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SHORT COMMUNICATION

Analysis of persistent macroaggregates on the surface of agricultural soils

Tian Tian, Joann K. Whalen, and Pierre Dutilleul

Abstract: In humid regions, the number of macroaggregates on the soil surface could decline because of rainfall disturbance, or increase due to rainfall-activated chemical and biological stabilization. We took digital images of macroaggregates at the surface of clay and organic soils six times during a 68 d period with 264 mm natural rainfall. Based on the constant or increasing number of surface macroaggregates during the five time intervals, rainfall did not disturb macroaggregates. Macroaggregate persistence was positively correlated with cumulative rainfall (both soils) and soil moisture (organic soil), so we infer that rainfall promoted macroaggregate assemblage through chemical and biological processes.

Key words: aggregate stability, soil surface, Grouped Aggregate Persistence Index (GAPI), field study, rainfall.

Résumé : Dans les régions humides, le nombre de macro-agrégats à la surface du sol peut diminuer en raison de perturbations dues à la chute de pluie, ou augmenter à la suite de l'activation de processus chimiques et biologiques par la pluie. Nous avons pris des photos numériques de macro-agrégats à la surface de sols argileux et organique six fois sur une période de 68 jours avec 264 mm de pluies naturelles. Sur base du nombre constant ou accru de macro-agrégats de surface au cours des cinq intervalles de temps, les pluies n'ont pas perturbé les macro-agrégats. La persistance des macro-agrégats étant positivement corrélée avec les pluies cumulées (les deux sols) et l'humidité du sol (sol organique), nous en déduisons que la pluie a favorisé l'assemblage des macro-agrégats par des processus chimiques et biologiques.

Mots-clés : stabilité des agrégats, surface du sol, Indice de Persistance d'Agrégats Groupés (IPAG), étude de terrain, pluies.

Introduction

Many vital functions occur at the soil surface (~1 cm deep), e.g., water and gas transfers between the soil matrix and the atmosphere, emergence of plant seedlings, and biochemical reactions catalyzed by diverse microorganisms. The stability of the soil surface depends on its coverage by cohesive structural units, especially macroaggregates (>0.25 mm), which can determine soil pore distribution and biological properties. Macroaggregates represent as much as 90% of the soil mass in the top 7 cm of a clay soil (Nunes et al. 2015) and 76% of the soil mass in the top 20 cm of an organic soil (Rubi and Stürme 2015). The number of macroaggregates covering the soil surface depends on the soil types, land use, and climatic conditions.

Macroaggregates break apart when dispersive forces, such as those exerted by rainfall, exceed their internal cohesion. Heavy rainfall events are expected to reduce the number of macroaggregates and diminish their coverage of the soil surface. For example, the mass of 0.25–2 mm macroaggregates in the top ~1 cm of a silty loam soil was 11% less when exposed to 33 mm rather than 16 mm rainfall in a 40 min interval (Shi et al. 2017). Rainfall, however, is not always destructive to macroaggregates at the soil surface. By replenishing soil water, rainfall could increase the amount of soluble substances that bind to minerals, and thereby promote organo-mineral assembly. In addition, rainfall increases biological activity, leading to greater production of microbial-binding agents and soil egestion by fauna that

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create aggregates from casts. For example, the number of earthworm casts (>0.2 g each) at the soil surface in a temperate corn field more than doubled to reach 250 casts·m^{-2} after two rainfall events of 14 mm and 10.5 mm (Le Bayon et al. 2002). Consequently, rainfall could activate soil chemical and biological processes that contribute to macroaggregate formation.

The objective of this study was to quantify macroaggregate dynamics at the surface of a clay soil and an organic soil in agricultural fields by applying the concept of persistence and a relevant index (Tian et al. 2021) from the counts made with a noninvasive imaging method of the visible macroaggregates on the soil surface at consecutive points in time. Considering field condition, soil properties, and climate of the study site, we hypothesized that the number of macroaggregates at the soil surface would increase because rainfall can activate chemical and biological processes involved in the macroaggregate assembly.

