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C – statistical analysis
D – data interpretation
E – manuscript preparation
F – literature search

Effectivity test of an eco-friendly sediment trap model as a strategy to control erosion on agricultural land

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Abstract

A sediment trap with bamboo materials can be utilized as one alternative of eco-friendly technology to reduce the erosion that occurred on agricultural land. This study aims to determine the most efficient form of that sediment trap in the field. Location study is in the Tulungrejo Village, Batu, Indonesia, which has andosol soil type and 35 cases of a landslide in 2013. Three forms of sediment traps were used (square, trapezoidal, and stratified type) with the purpose to find the most effective form. It is obtained that the most effective sediment trap is a stratified form with the 31.91% effectiveness or able to withstand sediment of 25.02 kg, while the adequate number is two pieces with the ability to withstand the most considerable sediment of (91.70%). Therefore this stratified form of sediment traps is effective in erosion prevention on agricultural land in the study area. For further development, it is required to test out the variations of the contents in a broader area with a more varied level of the slope.

Key words: *bioengineering, erosion control, land degradation, sediment trap*

INTRODUCTION

Food security is an important emerging issue in Indonesia. The sustainability of land and water resources must be improved, however, since the 1999 flood occurred with severe erosion resulting from the conversion of forest land to the watershed that leads to critical land condition [NUHFIL 2009]. The transformation of forest land into agricultural land increasing the potential for erosion and landslides due to the very shallow roots of farming crops [ASDAK 2007; BELLO *et al*. 2017].

Fertile soil that is suitable for agricultural land could be found mostly on hilly to mountainous topography. However, land clearing on slopes is prone to land damage [SOEWANDITA, SUDIANA 2009]. Steep slopes are not a severe problem if the principle of environmental sustainability is considered in land management. The problem is, traditional Indonesian farmer has limited capital and knowledge in land management.

In tropical areas, erosion is considered as the main cause of soil degradation and the sediment loads from river basins [CHAPLOT *et al*. 2011; ZHOU *et al*. 2005]. The tolerable range of erosion threshold in Indonesia is 1.1–13.5 $Mg \cdot ha^{-1} \cdot year^{-1}$ (depending on the nature of the soil and its substrate) [ARSYAD 2012]. The important nutrient for plants also decrease along with soil particles carried by rainfall runoff, so that the amount of organic C, nitrogen (N), phosphate (P_2O_5), potassium oxide (K_2O), which are transported by the eroded soil especially on agricultural land with steep slopes. This causes of the declining quality of land, resulting in the decrease in land productivity [CHEN *et al*. 2012]. As a result, the estimated economic losses in the island of Java reached 599 million rupiah (1 USD is about 14 320 rupiah) or equal to 2.8 billion rupiahs in 2010, adjusted to the rupiah exchange rate. This amount is very significant compared to Indonesia's national budget for environmental management and conservation, which amounted to 7.72 billion rupiahs [MAGRETH, ARENS 1989].

Some conservation actions are required to reduce erosion of the land, including vegetative and mechanical methods. Vegetation is beneficial in stabilizing the soil against the strong erosion flow; especially using the combination of several plants [VANNOPEN *et al*. 2017]. FRANKL *et al*. [2018] reported the use of vegetation addition for erosion barrier could decrease the erosion by 40% compared to the one without vegetation. Another similar report by RUIZ-COLMENERO *et al*. [2013] reported the planting pattern and land slope angle management could reduce erosion by 45% and increase the land infiltration capability. Generally, it is difficult for farmers to change their cultivation techniques, so that vegetative methods, such as planting protective plants in the same direction of the land contour, or mechanical methods, such as changing the terrace, are less acceptable. Also, the high cost, such as the manufacture of bench terraces, would be difficult to apply when there is no help from the government [MCHUNU, CHAPLOT 2012]. An alternative eco-friendly technology that is economical and easy to implement to reduce the erosion that occurs on agricultural land is the usage of sediment traps with bamboo materials [Regulasi… 2006]. Previous study observed that a very tight rooting system from bamboo is strong enough to trap the sediment in sloped land until 60–80% [PIMENTEL *et al.* 1995; SHIBATA *et al*. 2002; TAKAMATSU *et al*. 1997; ZHOU *et al*. 2005], but there is no reference on how is the most effective sediment trapper. Sediment traps made by using bamboo plants can be combined with the use of various types of stuffing material placed in the bamboo so that it can better withstand the sediment [SOEWANDITA, SUDIANA 2009]. Based on the above arguments, this study aims to determine the most efficient form of trap sediments when used on agricultural land. The study area condition is actively illustrating the state of general agricultural areas in Indonesia, which is dominated by hills and mountains areas. Therefore, the positive study results will be applied to the local community with the majority of farmers.

