



Division - Soil Processes and Properties | Commission - Soil Physics

## Aggregation rate as a function of soil organic matter in heavy clayey Ferralsols

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**ABSTRACT:** Heavy clayey Ferralsols are known for their high capacity to form water-stable macroaggregates. However, little is known about how different size classes of macroaggregates exchange mass with increasing organic matter content. This study aimed to characterize and detail aggregation dynamics with increasing organic matter content in these soils. Profiles of three heavy clayey Ferralsols were sampled to isolate the role of organic matter on the stability of aggregates. In this sampling scenario, a conceptual model was established to calculate the aggregation rate of different size classes of water-stable aggregates. This approach allowed the establishment of a critical value for classifying microaggregates in the studied soils ( $\leq 0.50$  mm) based on their behavior as “building blocks” for macroaggregates when organic matter content is increased. In surface soil layers, where organic matter is higher, most dynamics are expected to happen between macroaggregates classes because free microaggregates are scarce. Consequently, it is important to subdivide macroaggregates into different size classes when evaluating their stability. Quantifying macroaggregates as a single class (e.g.,  $>0.25$  or  $>0.50$  mm) was insufficient in representing the macroaggregation dynamics in heavy clayey Ferralsols.



**Keywords:** Oxisol, macroaggregate, microaggregate, soil aggregate stability, soil structure.

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## INTRODUCTION

The stability of soil aggregates in water increases soil resistance to water erosion (Lu et al., 2016). Although the presence of large water-stable aggregates does not result in high structural quality, it is essential to maintain the soil structure. The importance of soil management for improving aggregate stability through organic matter increment is well documented (Six et al., 2004; Tisdall and Oades, 1982).

Several studies have investigated how management practices or soil usage favor the formation of large macroaggregates in heavy clayey Ferralsols (Salton et al., 2008; Barbosa et al., 2015; Melo et al., 2019, and others). Despite the high capacity of these soils to form macroaggregates is well known, there is a gap in the knowledge about the mass dynamics between size classes of water-stable macroaggregates as a function of soil organic matter increment. This limits the understanding of their behavior and leads to uncertainties regarding the importance of metallic sesquioxides for macroaggregate stabilization (Barthès et al., 2008; Barbosa et al., 2015; Melo et al., 2018).

When other factors are constant, such as texture and mineralogy, organic matter is expected to be the most important factor stabilizing soil aggregates (Melo et al., 2018). We hypothesize that taking samples at different layers in heavy clayey Ferralsols without significant textural variations, isolates the role of organic matter on the stability of aggregates. In this sampling scenario, a high range and a good distribution within the observed range of both variables (organic matter and soil aggregation) can be obtained. Consequently, the calculation of the aggregation rate of each size class of water-stable aggregates as a function of organic matter increment is possible. Here, we aimed to characterize and detail aggregation dynamics with increasing organic matter content in heavy clayey Ferralsols.

## MATERIALS AND METHODS

### Description of sampling sites

Soil samples were collected from Londrina, Guarapuava, and Rondon (Marechal Cândido Rondon) municipalities in the state of Paraná, Brazil. The soils were classified as *Latossolos* according to the Brazilian System of Soil Classification (Santos et al., 2018) and Ferralsols according to the Internal System of Soil Classification (IUSS Working Group WRB, 2015). The X-ray diffraction analyses in the clay fraction revealed the predominance of kaolinite in all soils, with traces of aluminum hydroxy-interlayered vermiculite (diffractograms not presented).

These soils were derived from extrusive igneous rocks from the Serra Geral Formation. According to Köppen's classification system, the climate of Rondon and Londrina is Cfa – humid subtropical with a hot summer. The climate of Guarapuava is Cfb – humid subtropical with a temperate summer (Alvares et al., 2013). The soils from Londrina and Guarapuava had been cultivated under no-till. The soil from Rondon was plowed to a depth of 0.25 m three years before the samples were collected for this study. All areas were cultivated with annual crops. Corn or soybean was cultivated in the summer, and wheat or corn was cultivated in the winter.

### Research design

This observational study investigated the association between organic matter and soil aggregation. We collected three different soil profiles in each area to obtain a natural gradient of organic matter and soil aggregation; 10 samples were collected from each soil profile at different layers. For Londrina soil, samples were collected from the surface layer (0.00-0.10 m) up to 1.00 m. For Guarapuava and Rondon soils, samples were collected up to 0.60 m depth (Table 1). This sampling scheme yielded 30 samples per site, and

**Table 1.** Selected sites and soil properties

Variable/soil property	Unit	Site		
		Guarapuava	Londrina	Rondon
Elevation	m	1043	566	250
Temperature <sup>(1)</sup>	°C	17.2	21.1	20.1
Precipitation <sup>(2)</sup>	mm year <sup>-1</sup>	1938	1641	1656
Sampling layer <sup>(3)</sup>	m	0.00-0.60	0.00-1.00	0.00-0.60
Clay <sup>(4)</sup>	g kg <sup>-1</sup>	715	750	719
Silt <sup>(4)</sup>	g kg <sup>-1</sup>	211	117	148
Sand <sup>(4)</sup>	g kg <sup>-1</sup>	74	133	133
pH <sup>(4)</sup>	-log[H <sup>+</sup> ]	4.55	4.97	4.95
CEC <sup>(4)</sup>	cmol <sub>c</sub> kg <sup>-1</sup>	12.62	11.35	11.55
Al <sup>3+</sup> <sup>(4)</sup>	cmol <sub>c</sub> kg <sup>-1</sup>	0.33	0.05	0.31
Ca <sup>2+</sup> <sup>(4)</sup>	cmol <sub>c</sub> kg <sup>-1</sup>	3.35	4.38	4.31
Mg <sup>2+</sup> <sup>(4)</sup>	cmol <sub>c</sub> kg <sup>-1</sup>	1.23	0.99	2.06
K <sup>+</sup> <sup>(4)</sup>	cmol <sub>c</sub> kg <sup>-1</sup>	0.22	0.82	0.16
Na <sup>+</sup> <sup>(4)</sup>	cmol <sub>c</sub> kg <sup>-1</sup>	0.00	0.00	0.00
Fe <sub>Dit</sub> <sup>(5)</sup>	g kg <sup>-1</sup>	174	319	239