Materials and Methods

The study was conducted in agricultural fields at a commercial poultry farm located in Rivière- Héva, Québec, Canada (48.2°N, 78.2°W), where lacustrine deposits created two dominant soil types: (*i*) imperfectly drained clay soil classified as Orthic Gleysol (Bellecombe series), with 43 g organic matter·kg^{-1} and 361 g clay·kg^{-1} and (*ii*) a poorly drained organic muck soil classified as Mesisol organic soil, with 268 g organic matter·kg^{-1} and 297 g clay·kg^{-1} [details provided in Tian (2020)]. The clay soil was cultivated with a 1:1 mixture of winter wheat (*Triticum aestivum* L. cv. Warthog) and winter rye (*Secale cereal* L.) during the study period. The organic soil had been left fallow for 6 yr prior to this study, and had revegetated with naturally occurring grasses and forage, predominantly reed canary grass (*Phalaris arundinacea* L.), and rosso horsetail (*Equisetum* L.).

The experimental unit is a polyvinyl chloride (PVC) tube (inner diameter 10 cm and height 13 cm), containing clay soil (< 8 mm) or organic soil (unsieved) collected from the top 5 cm in each field. We packed the lower 6 cm of a PVC tube with field-moist soil (dry mass of 440–650 g clay soil or 270 g organic soil, to a bulk density of 0.9–1.4 g·cm^{-3} for clay soil and 0.6 g·cm^{-3} for organic soil. The upper 7 cm of the tube contained ~500 g clay soil at ~0.9 g·cm^{-3} or ~270 g organic soil at ~0.5 g·cm^{-3} (field-moist soil used; dry mass reported). The bulk density of soil in PVC tubes was similar to that of the surrounding undisturbed field soil, which should minimize the confounding factors, e.g., porosity and water–air exchange in the soil profile, that may affect macroaggregate appearance at the soil surface, thus providing a reasonable approximation of surface macroaggregate dynamics in these fields. Twenty-four replicate tubes were prepared for each soil. We inserted the tubes packed with clay soil into the clay field and those with organic soil into the organic muck field. In each field, tubes were placed in four trenches (each 12 cm deep, 15 cm wide, and 3.8 m long), and the top of tubes were leveled securely with the soil surface when the trench was backfilled with field soil. Thus, there were six tubes per trench with ≥50 cm spacing between adjacent tubes. The open bottom of each tube was in contact with the underlying soil, which allowed macrofauna to enter and exit the tubes. The top was covered with a 2 mm plastic mesh, secured with an elastic band to protect surface aggregates from animal disturbance. We made a permanent mark (dot) with nail polish on the top edge of each tube, to orient the digital images taken of each soil surface.

We photographed the soil surface in tubes with a Nikon D5300 camera attached to a tripod, starting on 21 June 2017 (day 0) and 12, 23, 34, 48, and 68 d later (i.e., 11–20 d between successive measurements; Table 1). Before image acquisition, weed leaves present in tubes were cut with scissors and removed with tweezers. Macroaggregates in images were segmented in MATLAB (R2017a, version 9.2.0) (Tian et al. 2021). Macroaggregate dynamics was quantified by the Grouped Aggregate Persistence Index (GAPI) for 0.25–10 mm aggregates (eq. 1), which is based on the ratio of the macroaggregate number at the beginning (t_{i0}) to that at the end (t_i) of the ith interval between two image acquisitions (Tian et al. 2021):

$$(1)\qquad GAPI_{t_i} = \frac{N_{t_i}}{\Delta t \times N_{t_{i0}}}$$

where N_{t_i} is the number of 0.25–10 mm aggregates detected on the soil surface image at time t_i, and $N_{t_{i0}}$ is this number at time t_{i0}; $\Delta t = t_i - t_{i0}$ is the time interval length. For unequal time intervals, GAPI-equivalent percentages can be calculated by dividing each $GAPI_{t_i}$ by the corresponding $1/\Delta t$. A GAPI-equivalent percentage = 100% when the number of macroaggregates is unchanged, and >100% if the number of macroaggregates increased.

