the 0-20 cm layer and 57.87 (slightly stable) in the (20-40 cm) layer. Oil palm and rubber plantations have the lowest aggregate stability index and are classified as unstable in the 0-20 cm and 20-40 cm layers. The soil stability index is closely correlated with the soil organic matter content. Although not significantly different, the topsoil organic matter content (0-20 cm) in forest land is 3.58%, slightly higher than the organic matter content in conservation agricultural land (3.45%), conventional agricultural land (3.38%), oil palm plantation land (3.09%) and rubber plantation land (2.82%) (Table 6). The correlation between soil organic matter content and soil aggregate stability index can be seen in Figure 3.

Unlike conservation and conventional agricultural land that is always cultivated every planting season, rubber and oil palm plantations are left uncultivated while the plantation is being developed. Plant maintenance and harvesting activities cause rubber and oil palm plantations to become denser, as indicated by higher soil bulk density (Table 7). High soil bulk density in rubber and oil palm plantations is not correlated with a high aggregate stability index because these soils have low soil organic matter content (Table 5). The organic matter content in dead slats (slats where the remaining fronds and leaves of oil palm plants are piled up) has a lower soil bulk density (i.e., 0.906 g cm^{-3}) and is significantly different from the organic matter content of oil palm plantations in live slats (slats where plant maintenance and harvesting activities take place), namely 1.121 g cm^{-3}.

Table 6. Soil organic matter content in several land-use

Land use type	n	Soil organic matter content (%)		
		0-20 cm	20-40 cm	Average
Forest	3	3.58	3.46	3.52
Conservation Agriculture	6	3.45	2.77	3.11
Conventional Agriculture	6	3.38	2.73	3.06
Ruber Plantation	4	3.08	2.46	2.77
Oil Palm Plantation	3	2.82	2.54	2.68

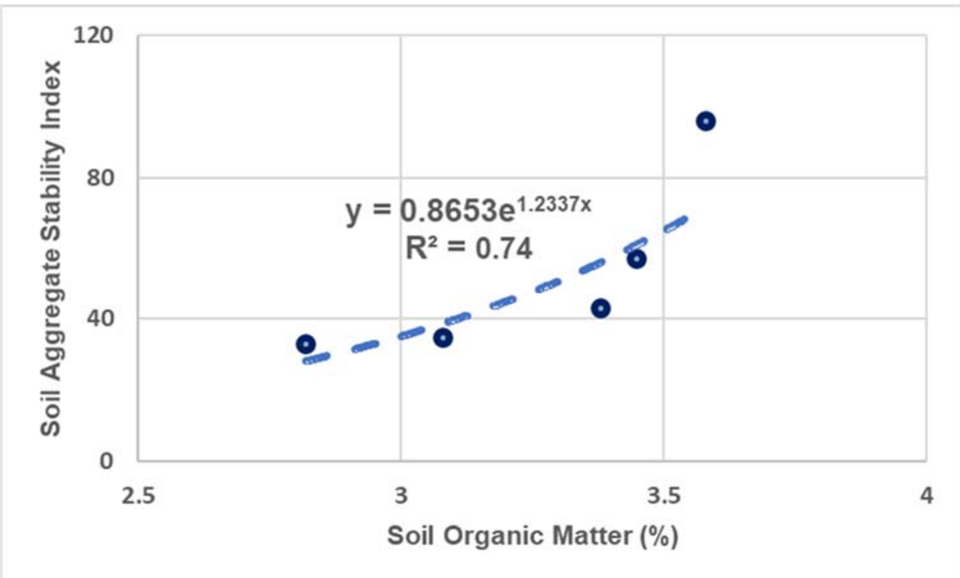

Figure 3. Correlation of soil organic matter content and soil aggregate stability index

