Process and Characterization of Aggregate Stabilization in Degraded Inceptisols by Earthworms

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ABSTRACT

Earthworms are widely recognized as a means of enhancing soil quality. However, less is known about their role in aggregate formation, especially their interaction with organic materials and soil aggregate size, as well as the output of this process. The objectives of this research are to assess the process and characterization of aggregate formation on degraded inceptisols by earthworms. Experiments were conducted in a random block design with factorial pattern using a combination of soil aggregate size, presence and absence of earthworms, presence and absence of compost. Sixteen treatments and 6 replication were used. A total of 96 pots were prepared, and 32 pots were examined every month during three months. The changes of mmorphological and elemental composition were observed using a scanning electron microscopy coupled with an energy-dispersive X-ray spectrometer (SEM-EDS). Aggregate stability was measured using the water aggregate stability method. The results showed that micro- and macro-aggregates were formed in less than two months, the aggregate surface became coarser and more porous. The interaction of aggregate size, earthworms and compost could improve degraded inceptisol quality through aggregate stabilization. This process started after the first month and increased after the second month. During the third month, 76.61% stable aggregates (without compost), 80.56% (without earthworms) and 91.74% (with both earthworms and compost) were formed. This finding suggests that stable aggregates are influenced more by a combination of earthworm and compost, however aggregates formation is strongly influenced by earthworm which is faster than compost.

Keywords: Aggregate morphology, aggregate size, compost, interaction, stable aggregate

INTRODUCTION

Soil degradation is a major constraint on agricultural production. Erosion is one of the major causes of soil degradation, which has affected about 500 million hectares of land in the tropics, including inceptisols (Lal, 2001). In tropical areas, the erosion rate of inceptisols by water is generally faster than the rate of soil formation. Erosion not only affects soil physically, but also influences the decline of chemical properties, such as loss of soil nutrients, loss of minerals charge positively. Eroded soil normally more acidic and less fertile. Degraded inceptisol by erosion affects the physical quality of soil by disintegration aggregate. Therefore, aggregate stability has become an important physical indicator of soil erosion, which reflects the measurement of the ability of the soil to retain its structure (Díaz-Zorita et al., 2002). Aggregate stability influences several aspects of soil's physical behavior, especially water infiltration and soil erosion. Splinters of soil particles get separated from aggregates by raindrop produced finer fragments that filled the soil pores (Nciizah & Wakindiki, 2014). This, in turn, decreases porosity, aeration, water infiltration (Díaz-Zorita et al., 2002), microbial community structure (Hattori, 1998), diffusion of oxygen (Hansel et al., 2008; Sexstone et al., 1985), and the regulation of water and cation exchange capacity (Barthès & Roose, 2002).

The biological properties of the soil deteriorate via loss of soil organic matter and loss of soil fauna (Lal, 2015). The restoration of soil quality through the aggregate formation process and stability is influenced by three main factors: soil fauna, soil organic matter (SOM), and soil minerals. This is known as the Biogenic Soil Structure concept. The interaction between these factors is essential for achieving healthy soil conditions (Wall et al., 2012).

Soil faunas, such as earthworms, have an apparent role in the formation of aggregate and aggregate stabilization. Through biological activity, earthworms convert leaf litters into fragments and destroy soil micro-structures by mixing mineral clays and organic materials in their gut system; consequently creating an organo-mineral structure with certain physical, chemical, and microbiological properties (Lavelle et al., 1997, 2006; Castellanos-Navarrete et al., 2012) as well as a biogenic structure in the form of casts, mounds, and fungus comb chambers (Bhadauria & Saxena, 2010). Earthworms have a higher stimulating effect on the formation of soil aggregates (macro-aggregates and micro-aggregates within macro-aggregates) when organic matters or residues are added (Fonte at al., 2009). Moreover, the addition of organic matters increases water, nutrients, and soil organic carbon (SOC) availability. Increasing SOC further triggers aggregate formation; which, in turn, increases porosity, aeration, and water infiltration simultaneously and adequately; thus improving soil structure stability (Food and Agriculture Organization [FAO], 2007, 2017).