Cumulative rainfall during each of the five time intervals (Table 1) is the sum of precipitation from t_{i0} to t_i. We estimated soil surface moisture (v/v) with a FieldScout TDR 100 probe (Spectrum Technologies, Inc., Aurora, Illinois, USA), inserted to 2 cm depth in the soil adjacent to each tube when images were acquired. Soil moisture for a given time interval is calculated as the average moisture values at the beginning (t_{i0}) and end (t_i). We could not measure moisture in clay soil at t_3 due to its dry condition, but the crop showed no sign of water stress. Accordingly, the clay soil moisture at t_3 was estimated as 18% vol., which is similar to the permanent wilting point reported for a heavy clay soil (0–20 cm) in the neighboring community of Malarctic, Québec (Guittonny-Larchevêque et al. 2016) and smaller than moisture of the near-surface clay soil at other image acquisition times. Associations between GAPI-equivalent

Table 1. Persistent macroaggregates at the surface of agricultural soils were quantified from digital images of the soil surface that were taken six times (from t_0 to t_5) during the 68 d field study and thus created five successive time intervals (t_i, t_{i+1}).

Variables		Time intervals				
		(t_0, t_1)	(t_1, t_2)	(t_2, t_3)	(t_3, t_4)	(t_4, t_5)
Time interval length (d)		12	11	11	14	20
Cumulative rainfall (mm)		26	49	11	52	126
Number of days since previous rainfall (d)		1	1	7	3	0
Macroaggregate number at the beginning of the interval[a]	Clay soil	189 ± 8	161 ± 9	153 ± 9	149 ± 10	146 ± 9
	Organic soil	54 ± 4	67 ± 6	79 ± 7	100 ± 6	46 ± 3
Average macroaggregate diameter (mm) at the beginning of the interval[b]	Clay soil	1.9 ± 0.0	1.9 ± 0.0	2.0 ± 0.0	2.2 ± 0.0	2.1 ± 0.0
	Organic soil	3.9 ± 0.1	3.9 ± 0.1	3.9 ± 0.1	4.7 ± 0.1	4.2 ± 0.1
GAPI-equivalent percentage (%)	Clay soil	88 ± 5	96 ± 4	99 ± 4	102 ± 8	142 ± 14
	Organic soil	135 ± 1	156 ± 26	144 ± 11	48 ± 4	176 ± 25

Note: We estimated the cumulative rainfall from 21 June 2017 to 28 August 2017 at the agricultural fields in Rivière-Héva, Québec, Canada, with rainfall data from the Val-d'Or climate station of Environment Canada located at 42.5 km distance. The mean ± standard error (n = 24) is reported for the number of 0.25–10 mm macroaggregates present in soil surface images, the average diameter of 0.25–10 mm macroaggregates, and the Grouped Aggregate Persistence Index (GAPI)-equivalent percentage values of 0.25–10 mm macroaggregates on the surface of each soil (clay, organic).

[a] The initial time point of each time interval, such that t_0 for time interval (t_0, t_1).

[b] The diameter of an aggregate is calculated as an equivalent disc diameter $= 2 \times \sqrt{\frac{\text{Area}}{\pi}}$ (Tian et al. 2021).

percentage, rainfall, and soil moisture are described by Pearson's correlation coefficients (r) computed with SAS version 9.4 (SAS Institute, Inc., Cary, NC, USA).