Table 7. Soil bulk density on several land-use

Land-use Type	n	Soil bulk density (g cm^{-3})		
		0-20 cm	20-40 cm	Rataan
Oil Palm Plantation (live slat)	2	1.121**a***	1.160**a***	1.080**a***
Rubber Plantation	3	1.017**b**	1.092**b**	1.046**a**
Conventional Agriculture	3	0.924**b**	1.023**b**	0.961**b**
Conservation Agriculture	3	0.908**b**	0.922**b**	0.957**b**
Oil Palm Plantation (dead slat)	2	0.906**b**	0.914**b**	1.012**a**
Forest	3	0.903**b**	0.914**b**	0.957**b**

CONCLUSION AND SUGGESTION

Conclusion

The projection of the aggregate stability index of conventional sieve-type soil to the OSK 10701 sieve type is closely correlated with a coefficient of determination (R2) of 0.89 so that the criteria for the aggregate stability class can be used for the OSK 1070 sieve.

Podsolic Jasinga has the highest soil aggregate stability index with a stability class classified as very stable in the 0-20 cm layer and stable in the 20-40 cm layer. Podsolic Dramaga, Regosol Dramaga, and Latosol Dramaga soils own the following soil stability index. The stability index of Podsolic Dramaga, Regosol Dramaga and Latosol Dramaga respectively are 91.60 (at the depth of 0-20 cm) and 59.75 (at 20-40 cm), 76.59 (at 0-20 cm) and 49.45 (at 20-40 cm), and 55.42 (0-20 cm) and 42.87 (at 20-40 cm)

Forests are a land use system with the highest soil aggregate stability index, followed by conservation agriculture, conventional agriculture, rubber plantations, and oil palm plantations.

The soil aggregate stability index is closely related to soil organic matter content.

Suggestion

The criteria soil aggregate stability index class on this study's OSK 10701 sieve type was constructed using data still limited to the soil around Dramaga and Jasinga. Hence, it needs to be developed for other types of soil with significantly different texture classes (sand, clayey sand, sandy loam, dusty loam, clay, sandy clay, dusty clay, and clay); significantly different levels of soil organic matter (natural forests, plantations, agroforestry, shrubs, mixed gardens, annual crop gardens, dry fields, and horticultural agricultural gardens).

The soil aggregate stability index class criteria can be arranged more simply using the results of wet sieving with the approach of the proportion of stable soil aggregates on various sieve sizes used. The soil aggregate stability index can be determined using the water-stable aggregate distribution, which is obtained through the wet sieving process.

REFERENCES

Angers, D.A. and M.R. Carter. 2020. Aggregation and organic matter storage in cool, humid agricultural soils. *in* Carter, M.R., & B.A. Stewart (Eds.). Structure and organic matter storage in agricultural soils (eBook Published.). CRC Press. Pp. 193–211. https://doi.org/10.1201/9781003075561-9

Baskoro, D.P.T. and H.D. Manurung. 2005. Effect of measurement method and wet sieving time on index of soil aggregate stability. *Jurnal Tanah dan Lingkungan*, 7(2): 54-57. https://doi.org/10.29244/jitl.7.2.54-57

Castrignanò, A. and M. Stelluti. 1998. Fractal geometry and geostatistics for describing the field variability of soil aggregation. *Journal of Agricultural Engineering Research*, 73(I): 13-18. https://doi.org/10.1006/jaer.1998.0385

Costa, O.Y.A., J.M. Raaijmakers and E.E. Kuramae. 2018. Microbial extracellular polymeric substances: Ecological function and impact on soil aggregation. *Frontiers in Microbiology*, 9(2018): 1636. https://doi.org/10.3389/fmicb.2018.01636

Doran, J.W., A.J. Jones and T.B. Parkin. 1996. Quantitative indicators of soil quality: A minimum data set. *In* Doran, J.W. and A.J. Jones (Eds.). Methods for assessing soil quality. Soil Science Society of America Special Publication. https://doi.org/10.2136/sssaspecpub49.c2