Soil minerals also play a role in determining how aggregates are formed through cation exchange. Besides having a high oxide content, tropical soils, such

as inceptisols, are well known for having a large content of mineral particles with variable charges (oxide and 1:1 clay minerals, such as kaolinite). Contrary to soils in the sub-tropics, which are dominated by type 2:1, and where organic matter acts as the primary binding agent for soil aggregates (Six at al., 2002), organic materials in oxide-rich soil bind to oxides. This prevents the expression of an aggregate hierarchy (Oades & Water, 1994) since an aggregate hierarchy occurs in aggregate soils, and stabilization is formed by organic soil matter. Thus, in such types of soil, plentiful mineral particles provide an alternative way of producing macro-aggregates through physiochemical mineral bonds. The large capacity of inceptisols for producing macro-aggregates through this kind of process is supported by Six et al. (2002), who reported that the positive charge of inceptisols was high, as high as difference between maximum pH (8-10) with points of zero net charge for kaolinite of type 1 : 1 (3.5 to 4.6). This characteristic also plays a significant role in the accumulation of organo-minerals produced by earthworms, since large margin of positive charges provides a considerable capacity for adsorption.

Based on the research concept and the mechanism of aggregate formation, the process of microaggregate formation by earthworms is believed to improve soil quality through changes in aggregate surface, soil chemistry (element) composition, and aggregate stability. Therefore the objectives of this research are to assess the process and characterization of aggregate formation on

degraded inceptisols by earthworms. The knowledge and information gained from this study will be valuable for the restoration of degraded inceptisols programs in the tropics.

MATERIALS AND METHODS

This research consisted of two phases. The first phase was the process of soil aggregate formation, which was studied by adding earthworms and/or compost to the soils of various aggregate sizes. The second phase was examination of morphological and aggregate stability under laboratory condition.

The soil in this experiment was collected from Gunung Geulis (=GG) area (832-943 m above sea level), with 45-60 % of slope. The geographical location of sample soil was between $06^0 55.443'$ S - $06^0 56.404'$ S and $107^0 48.045'$ E - $107^0 48.904'$ E at Sumedang Regency, West Java – Indonesia. In this area, three land-use systems are present: agrosystem, agroforestry, and forestry system. Based on land use, the agrosystem was classified into: banana garden, cereal crops, and mixed garden. Previous study had examined the soil profile and mineral type at agrosystems at GG. The results showed that the soil order was inceptisol (Supriyadi et al., 2014). Soil quality had been analyzed by scoring system, which integrated physical, chemical, and biological characters. The results revealed that the soil quality was degraded by erosion (Supriyadi et al., 2014).

The samples used in this experiment were taken from the agrosystem cereal crops, which were considered as degraded inceptisols. The experiment on soil

improvement process was conducted in the laboratory of School of Life Sciences and Technology, Institut Teknologi Bandung, Indonesia.

Soil Preparation

The soil samples of degraded inceptisols having aggregate size composition (27% macro-aggregate, 54% mesoaggregate, and 19% micro-aggregate) were filtered and grouped into three different measures; (841 – 2000) μm, (250 – 841) μm, and (44 – 250) μm.

The compost used in the experiment was made from a mixture of 60% agriculture waste and forest litter (1:1 v/v), 20% bran, and 20% manure. A starter solution was added to facilitate the composting process. This solution consisted of 8% effective microorganisms (EM4), 8% molasses, and 83% water. The solution was kept at 40% humidity (Supriyadi, 2017). The preparation of the starter solution followed the method used by Wididana and Higa (1995). The precursor, EM4, was made the day before composting by dissolving EM4 (1 L) and brown sugar (500 g) into water to make a 50 L solution.

In order to obtain the desired organic soil carbon (SOC) for this experiment (2%--which represents a healthy soil condition (Bot & Benites, 2005), compost was added to plots assigned for compost treatment. The amount of compost added was calculated using a formula given below from Ellert and Bettany (1995).

$$Ms : 0.20 \ (m) \times 10.000 \ (m^2) \\ \times BD \ (Mg/m^3) \qquad [1]$$

$$To : (Ct - Ce) \times 1.724 \times Ms \qquad [2]$$

Ct: The amount of soil organic carbon expected (%)
Ce: The amount of soil organic carbon existing (%)
BD: Bulk Density (Mg/m^3)
Ms: Sum of soil mass (Mg ha^{-1})
To: Total compost added (Mg ha^{-1})

For each treatment, 17 individual earthworms (about 20 g) were used. The earthworms were collected from a protected forest in the GG area. The earthworms were Anecic type and belonged to the species *Amynthas ilotus*, Megascolesidae family.