Results and Discussion

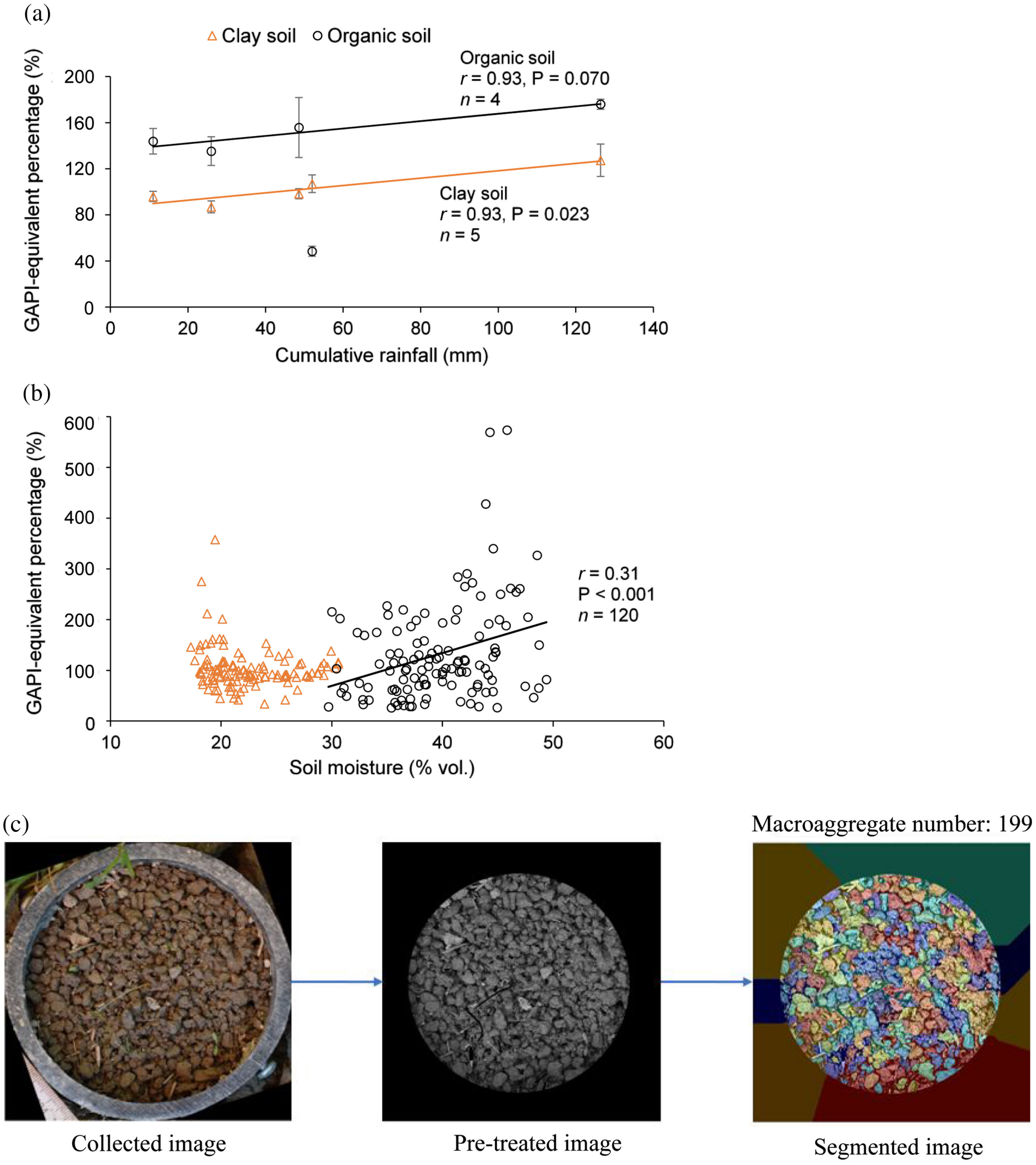
The number of macroaggregates at the surface of agricultural soils is related to rainfall, which supports our hypothesis. The GAPI-equivalent percentage is positively correlated with cumulative rainfall for clay and organic soils (Fig. 1*a*), and exceeds 100% for the interval (t_4, t_5) (with the highest rainfall) for clay soil and four time intervals for organic soil (Table 1), indicating gains in macroaggregates during these intervals. Since rainfall could not increase the proportion of original macroaggregates that maintained their size, shape, and location during each time interval (as quantified by Individual Aggregate Persistence Index, Tian et al. 2021; data not shown), rainfall generally promoted the formation of new macroaggregates [except for organic soil at interval (t_3, t_4)] rather than maintaining original macroaggregates on the soil surface.

Macroaggregate formation after rainfall is associated with increasing soil moisture, as shown by the positive relationship between macroaggregate persistence and soil moisture in the organic soil (r = 0.31; Fig. 1*b*). Greater soil moisture is expected to solubilize and move the polyvalent cations (e.g., Ca^{2+}) and sesquioxides through mass flow and diffusion. These reactive agents bond with clay minerals and create ligands that attach organic molecules to mineral surfaces, thus favoring macroaggregate assembly.

