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Effect of land management models on soil erosion in wet tropical cacao plantations in Indonesia

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ABSTRACT

Indonesia is one of the world's largest cocoa exporters and is located in a tropical wet region. In tropical regions, surface run off is a major factor behind the occurrence of erosion-driven land degradation. Both land slope and land cover influence the magnitude of surface run off and soil erosion. Cocoa plants are generally cultivated on land that has a steep slope without regard to existing land cover conditions resulting in a susceptability to soil erosion. The purpose of this research was to measure the influence of land management models used in cocoa plantations on soil erosion caused by surface run off. Soil erosion measurements were performed *in situ* using soil erosion plot models. Soil erosion plots were constructed in six different land conditions based on a combination of land slope (22 – 60%) and land cover or litter distribution (50 – 100%). Results of this researched showed that: 1) erosion was an exponential function of rainfall at all land slopes; 2) the amount of shade influenced theinitial soil moisture content; and 3) land cover is the primary factor behind soil erosion in cocoa plantation.

Key words : *Erosion, Cocoa land management model, Exponential function*

Introduction

Indonesia is one of the world's largest exporters of cocoa ranking below only to the Ivory Coast and Ghana (BP3, 2014; Mattyasovszky, 2015). Cocoa thrives in regions with high humidity and annual rainfall of 1,500 – 2,000 mm and less than three dry months per year (ICCO, 2013). Indonesia is located in a tropical wet zone (BPS, 2013) with annual rainfall greater than 1,500 mm, short dry season, and high air humidity (Michael, 2001). Due to this climatic suitability, cocoa is grown in all parts of Indonesia.

Cocoa plant cultivation is driven by its high economic value in comparison to other agricultural commodities. In addition, almost all regions of Indonesia are suitable for cocoa cultivation as the plant does not require specific land conditions for its growth. Hence the the cocoa growing area in the country continuously increase. However, the expansion of land used for growing cocoa plants has not resulted in an increase of production; this is caused by a decrease in land productivity of only 0.4 – 0.6ton/ha compared to potential productivity of 1 – 1.5ton/ha (Anonim, 2012). One factor behind this drop in productivity is the degradation of soil quality as a result of erosion (Li *et al*., 2013). Accordingly, the preservation of land quality is crucial as the productivity of cocoa plant production in South Sulawesi is influenced by soil fertility among other factors.

Surface run off plays a vital role in the degradation of land quality: it is a major factor behind the occurrence of soil erosion in tropical regions. Every

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land management model is unique in the way it influences soil erosion (Arsyad, 2006). Proper soil and vegetation management can reduce soil erosion up to 99% (Labrière, *et al*., 2015) and land cover is the most crucial element in erosion models (Ekpenyong, 2013). In addition to management models, different types of vegetation have their unique influence on surface run off (Musa *et al.*, 2013).

Generally, cocoa is grown by small, locally-run, community-managed businesses (Rubiyo and Siswanto, 2012). Cocoa is grown on lands that have slopes ranging from very small to over 40% (Liyanda *et al*., 2013). The over-pruning and excessive weeding of land where cocoa is cultivated lead to soil that is vulnerable to the physical effects of raindrop and surface run off scour.

Soil erosion is generally measured by using a mathematical approach. However, this method is simply an approach and does not provide actual results. Therefore, direct measurements must be performed in situ to accurately determine the influence of land management models and types of vegetation on soil erosion. Measurements were performed using soil erosion plots (Haggard, *et al*., 2005; Akbarimehr and Naghdi, 2012; Sensoy and Kara, 2014). Results collected were also used to determine erosion coeffecients.

This research was performed in situ with direct measurements, thus the data collected can be directly referenced by policy makers as a basis for soil preservation policy in attempts to guarantee continued productivity in agricultural activities.Therefore, this research was aimed to determine the effect of land slope, canopy and land cover by vegetation in cocoa plantations on soil erosion.

Materials and Methods

Field Description

Experiments were conducted during the rainy season 2012 in local cocoa farmers' plantations in the District of Bone, South Sulawesi Province, Indonesia. Six locations with differing levels of land slope and land cover were used in this trial. Measurement plots were constructed at each of these six locations to determine the surface run off and erosion at each location. In addition, supporting data related to land slope and rainfall levels throughout the duration of this research were also collected. Rainfall measuring tools were placed at each research location to minimalize the bias of measurement results with actual values collected in situ.