Experimental Design

The experiment on the process of soil aggregate formation was conducted using a combination of different sizes of soil aggregate (As) consist of four levels of soil aggregate size; as0 = the size of aggregate between (841 – 2000) μm, as1 (250 – 841) μm, as2 (44 – 250) μm, and as3 was the existing degraded soil (consist of different aggregate size: 27% 841 – 2000 μm, 54% of 250 – 841 μm, and 19% of 44 – 250 μm). Five kilograms of different sizes of soil aggregate and 1.98 kg of compost were mixed with 0.5 liter of water until the soil condition reached 70% of humidity and was placed in a pot (26 cm in diameter). To maintain the humidity, all the pots were

sprayed by water once every day. Each pot consisted of different size of degraded soil, the presence (ew1), and absence (ew0) of earthworms as well as presence (cp1) or absence (cp0) of compost.

These experiments were set in a random block design with a factorial pattern of three factors. A total of 16 treatments of different soil aggregate size, the presence and absence of earthworm and compost (Table 1) were prepared with six replications (in 96 pots). Every month, the samples were taken from each treatment (32 samples) to determine aggregate characteristics (morphology, stability) and element content of soil aggregate. The examination was repeated twice.

Morphology of Aggregates

The morphological characteristics of soil were observed using Scanning Electron Microscope (SEM). The element composition was analysed by Energy Dispersive X-ray Spectroscopy (EDS). The type of SEM used was EVO MA10, Carl-Ziess SMT. Prior to the analysis, the sample was gold spurted with the aid of a sputter coater (model Polaron SC) to produce 515 $\pm$ 20 nm sample thickness. The mounting of samples used double coated conductive carbon tape. The surface of samples was kept clean from abrasive or cracks after being last polished, especially for EDS analysis. Subsequently, magnetic electron lens was focused on the sample. SEM and

Table 1

The treatments of soil aggregate formation experiments

No.	Treatments			Code
	Aggregate Size (As)	Earthworms (Ew)	Compost (Cp)	
1	(841 – 2000) µm	-	-	as0ew0cp0
2	(841 – 2000) µm	V	-	as0ew1cp0
3	(841 – 2000) µm	-	V	as0ew0cp1
4	(841 – 2000) µm	V	V	as0ew1cp1
5	(250 – 841) µm	-	-	as1ew0cp0
6	(250 – 841) µm	V	-	as1ew1cp0
7	(250 – 841) µm	-	V	as1ew0cp1
8	(250 – 841) µm	V	V	as1ew1cp1
9	(44 – 250) µm	-	-	as2ew0cp0
10	(44 – 250) µm	V	-	as2ew1cp0
11	(44 – 250) µm	-	V	as2ew0cp1
12	(44 – 250) µm	V	V	as2ew1cp1
13	Existing degraded soil	-	-	as3ew0cp0
14	Existing degraded soil	V	-	as3ew1cp0
15	Existing degraded soil	-	V	as3ew0cp1
16	Existing degraded soil	V	V	as3ew1cp1

v : treatment application

EDS analyses were applied only for the samples of the existing degraded soil added with earthworms (Table 1; no. 14).

Stability of Aggregates

Aggregate stability was measured using the water stability aggregate (WSA) method. This method is used to isolate the stable micro-aggregates from inside macro-aggregates (McCarthy et al., 2008; Six et al., 2002; Tisdall & Oades, 1982), and the SOM dynamic (Six et al., 2000, 2002, 2004). The stable aggregates were subsequently measured with a wet-sieving method, which can distinguish three aggregate fractions; stable aggregates, rather-stable aggregates, and unstable aggregates (Six et al., 2002, 2004; Sohi et al., 2001; Sui et al., 2011). Eight grams of dry soil samples were placed on a sieve (1000 μm) and immersed into the deionized water until the soil was completely submerged. The sieve was then moved up and down for three minutes at 20 cycle's min^{-1}. The sieved particles collected inside a metal container were then dried and classified as unstable aggregates. Afterwards, the collecting vessel was changed with a vessel filled with 5%. NaOH Unsieved particles were again sieved for eight minutes. The collecting vessel was taken and the sieved particles inside were dried and classified as somewhat-stable aggregates. The remaining unsieved particles were classified as stable aggregates. The weight of stable aggregates (unsieved particles) was determined after drying at 40°C. The stable aggregate distribution was calculated following Sui et al. (2011), based on the total percentage of the mass of the stable aggregate in each aggregate fraction as follows:

$$\text{Stable Aggregate} = \frac{\text{Stable Aggregate Weight (g)}}{\text{Total Weighted Soil (g)}} \times 100$$

[3]

Statistical Analysis

The effect of compost and earthworms on soil aggregate stability on different aggregate sizes was tested using ANOVA with p = 0.05 for the interaction between three factors; aggregate size, earthworms, and compost. The Duncan Multiple Range Test (DMRT) was applied to determine the effect of interaction between the three factors and aggregate stability. This statistical analysis was followed (Gomez & Gomez, 1984; Oehlert, 2010; Steel et al., 1997).