<sup>(1)</sup> Average annual temperature. <sup>(2)</sup> Average total annual precipitation. <sup>(3)</sup> Sampling layers: Guarapuava and Rondon (0.00-0.05, 0.05-0.10, 0.10-0.15, 0.15-0.20, 0.20-0.25, 0.25-0.30, 0.30-0.35, 0.35-0.40, 0.40-0.50, 0.50-0.60 m); Londrina (0.00-0.10, 0.10-0.20, 0.20-0.30, 0.30-0.40, 0.40-0.50, 0.50-0.60, 0.60-0.70, 0.70-0.80, 0.80-0.90, 0.90-1.00 m). <sup>(4)</sup> Average values across all layers. <sup>(5)</sup> Dithionite-extractable iron; measurement performed at the 0.40-0.60 m layer (top of B horizon).

90 samples in the present study. The selected sites and soil properties, including the range of sampling depths, are presented in table 1.

### Total organic carbon content

Total organic carbon (TOC) content was obtained following organic matter oxidation in 0.5 g of soil with 10 mL potassium dichromate (0.167 mol L<sup>-1</sup>) in a sulfuric medium. After oxidation, the residual Cr<sup>6+</sup> was determined by titration with ferrous sulfate (1 mol L<sup>-1</sup>) using diphenylamine as the indicator. The total organic carbon (TOC) was estimated according to equation 1.

$$TOC (g kg^{-1}) = \frac{(Vol_{Blank} - Vol_{Sample}) \times 0.003 \times 1000}{Mass_{Sample} \times 0.77} \quad \text{Eq. 1}$$

in which: TOC is the total organic carbon of the sample (g kg<sup>-1</sup>);  $Vol_{Blank}$  is the volume of FeSO<sub>4</sub> (1 mol L<sup>-1</sup>) necessary in the blank (with 10 mL of potassium dichromate 0.167 mol L<sup>-1</sup>, but without soil);  $Vol_{Sample}$  is the volume of FeSO<sub>4</sub> (1 mol L<sup>-1</sup>) necessary in the sample (with 10 mL of potassium dichromate 0.167 mol L<sup>-1</sup> and with soil); 0.003 is the equivalent weight of C reacting with 1 mL of potassium dichromate (0.167 mol L<sup>-1</sup>); 1000 is a factor for expressing the TOC results in g kg<sup>-1</sup>;  $Mass_{Sample}$  is the mass of the sample used in the analysis; and 0.77 (77 %) is the method efficiency (Pavan et al., 1992).

### Stability of aggregates in water

Soil monoliths were sampled, air-dried, and passed through a sieve with 19 mm openings. Aggregates larger than 19 mm were manually broken in their natural shear planes until they passed through the sieve. For the stability analysis, aggregates were wetted by capillary for 10 min and sieved underwater for 15 min at 45 vertical cycles per minute. For each sample, 150 g of aggregates were analyzed in triplicates of 50 g each. The sieves used for the underwater separation of aggregates had openings of 8, 4, 2, 1, 0.5,

and 0.25 mm. The mass of water-stable aggregates in each class was expressed on a dry basis (105 °C).

The sand fraction was not discounted from the mass of the size classes of water-stable aggregates because it is a constituent of the aggregates in these soils (Castro Filho et al., 1998). Larger organic residues were manually removed before analysis. Additionally, sieves with 0.053 mm openings were not considered necessary because these soils do not disperse spontaneously in water [see Figure S2 in Melo et al. (2021)]. The mean weighted diameter was calculated according to equation 2.

$$MWD (mm) = \sum_{i=1}^n (D_i \times P_i) \quad \text{Eq. 2}$$

in which: MWD is the mean weighted diameter (mm);  $D_i$  is the arithmetic average between the upper and lower limits of the  $i$ -th size class of water-stable aggregates; and  $P_i$  is the proportion of mass (in relation to the role sample) of the  $i$ -th size class of water stable-aggregates.

### Predicting the size classes of water-stable aggregates

The mass of different size classes of water-stable aggregates was estimated as a function of total organic carbon using non-linear regression models in R software (R Development Core Team, 2020). The model parameters were estimated using the Gauss-Newton interactive algorithm in the *nls* function, and they were fitted through graphical analysis and through the functions *SSlogis*, *SSbiexp*, and *lm* from the *stats* package. The models were corrected to improve adjustment. The parameters' significance was tested using a t-test ( $p \leq 0.05$ ). Graphs were generated using the *ggplot2* package (Wickham, 2016).