MATERIALS AND METHODS

STUDY LOCATION

The research area is located on the farmland at Tulungrejo Village, Bumiaji Subdistrict, Batu City with coordinates 7˚49’11” S, 112˚31’28” E and an altitude of 1,068 m. The study area was characterized by steep agricultural land (>25%) with soil type was erode easily. Batu city has andosol soil type, which sensitive to soil erosion, with the addition of the rainfall precipitation of 1500 mm per year creates a high risk of landslide in this city. In 2013, it was recorded to have 35 landslide cases [NOORWANTORO *et al.* 2014]. The study was conducted in May 2016 (the beginning of the planting season for carrot commodities and the end of rainy season).

This study was conducted over an area of ±1,200 m^2, which was divided into four plots with similar soil texture and characteristics based on the sieve and soil hydrometer analysis issued by the national standardization committee. The soil was categorized as entisol with the credibility value of 0.43. To obtain a greater erosion potential, the study was conducted on land with shallow roots that located on the 35 ± 2% slopes (carrot plants vegetation), as well as property with minimal conservation efforts in the form of bunds in the same direction as the contour of the land (without stands), which is (Fig. 1). The data was recorded four times during the period of the study, at 8, 10, 11, and 14th of May. Precipitation data for each sampling date was retrieved based on data from the nearest rain station, Ngaglik, and Karangploso rain station.

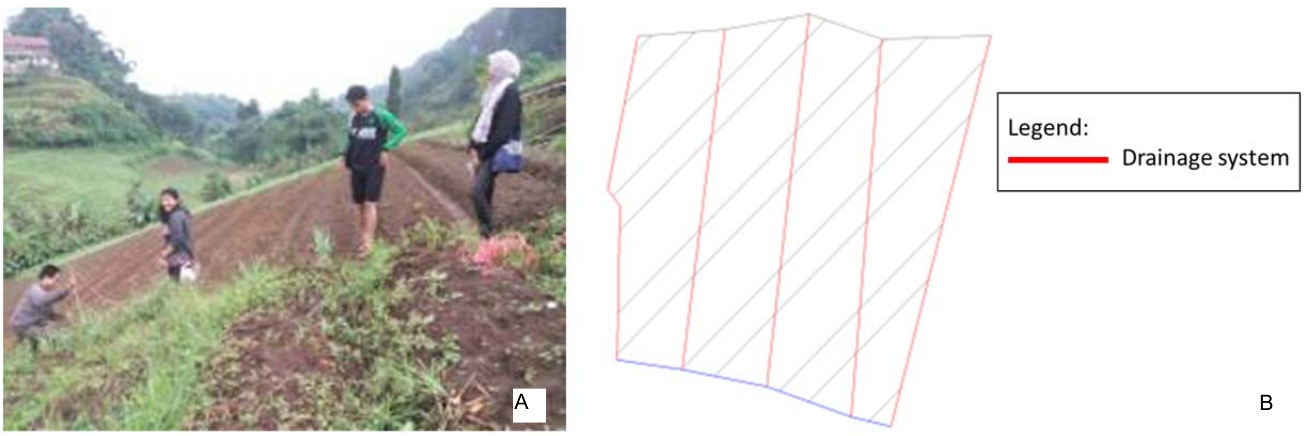

Fig. 1. The land condition for research: A) actual land condition during the experiment; B) the plot dimension for sediment trap experiment; source: own elaboration

SEDIMENT TRAP DESIGN

Design planning was based on land measurement and land topography, using the theodolite measurement device and roll meter. Sediment trap dimensions were planned according to the width of the land groove and the height of the bunds. Also, sediment traps were placed at the ends of the grooves of land drainage, so that the effectiveness of sediment traps on the whole plot could be seen. Ampel bamboo (*Bambusa vulgaris* Schrad. ex J.C.Wendl.) was used as the material for sediment traps because this type of bamboo can easily grow without treatment. The bamboo that was used was aged 1.0–1.5 years with the diameter of 7–11 cm. It was expected that the use of this material could reinforce the soil as a result of the roots of the growing bamboo. This type of bamboo is also commonly found around the study site.