RESULTS

Experiment on the process of soil aggregate formation and its characteristic on degraded inceptisols were explained through the changes of aggregate morphology, element composition, aggregate stability, and the interaction between aggregate size, earthworms and compost.

Morphology of Aggregates

Earthworm activity in degraded inceptisols resulted in the changes in soil aggregate structure, shown by the micrograph analysis from SEM (Figure 1 a-d). Before earthworm treatment, the morphological surface of the

degraded soil was smooth with no clumps or pores (Figure 1a). After one month of earthworm treatment, the aggregate surface became rough, clumps and the pores had formed (Figure 1b). After two months, the clumps segregated and formed macroaggregates and microaggregates (Figure 1c). After three months, inside of macro-aggregates showed a crack which indicate the formation of micro-aggregates within the macro-aggregates (Figure 1d).

The change in the aggregate surface from smooth surface became rough and the formation of clumps indicated the improvement of soil structure due to micro-aggregates and macro-aggregates formation.

Compared to smooth surfaces, the rough surface of macro-aggregates facilitates better storage of organic molecules through the process of flocculation and adsorption. This phenomenon was supported by Chenu and Plante (2006) that the rough surfaces could store organic carbon several times better than the smoother surface of degraded soil. According to Bronick and Lal (2004), the soil clumps in a macro-aggregate formation block the decomposition process of organic matters (Bossuyt et al., 2005), which may lead to the enrichment of stable C due to the combination of micro-porous space and cracks in coarse soil particles (Mayer, 1999). According to Trevisan
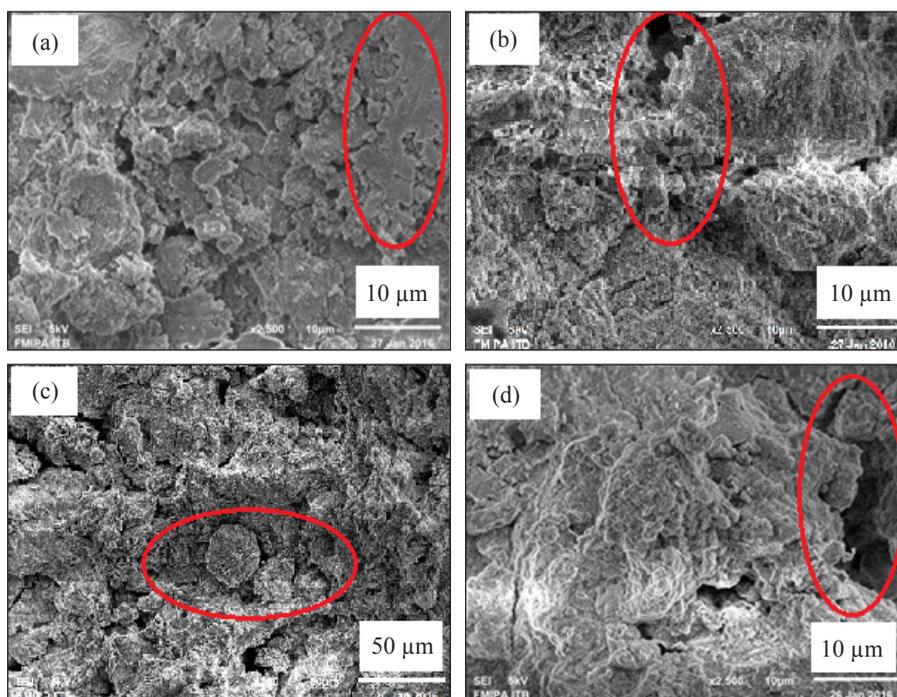

Figure 1. Morphological structure of aggregate formation by earthworm in existing degraded Inceptisols. (a) before earthworm treatment aggregate structure show smooth and flat surface; (b) after one month, the soil structure more rough with small clumps formation; (c) after two months, micro-aggregate formation appeared; (d) after three months, the clumps started to segregated signaling more microaggregate formation within macroaggregate

(2009), the porous soil particles and the cracked structure are more responsive to many soil characteristics. These results showed that earthworm activity triggering the aggregate formation in less than two months.