### Aggregation rate of size classes of water-stable aggregates

The predicted values described in the last section were used to calculate the aggregation rate of size classes of water-stable aggregates. As aggregates <0.25 mm comprise the smallest class, they do not receive mass from smaller classes, and its aggregation rate was calculated by equation 3:

$$\Delta_{< 0.25 \text{ mm}(C_0 - C_1)} = M_{< 0.25 \text{ mm}C_0} - M_{< 0.25 \text{ mm}C_1} \quad \text{Eq. 3}$$

in which:  $\Delta_{< 0.25 \text{ mm}(C_0 - C_1)}$  is the aggregation rate of <0.25 mm aggregates with an increase of TOC content from  $C_0$  to  $C_1$  (in the present study,  $C_1 - C_0 = 0.1 \text{ g kg}^{-1}$ ). The aggregation rate represents the mass flow (net mass transfer) from <0.25 to 0.25–0.50 mm aggregates;  $M_{< 0.25 \text{ mm}C_1}$  is the mass of aggregates (<0.25 mm) in a given TOC content ( $C_1$ ); and  $M_{< 0.25 \text{ mm}C_0}$  is the mass of aggregates (<0.25 mm) in a given TOC content ( $C_0$ ).

The size classes of 0.25–0.50, 0.50–1.00, 1.00–2.00, 2.00–4.00, and 4.00–8.00 mm (8.00–19.00 mm not included) lose mass due to aggregation to subsequent larger classes, but also gain mass by the aggregation of subsequent smaller classes. The mass of water-stable aggregates in these classes, when TOC changes from  $C_0$  to  $C_1$  can be understood as:

$$M_{X \text{ mm}C_1} = M_{X \text{ mm}C_0} + \Delta_{X-1 \text{ mm}(C_0 - C_1)} - \Delta_{X \text{ mm}(C_0 - C_1)} \quad \text{Eq. 4}$$

in which:  $M_{X \text{ mm}C_1}$  is the mass of X-mm aggregates in a given TOC content ( $C_1$ );  $M_{X \text{ mm}C_0}$  is the mass of X mm aggregates at a given TOC content ( $C_0$ );  $\Delta_{X-1 \text{ mm}(C_0 - C_1)}$  is the aggregation rate of X - 1 mm (subsequent smaller-size class) aggregates with an increase of TOC content from  $C_0$  to  $C_1$  (in the present study,  $C_1 - C_0 = 0.1 \text{ g kg}^{-1}$ );  $\Delta_{X \text{ mm}(C_0 - C_1)}$  is the aggregation rate of X mm aggregates (any class between 0.25 and 8.00 mm, in the present study) with an increase of TOC content from  $C_0$  to  $C_1$  (in the present study,  $C_1 - C_0 = 0.1 \text{ g kg}^{-1}$ ).

Consequently, the aggregation rate of these classes can be calculated by rearranging the previous equation:

$$\Delta_{X\text{ mm}(C_0 - C_1)} = M_{X\text{ mm}C_0} + \Delta_{X-1\text{ mm}(C_0 - C_1)} - M_{X\text{ mm}C_1} \quad \text{Eq. 5}$$

## RESULTS

### Estimated values

Considering all 90 samples, the study design allowed a high variation of TOC (coefficient of variation = 70.54 %), but a low variation of total clay content (coefficient of variation = 5.35 %). Organic matter's role in stabilizing aggregates can be practically isolated under these circumstances. The strong predictions presented in figure 1 suggest that organic matter was, by far, the most important factor stabilizing aggregates in these samples, despite the differences in agricultural management.

Even under low TOC contents, these soils presented a high proportion of water-stable microaggregates (<0.25 mm) and macroaggregates between 0.25–1.00 mm (Figures 1a, 1b and 1c) due to the high clay content and considerable proportion of sesquioxides (Table 1; Melo et al., 2018, 2020). With TOC increments, larger macroaggregates (1.00–8.00 mm) prevailed in intermediate TOC values (Figures 1d, 1e and 1f), and much larger aggregates (8.00–19.00 mm) prevailed in most of the observed values of TOC (Figure 1g).