EXPERIMENT DESIGN

The study site comprised four plots sized 340 m^2, which were divided into one control plot and three treatment plots as follows (Fig. 2). The dimension of each plot varied according to the real condition in the field, but the angle slope and total size were the same for each plot. In experiment 1, plot I was controlling land to determine actual erosion (complete erosion); in plot II, the land was given one piece of sediment trap, which had a square threshold form. Meanwhile, in plot III, the land was given one part of sediment trap, which had a trapezoid form; and in plot IV, the land was given one piece of sediment trap, which had a stratified structure (Fig. 3). The differences in

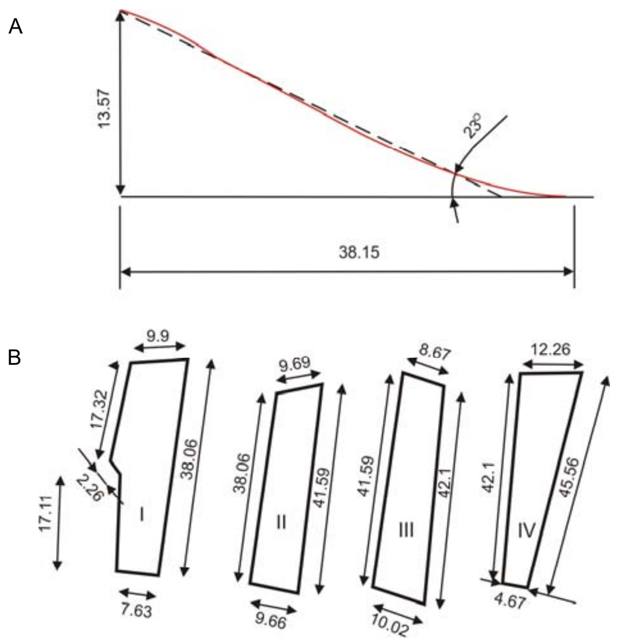

Fig. 2. Details in research plots: A) the slope angle of every plot; B) the size of each plot; source: own elaboration

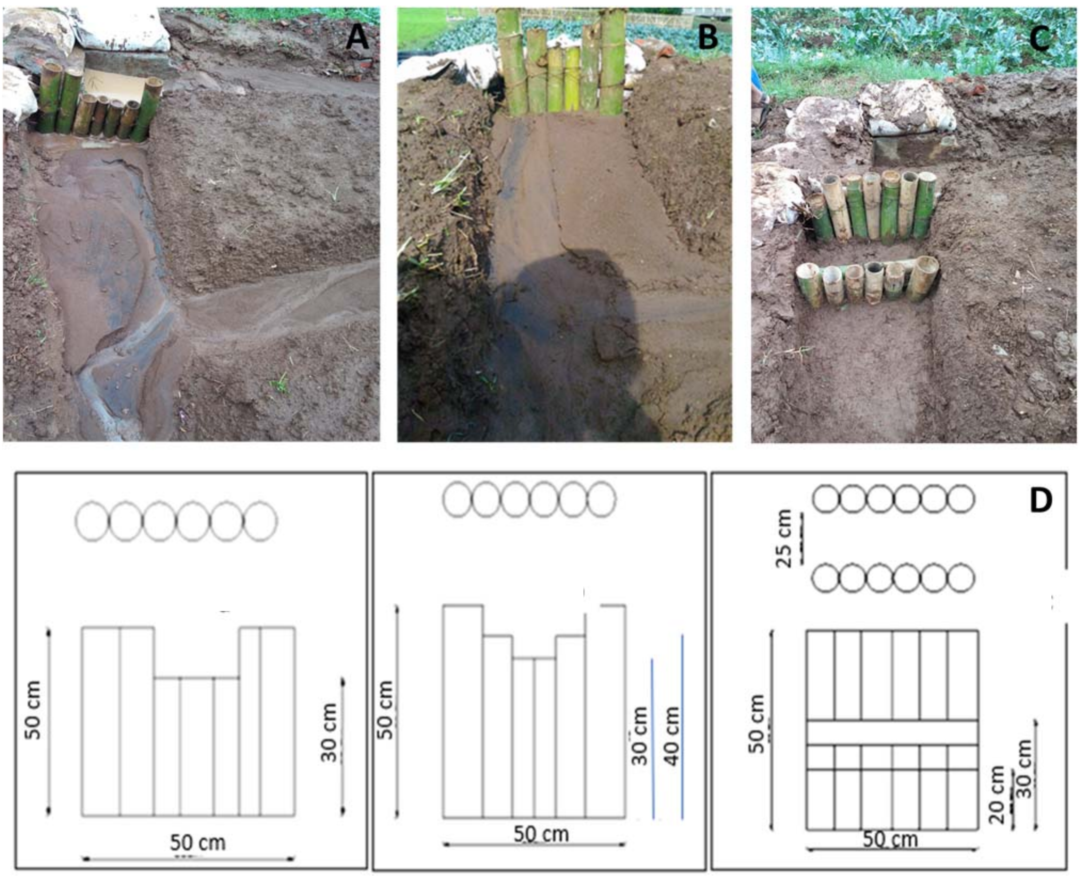

Fig. 3. Various threshold forms design such as: A) square threshold; B) trapezoidal threshold; C) stratified threshold; D) the schematic of each limit, bird-eye view (top), front view (bottom), and dimensions; source: own elaboration

form aimed to determine which type of sediment trap is most influential for the strength of resisting. The threshold model intends to ease the water to overflow, but by maintaining the storage capacity of the maximum sediment trap. However, the stratified or layered models were made to strengthen the sediment trap without a threshold by slowing the flow velocity through the sediment trap.