Element Compositions on Soil Aggregates

The elements C, N, Al, Si, K, Ca and Fe were consistently present throughout the treatment period with only slight changes in their relative abundance (Table 2). The presence of N and K in the early period (first month) suggests that the aggregation process was still unstable. The presence of Na tends to reduce aggregate stability as water can be easily absorbed by Na, which subsequently triggers soil dispersion. During the process of aggregate stabilization, Na can be considered as a labile element, or agent of dispersion. The decrease in Na and its disappearance after two months along with the higher abundance of cations with high valence (C_4^+, N, Al_3^+, Si_4^+ and Fe_3^+) throughout the treatment period indicate

the process of aggregate stabilization. A strong aggregate stabilization process was supported by the increase in Fe_3^+, which has high capability of binding organic matter in aggregate stabilization (Bronick & Lal, 2004; Six et al., 2004). Meanwhile, the consistent high proportion of C and N during the treatment period indicates that earthworm activity could stabilize organic soil carbon (SOC) (Bertrand et al., 2015).

Aggregates Stability

In all aggregate size, earthworm treatment without compost (as0cp0ew1, as1cp0ew1, as2cp0ew2, and as3cp0ew3) resulted on the increased of aggregate stable (Figure 2a). After one month of treatment, the highest amount of stable aggregates formed (66.65%) was found in as0, followed by (48.06%) in as1, and (35.39%) in as2. This pattern was persistent in the periods two and three month of treatments.

Similar situation was also found in all aggregate sizes that were given compost treatment without earthworms (as0cp1ew0,

Table 2

Elements composition in soil aggregate of degraded inceptisols during three months period

Element	0 month	1 month	2 months	3 months
	Mass (%)	Mass (%)	Mass (%)	Mass (%)
C	24.26	24.22	29.64	27.41
N	28.46	28.42	32.69	29.10
Na	0.09	0.04	0.09	-
Al	20.45	19.45	14.45	16.97
Si	23.96	22.96	17.96	20.46
K	0.44	0.49	0.44	0.07
Ca	0.76	0.67	0.31	0.21
Fe	1.58	3.75	4.42	5.78
Total	100.00	100.00	100.00	100.00

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as1cp1ew0, as2cp1ew0, and as3cp1ew) (Figure 2b). After one month of compost treatment, the highest amount of stable aggregates was formed 84.68% (in as0) followed by 83.67% (in as1). Meanwhile, aggregate stable in as2 was 7.86%. This value was lower than the amount of stable aggregate formed in as3 (degraded soil aggregate), which was 67.8%.

On larger aggregate size, treatment with compost or earthworm resulted in the higher aggregate stable. However, for all aggregate sizes, the levels of aggregate stable in soils with compost treatment were higher than those with earthworm treatment. This pattern was found during the second and third month of the experiments (Figure 2a and 2b). The influence of a single factor by adding earthworms (ew1) or compost (cp1) on all aggregate sizes [macroaggregate (as0), messoaggregate (as1), microaggregate (as2), and degraded soil (as3)] resulted in the highest stable aggregate on macroaggregate (a0), on mesoaggregate (as1) and microaggregate

(as2). These results indicate the influence of aggregate size factor, as shown by the percentage of stable aggregates of non-treatment soil.

On the combined treatment of earthworm and compost (as0ew1cp1, as1ew1cp1, as2ew1cp1, and as3ew1cp1) for three month periods, the aggregate stability also increased, except in microaggregates where it decreased after two months. Unlike the two previous treatments (earthworm or compost only), the as0 consistently had higher aggregate stability than as1 and as2 during the three months treatment. In the combined treatment, however, the aggregate stability of as1 in the second and third months (91.94% and 94.12%) was higher than that of as0 (87.40% and 93.67%) (Table 3 and Figure 3). These results showed also that there was no correlation between aggregate stability and aggregate size (R_{xy} = 0.28).