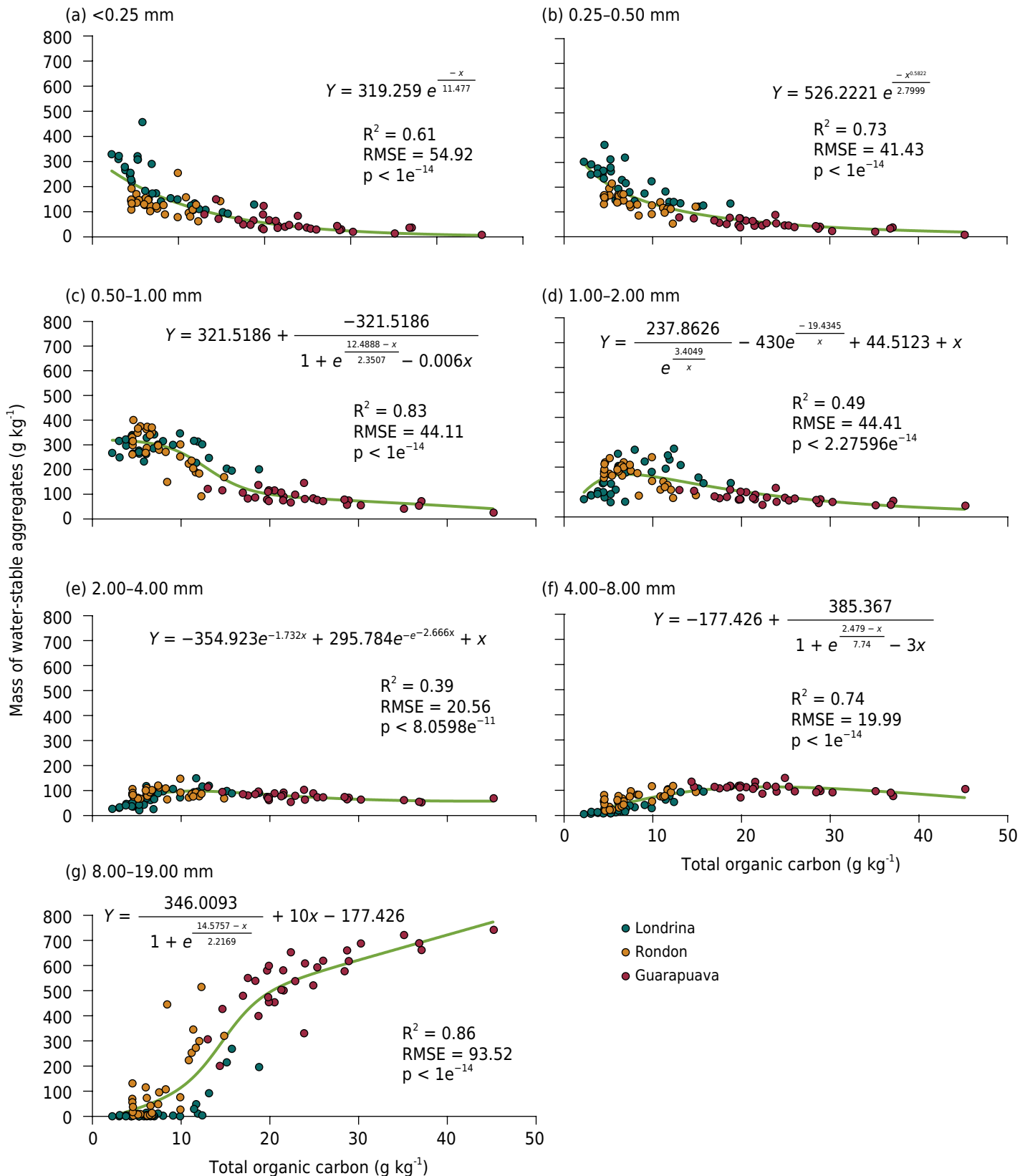
Additional validation was performed to ensure the accuracy of the adjusted models. The predicted values from the first six classes (<0.25, 0.25–0.50, 0.50–1.00, 1.00–2.00, 2.00–4.00, and 4.00–8.00 mm) were summed (values in g kg<sup>-1</sup>). This sum was subtracted from 1000; estimating the proportion of the 8.00–19.00 mm class by the difference. If all models are accurate, the values of the 8.00–19.00 mm class estimated by the model (Figure 1g) should approximate the values estimated by the difference. Figure 2 shows that the obtained models accurately estimated the proportion of the size classes of water-stable aggregates.

### Aggregation rate

The aggregation rate of the first six classes of water-stable aggregates is shown in figure 3. These values are expressed in proportion of mass in the sample (g kg<sup>-1</sup>) by an increment of 0.1 g kg<sup>-1</sup> of TOC. The aggregation rate of a given class represents the mass change (by aggregation) from this class to the subsequent larger class. For example, the aggregation rate of the <0.25 mm class represents how much mass of <0.25 mm aggregates are transferred to the 0.25–0.50 mm class. As the 8.00–19.00 mm class is the largest, its aggregation rate could not be quantified.

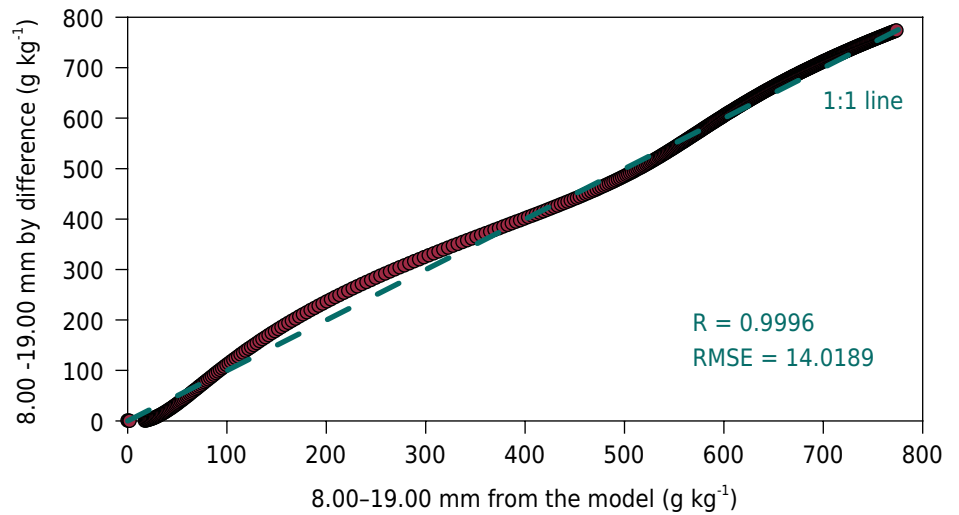
It is possible to distinguish four groups of aggregates with similar behavior based on the data presented in figure 1 and figure 3a. The first group includes microaggregates (<0.25 mm) and small macroaggregates (0.25–0.50 mm), which presented the highest aggregation rate at extremely low values of TOC (Figure 3a). These aggregates always lose mass with increasing organic matter content, meaning that they are the building blocks for larger aggregates. This also suggests that these aggregates depend less on organic matter for stabilization.

The second group also presented a high aggregation rate at extremely low values of TOC; however, in the intermediate values of TOC, another peak was observed (Figure 3a). This behavior was present in intermediate macroaggregates (0.50–1.00 and 1.00–2.00 mm). The initial reduction in these aggregate contents shows that these aggregates are bound to form larger aggregates. The second peak is explained by the mass increment of these intermediate macroaggregates due to the aggregation of smaller aggregates (<0.25 and 0.25–0.50 mm).