Land slope

Land slope was determined by measuring the distance (run) and the difference in height (rise) between two points using waterpass. The measurement data were used to calculate the percentage of slope using the following equation:

$$Slope = \frac{rise\ (m)}{run\ (m)} \times 100\%$$

Shadow-covered area

The shadow-covered area was determined by capturing photos of soil surface conditions on clear weather at 12:00 local time. The percentage of shadow-covered area was calculated by comparing the area of land that did not receive sunlight to total land area.

Field Experiment Design

Surface run off data was obtained from surface run off measurement results collected from each plot. Six plots were constructed each varying in land slope, shadow-covered area, and land cover rate. These plots with their respective land conditions shall heretoafter be referred to as cocoa land management models. The following is a list of all land conditions measured at each plot (Table 1).

Model plots were created by constructing plot dividers from plastic (tarpaulin). The purpose of these dividers was to prevent the entrance of water from sources external to the plot. The butt of each divider was buried 10cm into the soil and the exposed 20cm of the divider served as walls to retain run off and total construction was relatively stable. The dividers also worked to prevent seepage of water into or out of the plot. An outlet and pipe were placed at the lower end of each plot to allow the flow of water from the plot to a surface water receptacle. The upper end of the receptacle is covered to prevent rainwater or soil to splash into it.

Manual rainfall monitoring stations were placed beside each of the model plots at a height of 1.5m above ground level. Observation was carried out at the end of every instance of rain. Water collected in the measuring tube was poured into a measuring cup to measure the volume of rain water (V), where the funnel surface area was known. After each mea-

Table 1. Plant shade , land cover, and land slope at each model plot

Plot No.	Outlet Coordinates (LS; BT)	Area (m^2)	Shade area (%)	Land Cover (%)	Land Slope (%)
1	4035'52,4";120002'54,2"	119.05	80	100	22.11
2	4035'53,8";120002'54,3"	123.58	70	80	25.00
3	4035'54,6";120002'56,4"	93.26	75	100	40.10
4	4035'55,7";120002'56,6"	100.22	60	90	53.95
5	4035'54,0";120002'56,6"	100.49	95	100	38.77
6	4035'54,0";120002'58,3"	156.46	95	50	60.56

surement, the receptacle was dried by wiping it with a piece of cloth.

Runnoff water volume and eroded soil mass were determined by using Boix-Fayos's method Boix-Fayos *et al.*, 2006). Water collected from each surface water receptacle in each model plot was measured to determine the run off water volume. To assess the eroded soil mass, water collected in receptacle was stirred until the sedimentation had dissolved or suspended evenly. Sample of 100 ml of suspension was taken from each receptacle and individually pass through a filter paper. The retained solid in the filter was heated in an oven for 48 h at 105°C before it was weighted.

Data Analysis

Calculating Soil Erosion

Soil erosion is calculated based on the amount of sediment with the following equation:

$$E = \frac{Cap \times Vap \times 10^{-3}}{A}$$

where:
E = eroded soil (ton/ha)
Cap = sediment concentration (kg/m3)
Vap = surface run off volume (m3)
A = area of land affected by erosion (ha)
10^{-3} = conversion value from kg to ton

Calculation of Erosion Coefficient

Surface run off coefficient is calculated by comparing the volume of surface run off to the volume of rainfall (Norbiato *et al.*, 2009)– this is used to calculate the erosion coefficient – or by plotting a graph comparing rainfall and erosion. When using the graph method, the erosion coefficient value can be determined using an equation from data trends. Mathematically, this can be calculated using the surface run off coefficient method (Asdak, 2010; FAO, 2012):

$$K = \frac{surface\ runoff\ (mm\ or\ cm^3)}{rainfall\ (mm\ or\ cm^3)}$$

where K = surface run off coefficient

Results

Model Plot Construction

All plots were constructed in the same cocoa plantation, though placed in areas with differing land conditions and vegetation. These variables were intended to discover the influence of vegetation shade and land conditions on surface run off and erosion. Each plot had a different area and shape; the purpose of this was to ensure the physical conditions of each plot wereuniform. Thus, the collected data accurately represents the conditions at each plot. The model plot layout and imagecan be seen in Fig. 1.

Influence of Land Cover on the Quality of Soil moisture and Surface Run off

Changes in soil water content with different levels of land cover and shade during the experiment can be seen in Fig. 2.