Dou, Y., Y. Yang, S. An and Z. Zhu. 2020. Effects of different vegetation restoration measures on soil aggregate stability and erodibility on the Loess Plateau, China. *Catena*, 185(2020): 104294. https://doi.org/10.1016/j.catena.2019.104294

Edwards, A.P. and J.M. Bremner. 1967. Microaggregates in soils. *European Journal of Soil Science*, 18(1): 64–73. https://doi.org/10.1111/j.1365-2389.1967.tb01488.x

Kemper, W.D. and R.C. Rosenau. 1986. Aggregate stability and size distribution. *In* A. Klute (Ed.). Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods. 2nd ed. ASA Inc. and SSSA Inc. Publisher. Madison, Wisconsin. p. 425-442. https://doi.org/10.2136/sssabookser5.1.2ed.c17

Kurnia, U., F. Agus, A. Adimihardja dan A. Dariah. 2006. *Sifat Fisik Tanah dan Metoda Analisisnya*. Balai Besar Penelitian dan Pengembangan Sumberdaya Lahan Pertanian. Departemen Pertanian RI.

Lal, R. 2016. Soil health and carbon management. *Food and Energy Security*, 5(4): 212–222. https://doi.org/10.1002/fes3.96

Li, Y., Z. Ma, Y. Liu, Z. Cui, Q. Mo, C. Zhang, H. Sheng, W. Wang and Y. Zhang. 2023. Variation in soil aggregate stability due to land use changes from alpine grassland in a high-altitude watershed. *Land*, 12(2): 393. https://doi.org/10.3390/land12020393

Lynch, J.M. and E. Bragg. 1985. Microorganisms and soil aggregate stability. *In* Stewart, B.A. (Ed.), Advances in soil science, Vol. 2. Springer, New York, NY. pp. 133–171. https://doi.org/10.1007/978-1-4612-5088-3_3

Moncada, M.P., D. Gabriels, W. Cornelis and D. Lobo. 2015. Comparing aggregate stability tests for soil physical quality indicators. *Land Degradation and Development*, 26: 843-352. https://doi.org/10.1002/ldr.2225

Niewczas, J. and B. Witkowska-Walczak. 2003. Index of Soil Aggregates Stability as Linear Fraction Value of Transition Matrix Elements. *Soil and Tillage Research*, 70(2):121-130. https://doi.org/10.1016/S0167-1987(02)00155-1

Papadopoulos, A., N.R.A. Bird, A.P. Whitmore, S.J. Mooney. 2009. Investigating the effects of organic and conventional management on soil aggregate stability using X-ray computed tomography. *European Journal of Soil Science*, 60(3): 360–368. https://doi.org/10.1111/j.1365-2389.2009.01126.x

Poirier, V., C. Roumet and A.D. Munson. 2018. The root of the matter: Linking root traits and soil organic matter stabilization processes. *Soil Biol. Biochem*, 120(2018): 246–259. https://doi.org/10.1016/j.soilbio.2018.02.016

Rillig, M.C., S.F. Wright and V.T. Eviner. 2002. The role of arbuscular mycorrhizal fungi and glomalin in soil aggregation: Comparing effects of five plant species. *Plant and Soil*, 238(2002): 325–333. https://doi.org/10.1023/A:1014483303813

Six, J., H. Bossuyt, S. Degryze and K. Denef. 2004. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research*, 79(1): 7–31. https://doi.org/10.1016/j.still.2004.03.008

Spohn, M. and L. Giani. 2010. Water-stable aggregates, glomalin-related soil protein, and carbohydrates in a chronosequence of sandy hydromorphic-soils. *Soil Biology and Biochemistry*, 42(9): 1505–1511. https://doi.org/10.1016/j.soilbio.2010.05.015

Tisdall, J.M. and J.M. Oades. 1982. Organic matter and water-stable aggregates in soils. *European Journal of Soil Science*, 33(2): 141–163. https://doi.org/10.1111/j.1365-2389.1982.tb01755.x