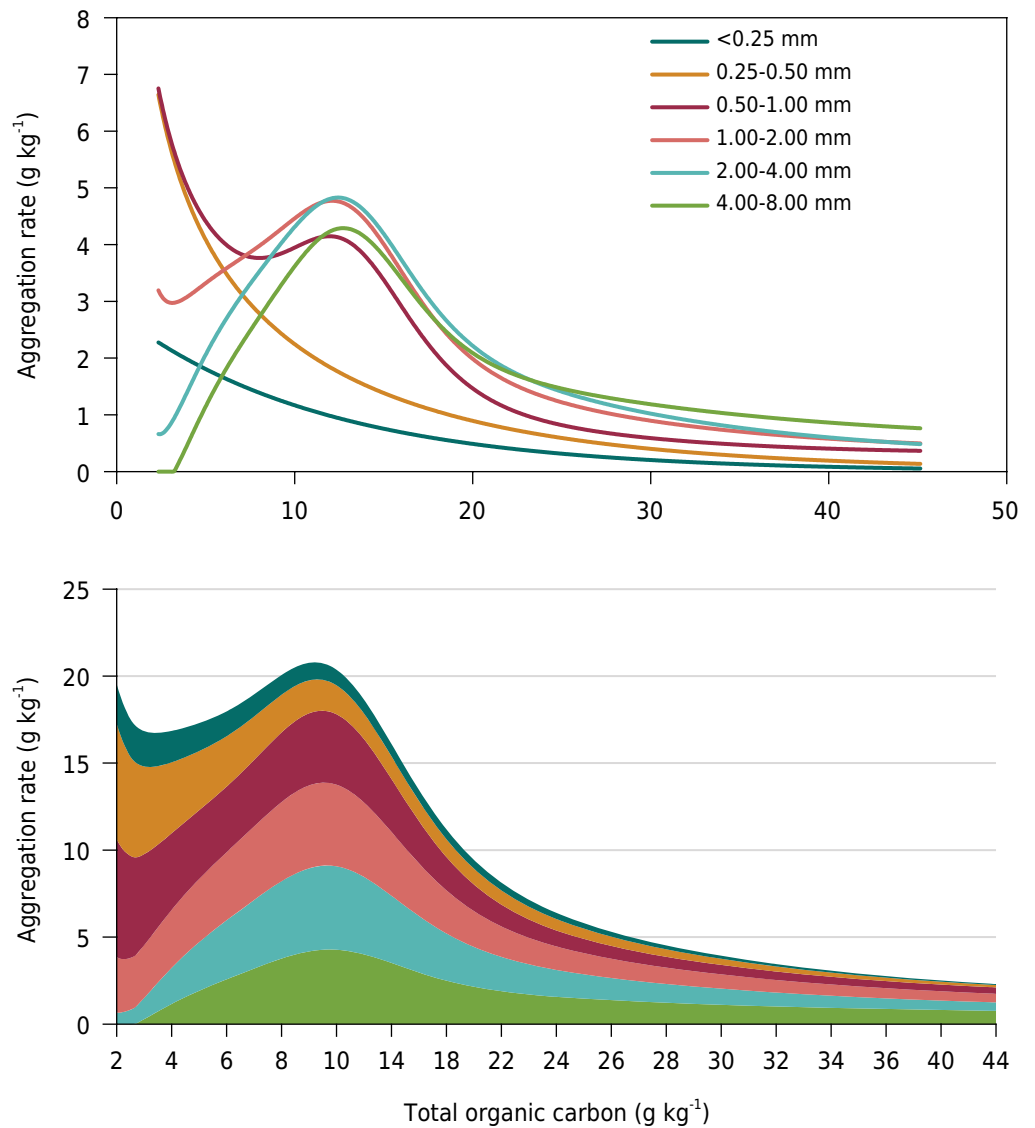


**Figure 1.** Mass of size classes of water-stable aggregates as a function of total organic carbon.

The third group presented aggregation rates close to zero at extremely low values of TOC, owing to their nearly absent content when TOC was lower than 5 g kg<sup>-1</sup> (Figure 3a). The highest aggregation rate of these aggregates was observed at intermediate values of TOC (between 10 and 15 g kg<sup>-1</sup>), suggesting that they require higher values of TOC



**Figure 2.** Relationship between the mass of the 8.00–19.00 mm class estimated from the model (Figure 1g) and calculated by difference.



**Figure 3.** Aggregation rate of size classes of water-stable aggregates as a function of total organic carbon. Individual (a) and stacked (b) lines are presented.

to maintain their stability; this type includes large macroaggregates (2.00–4.00 and 4.00–8.00 mm).

The fourth group is composed of 8.00–19.00 mm aggregates. They behaved differently in comparison to the other size classes (Figure 1). This group was absent when TOC was low and predominated in the sample when TOC was high ( $>20 \text{ g kg}^{-1}$ ). It is important to highlight that aggregates larger than 19.00 mm were manually broken in their weakness planes to be included in the analysis. Consequently, the 8.00–19.00 mm class also includes larger aggregates under field conditions.

## DISCUSSION

### Employed methods

Observational studies are characterized by the absence of control over the independent variable (organic matter, in this study). We chose this design to preserve the natural organo-mineral bonds formed under field conditions and to allow a high range of organic matter and soil aggregation. Performing an experiment (instead of an observational study) with increasing inputs of organic matter (i.e., manures or vegetal biomass) and sampling the soil in a single layer (e.g., 0.00–0.20 m) to control soil factors that change with depth (i.e., biological activity, pH, among others) would limit the range of TOC content because the lowest values would be much higher than the contents observed in the deeper layers ( $\approx 3 \text{ g kg}^{-1}$ ). Using deeper soil layers to perform this experiment (e.g., 0.80–1.00 m) would increase the range of TOC content, but the aggregates formed due to organic matter input would not include the complex interactions present under long-term field conditions.