At single treatment (compost or earthworm), aggregate size influences aggregate stability in that the larger aggregate

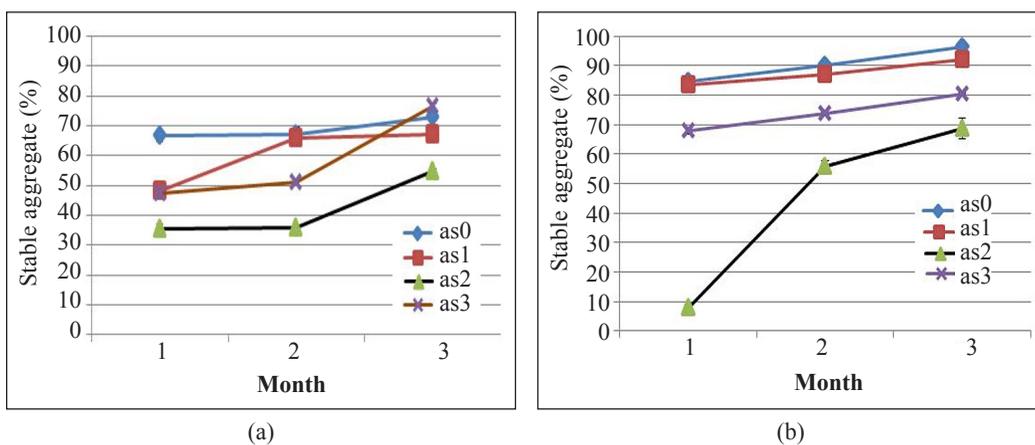(a)   (b)

Figure 2. Stable aggregate formation on soils with different size of aggregates during three months of treatments by adding (a) earthworm and (b) compost separately

Table 3
Interactions among aggregate size, earthworm and compost on stable aggregate formation based on simple effect analysis

As	Cp	Ew (Earthworm)											
		After one month				After two months				After three months			
		Ew0		Ew1		Ew0		Ew1		Ew0		Ew1	
		-------------------------				Stable Aggregate (%)				----------------------------			
as0	cp0	52.81 A	d	66.65 B	d	50.58 C	d	67.04 D	c	45.90 E	c	73.02 F	c
	cp1	84.68 A	f	85.50 A	e	90.15 D	h	87.40 C	e	92.47 E	f	93.67 E	e
as1	cp0	19.87 A	c	48.06 B	b	19.99 C	b	65.90 D	c	21.75 E	b	67.14 F	b
	cp1	83.67 A	f	82.52 A	e	87.07 C	g	91.94 D	f	91.97 E	f	94.12 F	e
as2	cp0	2.26 A	a	35.39 B	a	2.96 C	a	36.02 D	a	6.05 E	a	54.80 F	a
	cp1	7.86 A	b	60.18 B	c	55.89 C	e	78.19 D	d	68.71 E	d	87.31 F	d
as3	cp0	23.02 A	c	47.57 B	b	23.65 C	c	51.01 D	b	25.03 E	b	76.61 F	c
	cp1	67.80 B	e	63.98 A	d	73.85 C	f	78.04 D	d	80.56 E	e	91.74 F	de

As = Agregates size, Ew = Earthworms, Cp = Compost
Note: The pair of numbers followed by same lowercase letters (on the vertical direction) and same capital letters (the horizontal direction) indicate no significant difference according to the Duncan's Multiple Range Test P=0.05
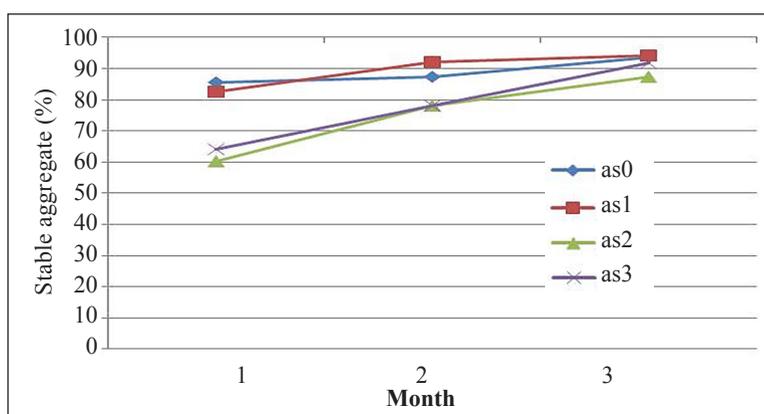

Figure 3. Formation of stable aggregate by earthworm and compost on different size of aggregates during three months period of treatments

size resulted in higher aggregate stability. However, on combined treatment (compost and earthworm), the effect of aggregate size was less. It seems that the role of organic materials (earthworm and compost) are more significant in increasing aggregate stability. Analysis on the effect of treatment on the degraded soil samples (Figure 2a, 2b and 3) showed that the earthworm treatment resulted in a faster increase of stable aggregates than other treatments. During the three months treatment, aggregate stability increased by 29.04%, 12.76%, and 27.76% in earthworm, compost and combined treatment respectively.