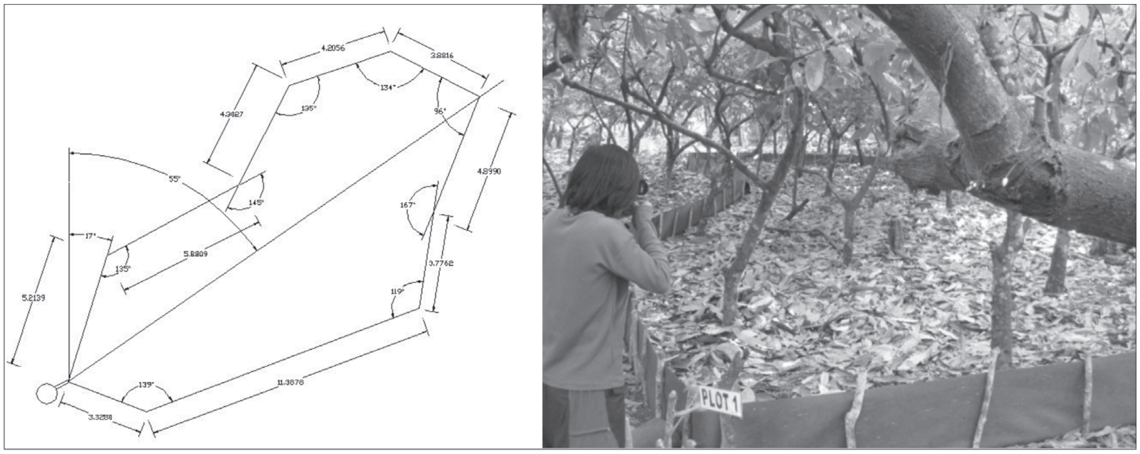
Figure 3 expresses the surface run off for several instances of rain at each plot.

Effect of Initial Soil moisture Content on Soil Erosion

At the research locations, initial soil moisture content greatly influenced erosion. The majority of instances of soil erosion occurred as a result of surface run off. In addition, the research locations had relatively good canopy cover and land cover, reducing the erosive effect of kinetic energy from rain fall on the soil surface. This phenomenon is expressed in the following Fig. 4.

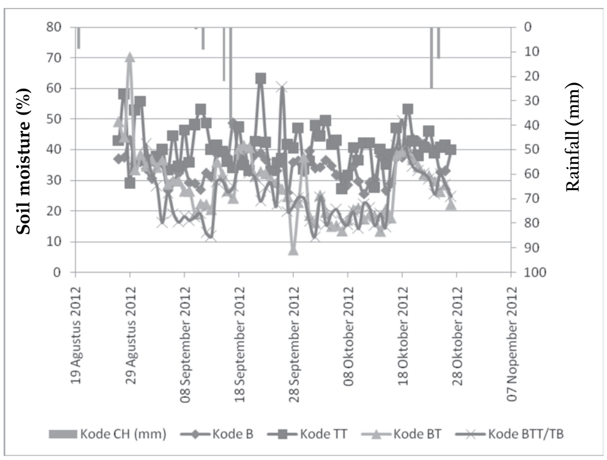
Relationship between Rainfall Level and Surface Run off

Surface run off is the primary factor behind erosion.



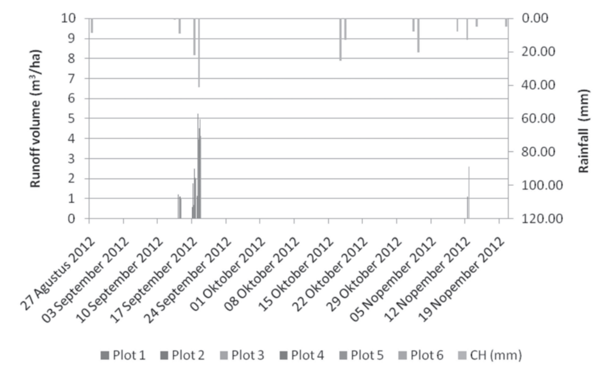
A B

Fig. 1. Experiment plot used to measure water run off and erosion. Lay out of the experiment plot (A) and experiment plot (B).



Notes: B = Land covered but unshaded
TT = Land covered and shaded
BT = Land uncovered but shaded
BTT = Uncovered and unshaded

Fig. 2. Changes in soil moisture content with different levels of land cover and shade.