Adopting the observational study might lead to criticisms because not all factors are controllable when sampling different soil depths. Several organic compounds act as binding agents for macroaggregates, such as fungal hyphae, partially decomposed plant roots, and polysaccharides, among others (Amezketta, 1999). Their proportion in relation to TOC are expected to vary with depth. However, as good predictions were found between TOC and the stability of aggregates (Figure 1), it is possible to assume that a good correlation between TOC and the fractions affecting macroaggregate stability exists in these samples; this assumption is particularly reasonable considering that most of the TOC variation was caused by sampling different layers, so the biological activity and organic matter compartments are also supposed to correlate with TOC content positively.

Despite good predictions as a function of TOC, the role of organic compounds in aggregation cannot be completely isolated from inorganic factors. Several physicochemical properties also change with depth, including cation exchange capacity, pH, point of zero charge, and exchangeable cations. However, these properties are more important for lower levels of aggregation. Details about clay behavior and stabilization of microaggregates in these Ferralsols are presented in Melo et al. (2021). These authors showed that the charge imbalance on clay particles has a minimal influence on the stability of macroaggregates in heavy clayey Ferralsols. This charge imbalance, which can be caused by changes in the pH, exchangeable cations, or point of zero charge, is only expressed when aggregates are mechanically disrupted, explaining the low spontaneous clay dispersion in the studied Ferralsols.

Drying and wetting cycles are also more intense in the surface layers, where the organic matter content is higher. However, the good continuity between samples from Guarapuava, with low TOC from deeper layers (0.40–0.60 m), and those from Londrina and Rondon, with high TOC from shallower layers (0.00–0.20 m), revealed that the effect of organic matter was able to minimize the effect of drying and wetting cycles (Figure 1). In fact, the strong predictions presented in figure 1 suggest that organic matter was the most



important factor stabilizing aggregates in these samples, despite the differences in agricultural management and sampling depths.

Using the aggregation rate approach, the present study supplements the current knowledge on aggregation in heavy clayey Ferralsols. Discussions on a criterion for determining the critical size to separate microaggregates from macroaggregates and implications for macroaggregate stability analysis in heavy clayey Ferralsols, in addition to a conceptual model of the aggregation rate approach are developed in the following sections.

### **Microaggregates in heavy clayey Ferralsols**

Based on the data from the present study, a criterion for classifying microaggregates could be established by considering how they agglomerate into larger aggregates with increasing organic matter content. As commonly adopted in the literature, the limit between macroaggregates and microaggregates of 0.25 mm was proposed by Edwards and Bremner (1967) based on the strength of intra-aggregate bonds to ultrasound. They consider microaggregates as a group of more resistant secondary particles.

The data from the present study suggests that the <0.25 and 0.25–0.50 mm (or  $\leq 0.50$  mm) aggregates behave similarly as “building blocks” in heavy clayey Ferralsols (Figure 1 and Figure 3). This means that their stability does not depend necessarily on organic matter because they are stable even when TOC content is very low. When organic matter is incremented, it binds these “building blocks” to form larger aggregates. It is important to highlight that, in surface horizons, the organic matter seems to be an important factor in microaggregate stabilization once they can present concentrations of TOC higher than macroaggregates (Madari et al., 2005). This agrees with the findings of Sousa et al. (2005), who observed, in a Ferralsol with 485–525 g kg<sup>-1</sup> of clay, that increasing the biosolid application dose up to 50 Mg ha<sup>-1</sup> reduced the proportion of water-stable aggregates <1 mm and increased the proportion of aggregates >2 mm. This trend was observed by the authors in all studied layers (0.00–0.10, 0.10–0.20, and 0.20–0.30 m). These authors do not present the data of <0.25 and 0.25–0.50 mm aggregates separately.

Results from Neufeldt et al. (1999) suggest that the higher the clay content of the Ferralsol, the larger the size of the aggregates acting as “building blocks”. These authors studied two Ferralsols with contrasting clay content (660–760 and 170–240 g kg<sup>-1</sup> of clay). The heavy clayey soil presented smaller proportion of 0.05–0.25 mm aggregates than the sandy loam soil under the same soil management systems due to their more intense aggregation and consequent formation of larger classes (0.25–1 mm). This is expected due to the high sensibility of clay to cementing agents, such as organic matter (Nimmo, 2013).

The criterion proposed in the present study might be more closely related to the aggregate behavior of soils under natural conditions because of the mild forces involved in wet sieving in comparison to ultrasonic dispersion used by Edwards and Bremner (1967) and because of its association with organic matter content. For the studied soils, aggregates <0.50 mm can be defined as microaggregates according to the proposed criterion.

### **Macroaggregate stability evaluation in heavy clayey Ferralsols**

Heavy clayey Ferralsols commonly present a high proportion of large macroaggregates in the surface layer. Tivet et al. (2013) studied Ferralsols from the same state as the present study (Paraná, Brazil) and observed that water-stable aggregates between 8 and 19 mm comprised at least 600 g kg<sup>-1</sup> of soil mass, regardless of soil use or management. Our data corroborate their study and show that most of the aggregate dynamics occurred in samples with TOC <20 g kg<sup>-1</sup> (Figure 3b) because when TOC >20 g kg<sup>-1</sup>, 8–19 mm aggregates prevailed (Figure 1g).