Interaction on Aggregate Size, Earthworms and Compost

Experiment on formation of stable aggregates showed by the results of WSA in the period of sample analysis during three month experiments (Table 3). After one month, as0 treatment with compost and earthworms (as0cp1ew1) resulted on 85.5% stable aggregate. Treatment without earthworms (as0cp1ew0) found 84.68% stable aggregate. Based on simple effect analysis on the stable aggregate interactions between (as0) and (as1), the addition of compost with and without earthworms resulted in zero interaction (Table 3). However, the simple effect between (as0cp1ew0) and (as0cp1ew1) showed no significant difference (A-A). Experiment as1, with compost and earthworms (as1cp1ew1) found 82.52% stable aggregate and treatment of as1 with compost without

earthworm (as1cp1ew0) resulted in 83.67% of stable aggregate. The difference between treatments (simple effect) between the treatments of (as1cp1ew1) and (as1cp1ew0) showed no significant difference (A-A).

Experiment on as0, with compost and absence of earthworms (as0cp1ew0) resulted in 84.68% stable aggregate and experiment with as1, with compost and absence of earthworms (as1cp1ew0) resulted on 83.67% stable aggregate. Base on ANOVA and DMRT the simple effect (as0cp1ew0) with (as1cp1ew0) showed no significant difference (f-f). Experiment on as0 with compost and earthworms (as0cp1ew1) resulted in 85.5% of stable aggregate and experiment on as1 with compost and earthworms (as1cp1ew1) resulted on 82.52% stable aggregate. The difference between the two treatments showed no significant difference (e-e) or the simple effect between two treatments showed no significant different (e-e).

Experiment on as2 with compost and absence of earthworms (as2cp1ew0) resulted on 7.86% stable aggregate however at experiment as3 with compost and absence of earthworms (as3cp1ew0) resulted on 67.80%. The simple effect showed significant difference (b-e). In these experiments, the initial aggregate size (as2 and as3), the addition of compost or without compost and the presence or absence of earthworms showed the difference in stable aggregate. Addition of compost on different size of aggregate and the presence or absence of earthworms was significantly

differ than treatment without compost. If we compare the presence of earthworm at all aggregate size and the absence of earthworms showed significant difference in stable aggregate formation except in as0cp1 and as1cp1.

Based on simple effect analysis on the stable aggregate interactions between (as0) and (as1), the addition of compost and the presence or absence of earthworms resulted in zero interaction (Table 3). It can be concluded that the simple effect analysis on data during the first month showed that not all pairs resulted in interaction. There are pairs that did not show any interaction during the first month, that were: 1) [(as0cp1ew0-as1cp1ew0) and (as0cp1ew1 - as1cp1ew1)], 2) [(as1cp0ew0-as1cp0ew1) and (as3cp0ew0-as3cp0ew1)], 3) [as0cp0ew0-as0cp0ew1) and (as2cp0ew0-as2cp0ew1)].

Interactions of three-factor occurred during the second month period. The highest interaction found in (as1) with compost and the presence of earthworms (as1cp1ew1) resulted in (91.94% of stable aggregate. Based on a simple effect analysis for every aggregate size, the addition of compost provided significantly different results as compared to soil without compost. The addition of earthworms also furnished significantly different results as compared to soil without earthworms.

At the third month period, the formation of stable aggregate influenced by the presence of compost and earthworms at all aggregate size. Experiment of as1 with compost and earthworms (as1cp1ew1)

resulted the highest stable aggregate (94.12%). The results of the simple effect analysis of the third month period were similar to those of the first month. Not all simple effect pairs displayed interaction. For all aggregate sizes, the effect of interaction on the formation of stable aggregate found at almost all of the pair of simple effect. Exceptions were shown by pairs of (as0cp0ew0 and as1cp0ew0) and also pairs of (as0cp0ew1 and as1cp0ew1). In this case, experiment with compost and the presence or absence of earthworms was not significantly different.