Macroaggregate formation after rainfall events is also associated with biological activity, which produces microbial byproducts (metabolites and necromass), and stimulates soil fauna to increase their soil-working and feeding activities. Soil water content was at 30–65% water-filled pore space (WFPS) in clay and organic soils during our study, which is suitable for aerobic soil microorganisms, although suboptimal for *Lumbricus terrestris*, which achieves maximal activity at about 75% WFPS (Evers et al. 2010). The soil moisture range in our study should be favorable for *Aporrectodea caliginosa*, which deposited 3–4 times more casts when soil moisture increased from 40% to 48% WFPS (Perreault and Whalen 2006). Earthworms were abundant, as we found 106 *Lumbricus* spp. and 56 *Aporrectodea* spp. earthworms·m^{-2} in the clay soil and 231 *Lumbricus* spp. and 325 *Aporrectodea* spp. earthworms·m^{-2} in the organic soil in July 2017. Hence, we suspect that many of the de novo macroaggregates on soil surfaces were earthworm casts classified as macroaggregates in our image analyses. This could be confirmed by preparing PVC tubes with and without earthworms, or developing filters to distinguish casts from other types of macroaggregates in digital images.

We noted differences in macroaggregate dynamics at the surface of clay and organic soils, which we attribute to contrasting soil properties and site conditions. In these fields, the clay soil should have a lower water-holding capacity and faster drainage, because it was on hillslope with a subsurface tile drainage system, compared with the organic soil that was in a low-lying area and relied on natural drainage. This explains why the clay soil tended to be drier than the organic soil throughout the study period (Fig. 1*b*). The wetter conditions in the organic soil were associated with greater macroaggregate formation at the soil surface, which may justify maintaining the natural drainage in fallow organic soils.

Fig. 1. Persistent macroaggregates at the surface of agricultural soils in relation to (*a*) cumulative rainfall and (*b*) soil moisture (% vol.), with an image of these macroaggregates shown in (*c*). The Grouped Aggregate Persistence Index (GAPI)-equivalent percentage of macroaggregates (0.25–10 mm) was calculated at the surface of a clay soil and an organic soil for five successive time intervals (Table 1). Plotted values of GAPI-equivalent percentage are in (*a*), the sample mean for each time interval, with standard error bars (number = 24); and in (*b*), the value for each experimental unit (PVC tube) and each time interval (number = 120). The strength of the relationship between persistent macroaggregates and rainfall or soil moisture is measured with Pearson's sample correlation coefficient and the associated probability of significance (P), where *n* denotes the number of data points involved in the test of significance. When the estimated correlation coefficient is significantly different from zero at 10% level or less, a best-fit line is displayed to show the trend. Figure (*c*) shows the image processing for one clay soil sample, including the original image collected from the field, the image after pretreatment, and the image output after segmentation (see Tian et al. 2021 for pretreatment and segmentation procedure). A total of 199 macroaggregates were detected from the segmented image on (*c*) (segmented objects were color-labeled).



Moreover, macroaggregate response to rainfall was likely related to the development stage of cereal crop (clay soil) and the composition of natural plant community (organic soil), which can intercept raindrops from hitting and disrupting macroaggregates at the soil surface. The dispersive force of a high-intensity, short-term rainfall event is expected to destroy more macroaggregates than rainfall that slowly wets the soil surface, but it may also depend on the antecedent soil moisture content, wind speed at ground level, and other factors, to be explored in future studies. For example, the distinctly lower GAPI-equivalent percentage for the organic soil over (t_3, t_4) could be related to a strong windstorm event during this time interval (data not shown). We, therefore, encourage further investigation into the effects of soil hydrology, vegetation, and wind, since these factors could interact with rainfall to modulate macroaggregate dynamics at the surface of agricultural soils.

Conclusion

We found that rainfall favored macroaggregate formation at the surface in clay and organic agricultural fields during the growing season, suggesting that rainfall-activated chemical and biological processes led to macroaggregate formation. This suggestion could be tested by comparing aggregate-binding substances present before and after rainfall events, across agricultural fields with variable chemical and biological factors. The impact of rainfall on macroaggregates at the soil surface is likely moderated by growing vegetation, which intercepts rainfall and directs it to the soil surface via stemflow and throughfall, as well as surface residues. We recommend further study of persistent macroaggregates at the surface of agricultural soils that consider vegetation along with other site-specific environmental factors. Overall, we conclude that regular, moderate rainfall events maintain or increase the number of macroaggregates at the surface of agricultural soils in humid temperate regions.

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