These soils commonly present values of TOC higher than 20 g kg<sup>-1</sup> in the surface layer because of their high clay content (Melo et al., 2019). Consequently, most of the dynamics caused by organic matter change in the surface layer are expected to happen in macroaggregates because free microaggregates (not aggregated into macroaggregates) are scarce (Figure 1 and Figure 3b).

The predominance of organic matter or metallic sesquioxides on the macroaggregate stabilization in heavy clayey Ferralsols is still controversial. Barthès et al. (2008) suggested that Al sesquioxides were the major determinants of macroaggregate stability in low-activity clay tropical soils. However, these authors considered macroaggregates as particles of 0.200–2.0 mm. Barbosa et al. (2015), studying the effect of manure application on aggregate stability of a heavy clayey Ferralsol similar to Londrina soil of this study, observed that macroaggregates between 2–8 mm were more responsive to different organic matter inputs than macroaggregates <2 mm.

This suggests that ignoring macroaggregates >2 mm in the evaluation of the aggregate stability, as in Barthès et al. (2008), might lead to existing inconsistencies on the importance of organic matter for macroaggregate stabilization in heavy clayey Ferralsols. Additionally, this approach might not reflect aggregate dynamics under field conditions very well because important changes are observed within the classes of water-stable aggregates between 2–19 mm as a function of TOC (Figures 1 and 3).

However, it is important to highlight that there is still a loss of information by quantifying macroaggregates as a single class (e.g., >0.25 or >0.50 mm) instead of subdividing macroaggregates in different classes (e.g., as performed in the present study). Melo et al. (2019) studied the short-term effects of chicken manure on the stability of aggregates in a heavy clayey Ferralsol. They observed that increasing chicken manure dose increased the proportion of 8–19 mm aggregates mainly due to the aggregation of 0.5–2 mm aggregates. This change would not be noticeable if a single class of macroaggregate was quantified.

Some studies on aggregate stability in heavy clayey Ferralsols quantify seven size classes (Tivet et al., 2013; Melo et al., 2019), as in the present study. This makes the analysis laborious and discourages its use by commercial laboratories. The aggregation rate approach might be useful for optimizing the analysis (by selecting a minimum set of sieves) without losing significant information about aggregate stability dynamics. This can be performed by grouping size classes of water-stable aggregates as performed in the present study. New studies must test the capacity of the aggregation rate approach to optimize aggregate stability analysis for different soils, encouraging its commercial use, which is virtually null in Brazil currently.

### **Conceptual model of the aggregation rate approach**

Aggregation rate can be physically interpreted as the net mass transfer from a smaller to a larger size class of water-stable aggregates as the result of an increasing organic matter network between the soil particles. With increasing organic matter content, the activity of soil organisms is favored, and fungal hyphal growth enhances soil stability, yielding larger water-stable aggregates (Ji et al., 2019; Veloso et al., 2020). The method allows a pragmatical understanding of the aggregate dynamics of a given soil or group of soils as a function of soil organic matter content. In the present study, we have applied it to a group of soils (heavy clayey Ferralsols) because they behaved similarly (Figure 1).

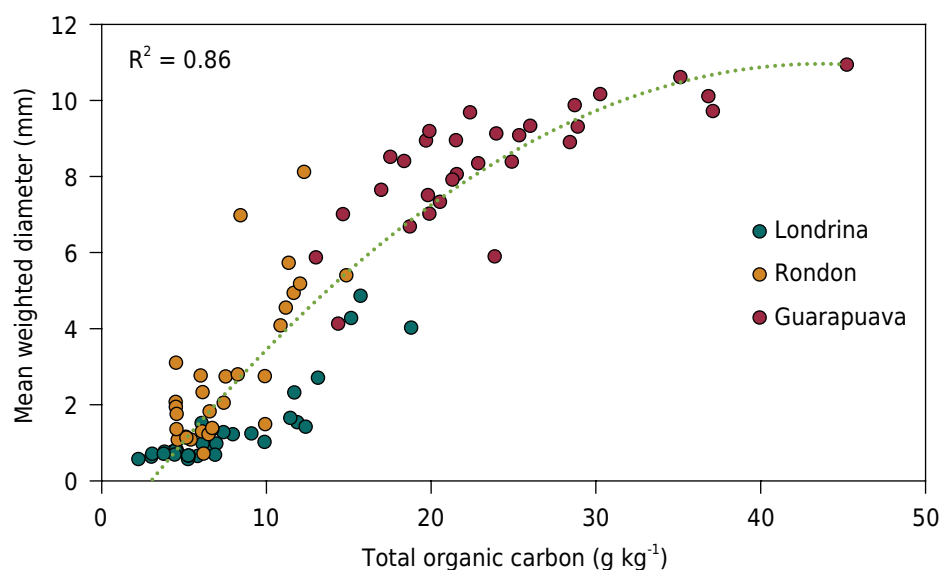
Aggregation rate's calculations have two assumptions. The first is that with TOC increment, smaller aggregates transfer more mass for larger aggregates (by aggregation) than receive mass from larger aggregates (by disaggregation), meaning the net aggregation (aggregation minus disaggregation) is always positive. This assumption does not ignore

the turnover of aggregates; it only considers that in higher contents of organic matter, the equilibrium is reached with a higher proportion of larger water-stable aggregates. This assumption is also supported by the increment in the mean weighted diameter as a function of organic matter in the studied samples (Figure 4). Such behavior is expected since organic matter is one of the most important factors stabilizing soil aggregates.