Notes:
Plot 1: Shaded 80%, covered 100%
Plot 2: Shaded 70%, covered 80%
Plot 3: Shaded 75%, covered 100%
Plot 4: Shaded 60%, covered 90%
Plot 5: Shaded 95%, covered 100%
Plot 6: Shaded 95%, covered 50%

Fig. 3. Run off rates at different land coverage levels.

Theoretically, the relationship between rainfall and surface run off can be explained using a model as an approach. The relationship between rainfall and surface run off is exponential (Suhardi, 2014). This is in agreement with Musa *et al*. (2013) suggesting that changes in surface runoff caused by rainfall is not linear. Only certain high volumes of rainfall will result in high amounts of surface run off and, inversely, low rainfall volume will not result in surface run off. The exponential correlation shows that surface run off will increase dramatically as rainfall volume increases.

In the risk model there are two defining coefficients: the exponential coefficient which acts as the intercept as the lower limit of the model, and coefficient x (rainfall) which shows the slope of the line. The greater the value of the exponential coefficient is, the greater the probability of surface run offto occur in higher levels of rainfall. The coefficient x (rainfall) is an expression of the sensitivity of change in surface run off caused by a change in rainfall.The greater the value of x the more sensitive surface run off is to changes in rainfall volume (Suhardi, 2014).

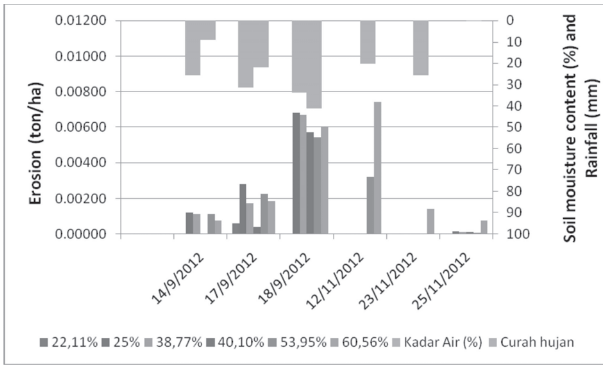


Fig. 4. Effect of slope, initial soil moisture content, and rainfall on erosion rate.

Table 2. Exponential coefficient and rainfall (variable x) values in six experimental plots

Plot	Exponential coeffcient	Rainfall (variable x)
1	10.200	1.245
2	9.410	0.288
3	0.022	0.130
4	0.150	0.090
5	0.231	0.083
6	0.639	0.043

Relationship between Rainfall Level and Soil Erosion

Generally, the relationship between rainfall and erosion rates was similar to the relationship between rainfall rate and surface run off (Zhu and Zhu, 2014). This phenomenon was also evident with the correlation between rainfall and soil erosion, which was exponential just as the relationship between rain fall and surface run off (Fig. 5).

Relationship between rainfall and erosion was exponential in all model plots tested. This correlation implied that erosion increased subastantially as rainfall rate increased. This was a result of high rain water volume either due to high intensity of rain or long duration of rain resulting in soil saturation. In this case, most of rain water could not enter the soil surface so it became surface run off and resulted in erosion.Therun off can also occur when rainfall rate is greater than the water infiltration rate due to soil covere.

Discussion

Model Plot Construction

All six plots had different canopy closure conditions and distribution of vegetation. These differences influenced the quantity of the soil moisture and the soil's rainwater absorption. These two parameters also influence the volume of run off and magnitude of soil erosion in a given plot.

Influence of Land Cover on the Quality of Soil moisture and Surface Run off

In some instances of rain, therun off was still clear with minimal erosion. This was caused by the soil moisture content at the time of rain was still quite low, thus a large volume of rainwater infiltrated the soil reducing the soil run off and low erosion potensial.Change in soil moisture content was influenced by land cover at all levels of rainfall.

Both the shading conditions and land cover greatly influenced the soil moisture content after rainfall.Changes in soil moisture content affected the surface run off and erosion. Land that is protected by a canopy and covered with vegetation did not experience an immediate increase in surface run off. The effects of rainfall became evident two days after rain when soil moisture volume increased despite the lack of rain. This was due to the protection provided by plant canopy intercepting rainwater before it reached the soil surface, thus delaying its absorption by the soil. In addition, not all of the rain water reached the soil surface but a portion of it evaporated into the atmosphere. Land with high canopy closure and land cover will have lower surface run off in comparison to land lacking in canopy closure and land cover.

This difference in soil response to surface run off as a result of canopy cover and land cover is expressed similarly with soil moisture. This response difference is also influenced by interception, stem flow, surface depression, and evaporation. Land that has good canopy coverage and land cover will also have low surface run off.