DISCUSSION

Erosion in degraded Inceptisols is one of the factors causing low soil quality, including physical, chemical, and biological quality of the soil (Lal, 2001). Aggregate stability and changes of the soil structure are important indicators in eroded soils (Bronick & Lal, 2004). This research reveals that the structure of degraded inceptisol due to erosion has smooth surface and low aggregate stability. Addition of compost, earthworms, or both (compost and earthworms) resulted on the change of soil structure and increase stable aggregate. This was occurred during the first, second and third months after treatments (Figure 1 and Table 3). Before treatment, the structure was visually fine (Figure 1a.). The presence of earthworms resulted in coarser soil structures (Figures 1b, 1c and 1d). The change in soil surface from smooth to rough was an indication of increasing number of pores and organic carbon content. This was

supported by (Bronick & Lal, 2004) that the rough surface of soil is an indication of soil aggregate formation. Rough surface can store organic carbon several times higher than a smooth surface (Chenu & Plante, 2006). The increased on organic carbon content inside the soil affects aggregate stability through the binding of cation and organic carbon. The binding agent produced by earthworms induces the formation of macroaggregates which strengthen the bond between soil particles (inter-particles binding) to form stable macroaggregates (Six et al., 2000, 2004; Tisdall & Oades, 1982). The stability of macroaggregates are due to presence of more labile organic carbon and cations that prevent dispersion (Kong et al., 2005; Pulleman et al., 2005). This research suggests that the size of aggregate is an important factor in aggregate stabilization (Table 3) as shown by the highest percentage of stable aggregates in treatment as0 (the size of aggregate between $841 - 2000$ μm) without compost and earthworms (as0cp0ew0) compare with as1cp0ew0 and as2cp0ew0 in first month period. This is because larger size of soil aggregate has more soil organic carbon (SOC) content than the smaller one (Bronick & Lal, 2004).

Addition of both earthworms and compost facilitate the stable aggregate formation (Table 3). However, earthworms can facilitate faster stable aggregate formation than compost. The activity of earthworms in digging, burrowing soil and feeding on soil particles containing carbon and other organic materials produce cast containing organic carbon in the form of carbonic acid, fulvic acid and humic acid (Fonte et al., 2007; Knoepp et al., 2000; Pulleman et al., 2005; Zhang, et al., 2013). The increase of carbonic acid could trigger an increase in the negative charge on the surface of soil particles and then strengthen the binding of soil particle (Six et al., 2004; Tisdall & Oades, 1982).

Even though addition of compost facilitates the process of stable aggregate formation, the process was slower than in the treatment by earthworms (Table 3). The compost released cations and organic materials at a slower rate, because it had to undergo the decomposition and mineralization process first. In general, the release of cations and organic carbon from compost are slow (Maheswari et al., 2014). The difference in the release of binding agents by compost and earthworms resulted in a difference in the stable aggregate-forming process. Although stable aggregate-forming process induced by compost was slower than that of earthworms, but the aggregate stability might persist longer.

The presence of stable macroaggregates can protect soil organic carbon (SOC) from decomposition by microfauna or microorganisms. This facilitates the accumulation of stable organic carbon in the soil. (Six et al., 2004). Therefore, soil organic carbon and what aggregates mutually protect each other. SOC efficiently influences the soil aggregation (Six et al., 1998). On the other hand, SOC is physically protected and stabilized between and within micro-aggregates (Six et al., 1998, 2000, 2002,

2004). The effect of interaction among the size of aggregates, earthworms, and compost increases aggregate stability. Subsequently, aggregate stability increases formation of micro-aggregates within macro-aggregates. This interaction (aggregate stability and organic content) resulted in stable soil aggregate structure that has higher organic carbon contents as a consequence of a higher degree of physical protection.

CONCLUSIONS

The process of aggregate formation was indicated by the changes in the morphological structure of aggregate, i.e. the surface became rough and the aggregate has more pores. The size of the aggregate is an important factor in determining aggregate formation, however in the three-month period, the formation of stable aggregates was more influenced by the presence of earthworms and compost. Aggregate stabilization is initiated by the formation of macro-aggregates. Subsequently, aggregate stability increases with the formation of micro-aggregates within macro-aggregates. The interaction effects among the size of aggregates, earthworms, and compost become stronger and was related to the changes in cation composition that function as binding agents to stabilize the soil aggregates. In general, this research showed that the process of aggregate stabilization was visible after the first month of treatment and increased until the third month.

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