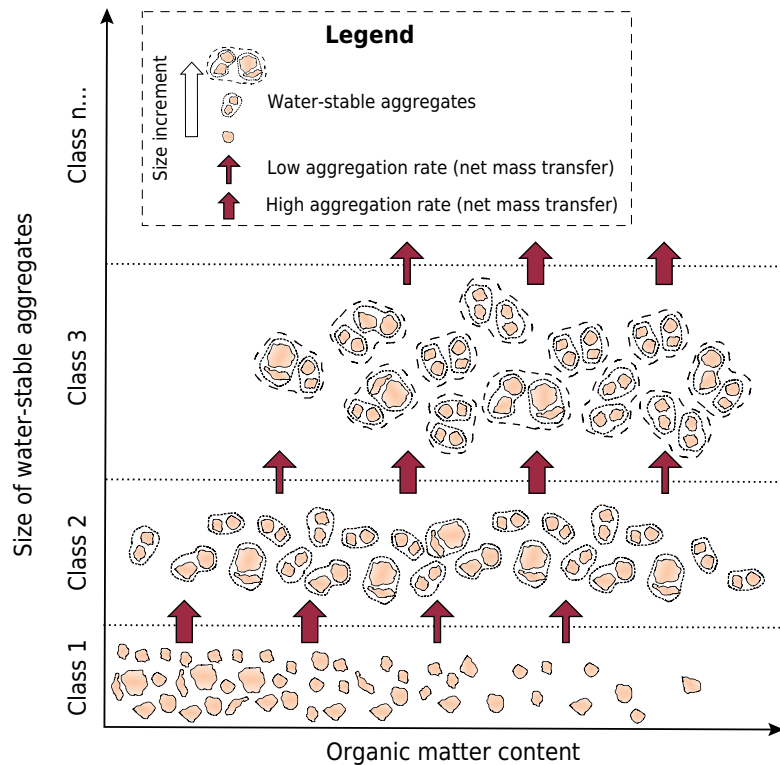
The second assumption is that the aggregation of a given size class results only in aggregates for the subsequent larger class. This means that, for example, the <0.25 mm class does not form aggregates 0.50–1.00 mm directly, but aggregates 0.25–0.50 mm are formed, which are then available to form aggregates of 0.50–1.00 mm. This assumption does not exclude the possibility of a multiple aggregate union, which would result in a “class jump” (from <0.25 mm directly to 0.50–1.00 mm aggregates, for example). If this is the case, the aggregate rate approach will compute that first, aggregates 0.25–0.50 mm are formed from <0.25 mm aggregates, which will then form aggregates of 0.50–1.00 mm. It is important to consider that the aggregation rate was calculated considering a very small TOC increment of 0.1 g kg<sup>-1</sup>, or 0.01 % in this study. When TOC increment tends to zero, the probability of a multiple aggregate union also tends to zero. Consequently, it is hypothesized that most of the aggregation follows this second assumption.

Figure 1 also supports the second assumption. It is possible to see that the TOC content related to the highest proportion of mass of a given size class is positively associated to its size; aggregates <0.50 mm presented the highest proportion of mass when TOC was approximately 3 g kg<sup>-1</sup>; aggregates of 0.50–1.00 mm when TOC was 5 g kg<sup>-1</sup>; aggregates of 1.00–2.00 mm when TOC was 7 g kg<sup>-1</sup>; aggregates of 2.00–4.00 mm when TOC was 10 g kg<sup>-1</sup>; aggregates of 4.00–8.00 mm when TOC was 20 g kg<sup>-1</sup>; and aggregates of 8.00–19.00 mm when TOC was 45 g kg<sup>-1</sup>. This shows that a given size class of water-stable aggregates only reaches its peak of mass (the highest proportion in the sample) after the subsequent smaller class has reached its peak.

Aggregation rate approach can be summarized in a conceptual model, as presented in figure 5. The initial condition for applying this conceptual model is the obtention of good predictions of all size classes of water-stable aggregates as a function of soil organic matter or organic carbon (Figure 1). This model shows that, when organic matter increases, smaller aggregates (Class 1 in Figure 5) agglomerate and form intermediate aggregates (Class 2 in Figure 5). With increasing organic matter, these intermediate



**Figure 4.** Mean weighted diameter of water-stable aggregates as a function of total organic carbon.



**Figure 5.** Conceptual model of the aggregation rate approach.

aggregates also agglomerate and form larger aggregates (Class 3 in Figure 5). These larger aggregates can still agglomerate to form even larger aggregates and so on (Class “n...” in Figure 5), however this is only partially represented in figure 5. In our study, for example, we used seven size classes of water-stable aggregates.

## CONCLUSIONS


Four groups of aggregates with similar behavior were identified based on aggregate distribution and aggregation rate values as a function of total organic carbon content. The groups are composed of aggregates with the following sizes: <0.50; 0.50–2.00 2.00–8.00; and 8.00–19.00 mm. This approach allowed the establishment of a critical value for classifying microaggregates in the studied soils ( $\leq 0.50$  mm) based on their behavior as “building blocks” for macroaggregates when organic matter content is increased. In surface soil layers, where organic matter content is higher, most dynamics are expected to happen between macroaggregates classes because free microaggregates are scarce due to the high clay content. Consequently, it is important to subdivide macroaggregates into different size classes when evaluating their stability. Quantifying macroaggregates as a single class (e.g., >0.25 mm or 0.50 mm) was insufficient in representing the macroaggregation dynamics in heavy clayey Ferralsols. Grouping size classes of water-stable aggregates based on their behavior, as observed by applying the aggregation rate approach, could help optimize the aggregate stability analysis by reducing the number of size classes quantified, especially of macroaggregates, without losing significant information regarding aggregate behavior.



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