Canopy cover and plant litter both played substantial roles in minimizing surface run off, especially during instances of low rainfall rate. Land cover played a larger role during high-intensity rain; the greater the vegetation coverage the greater the soil surface run off. This is true because thicker vegetation coverage serves as a barrier that prevents a good portion of rain water from entering the soil.

Effect of Initial Soil moisture Content on Soil Erosion

Initial soil moisture content greatly influenced ero-

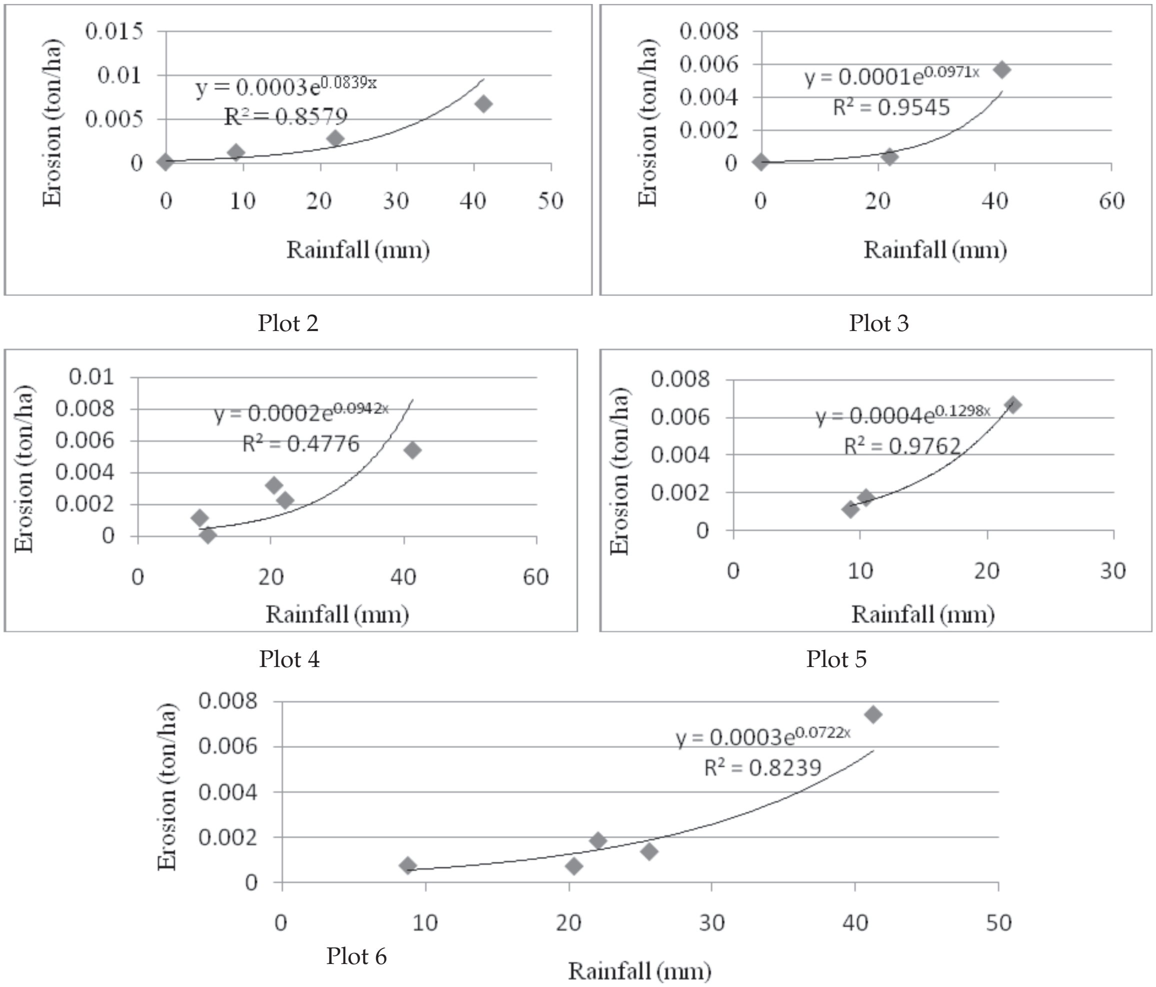


Fig. 5. Relationship between rainfall and erosion in Model Plots 2- 6.

sion due to the rain in a location. Whenthe soil moisture content was greater than 25% and there was an instance of rain, then there would be a greater potential for erosion. According to the data expressed in Fig. 5, land slope does not clearly influence soil erosion. This is caused by the physical characteristics of the cocoa plantation with a lot of plant litter that was capable of holding back the surface run off. Thus the kinetic energy of surface run off will decrease until it is no longer capable of carrying erosion materials.

Relationship between Rainfall Level and Surface Run off

Table 2 shows that plot 1 had the largest exponential coefficient value. There must be high intensity rain or large rainfall volume over a long duration before there is any surface run off. This is due the low land slope at plot 1 of only 20%. This is in line with the results of the research conducted by Akbarimehr and Naghdi (2012) showing that there is a clear difference in the influence of land slope on surface run off between areas with a land slope of 20% and areas with land slope above 20%. In addition, plot 1 had a canopy cover of 80% and 100% land cover by vegetation. Plot 2 had the largest value for coefficient x; this means that once surface run off has occurred then surface run off volume will drastically increase to even small increases in rainfall volume. This is due to the relatively open canopy cover in plot 2 of 70% and land cover of only 80%; thus rainfall makes direct contact with the soil surface causing the soil to reach saturation much more quickly. Any increase in rain water after the soil has reached water saturation level will become surface run off. These conditions are in line with research results reported by Haggard *et al*. (2005) stating that surface run off is affected by the levels of soil water saturation and soil cover. However, the influence of a combination of individual factors of a plot on the volume of surface run off is quite complicated and difficult to separate (Zhu and Zhu, 2014).

Plot 6 had the greatest land slope of 60.56%, hence the potential for surface run off was greatest in plot 6. This was due to the greater potential of rain water becoming surface run off instead of becoming soil moisture through infiltration. This was a result of the influence of gravity pulling water into the soil thus creating a tendency for rain water to become surface run off. The friction between water molecules and soil surface was lower in comparison to the adhesive friction between water molecules and the soil surface particles at the moment the water entered the soil.

Relationship between Rainfall Level and Soil Erosion

The dominant factor causing erosion was surface run off. Erosion caused by surface run off has great potential to create erosion grooves. The model for calculating the risk of erosion as a result of rainfall has two coefficients: an exponential coefficient that functions as an interceptor and the initial limit for the model, and coefficient x (rainfall) expresses the slope of the line. A greater value of the exponential coefficient expresses that greater rainfall is required to cause erosion at existing land conditions in the tested area. Coefficient x is an expression of the sensitivity of the magnitude of erosion that occurs as a result of changes in rainfall. The greater the value of x, the greater the sensitivity of the land to changes in rainfall that causes erosion.

Plot 5 had the largest value for coefficient x. This was caused by plot 5 having very high canopy cover (95%) coupled with high land cover. These land conditions preserve soil saturation for a long period of time. Saturated soil accelerates the formation of surface run off, however when the land cover is good,it can, in fact, suppress erosion (Labrière *et al.,* 2015). This land is sensitive to long durations of rain fall.Unlike land with insufficient canopy cover and land cover, during breaks in rainfall, the land requires high intensity rain or long durations of rainfall before surface run off appears.

Plot 6 had the greatest land slope of 60.56%. Thus, this land had the greatest potential for surface run off and erosion because most of the rain water became surface run off and not soil moisture through infilitration. This is a result of gravity causing smaller amounts of water to enter the water and more likely to flow on the surface as a result of a lack of friction in comparison to water entering the soil due to the presence of adhesion between water and soil particles. In general, cocoa plantations are not at high risk of erosion because their structures are similar to forest floors where land is highly covered by plant canopies and litter.

Fig. 5 does not include Model Plot 1 because only two samples of erosion occurred throughout the multiple instances of rainfall during the research period, making it impossible to plot the data and calculate an erosion risk model. This is due to the land at the plot having a very low land slope of only 20.56%. Because of this condition, rainfall was more likely to become soil moisture and not surface run off, in addition to the low initial soil moisture content. Surface run off occurs in land with low slope only once soil saturation has been reached.

Conclusion

Our results indicated that the magnitude of erosion was affected by canopy coverage, rainfall rate, and slope of the land.Relatively low canopy coverage increases the potential of surface run off causing soil erosion; however, high land coverage by vegetation also increase the run off because a high percentage of the rain water directly became surface run off particularly during instances of high-intensity rain but the erosion rate was smaller.

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