In experiment 2, plots II, III and IV were given the most efficient sediment trap model in the first experiment in a series with two pieces, three pieces and or four pieces, respectively. This experiment aimed to determine the ratio of sediment catchment area to sediment trap efficiency.

The actual erosion measurement of the land using the transported soil deposition method is based on the technical guidance of erosion measurements of agricultural land [PRIYONO 1996], using two drum collectors each with a capacity of 1200 dm^3 coupled with a PVC pipe and given four holes on the first drum to calculate the flow coming out of the drum (Fig. 4). Collectors caught sediments (Fig. 4) then were collected in two drums, so that the measurement and sampling were both conducted in the drum [WAHYUNTO *et al.* 2016]. Samples of suspended load and bed load of up to 3 dm^3 were taken using a bucket before being transferred to a sample bag. The sediment sample was then weighed and dried in the oven until the water content completely disappeared to determine the level of sediment in runoff. Sampling was conducted at all three sediment trap models.

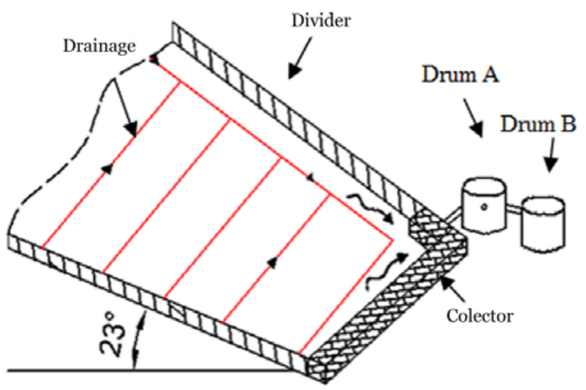

Fig. 4. The schematic for land erosion measurement; source: own elaboration

Erosion rate calculation. The erosion rate prediction was based on MUSLE (Modified Universal Soil Loss Equation) method [RADECKI-PAWLIK *et al.* 2014]. The following is the formula of MUSLE:

$$A = Rw \cdot K \cdot L \cdot S \cdot \tag{1}$$

Where: A = estimated long-term annual soil loss (Mg soil loss·ha^{-1}·yr^{-1}); Rw = rainfall and runoff factor representing the summed erosive potential of all rainfall events in a year (MJ·mm·ha^{-1}·h^{-1}·yr^{-1}); K = soil erodibility factor representing units of soil loss per unit of rainfall erosivity (Mg·ha·h·ha^{-1}·MJ^{-1}·mm^{-1}); L = slope length (dimesionless); S = slope steepness (dimesionless); CP = characterizer land cover and conservation management practices (dimesionless).

Runoff and sediment trap efficiency calculation. In general, the sediment the collection drums were floating and settling below. Samples were taken for 3 dm^3 using the bucket to be put inside a sample bag and labeled. Following this, the collector drums were drained to be tested in the laboratory with the drying method to measure the sediment percentage and runoff. The runoff was calculated with these formulas:

$$V_b = V_{bA} + 4V_{bB} \tag{2}$$

$$V_s = V_{sA} + 4V_{sB} \tag{3}$$

$$V_{\mathrm{tot}} = V_b + V_s \tag{4}$$

Where: V_b = volume of settling sediment (dm^3); V_s = volume of floating sediment (dm^3).

Furthermore, the total sediment was calculated with this formula:

$$A = \sum_{n=1}^{n} K_{b_n} V_{b_n} + \sum_{n=1}^{n} K_{s_n} V_{s_n} \tag{5}$$

Where: A = actual erosion per plot (kg per 340 m^2); Kb = bed load per volume (kg·dm^{-3}); Ks = suspended load per volume; n = collector number.

The height of suspended sediment in every sediment trap was measured using measuring meter by taking 3 dm^3 of the sample. The dry mass of sediment was further compared to actual erosion to obtain the sediment trap efficiency as in formula (6):

$$\text{Efficiency (\%)} = \frac{\sum_{n=1}^{n} \text{Suspended sediment}}{\sum_{n=1}^{n} \text{Actual erosion}} 100 \tag{6}$$

Statistical analysis. The research data is presented in the mean ± standard deviation (*SD*). The trap model data were analysed using one-way ANOVA ($p < 0.05$) and the total sediment data in each condition were analysed using two-way ANOVA, followed by Tukey's ($p < 0.05$) and Games–Howell assays when the data assumption was not homogeneous. Data were analysed with Microsoft Excel 2013 for Windows.

RESULTS

The largest total runoff was on the 2nd experiment on 10th May, with a total runoff of 246.66 dm^3. However, the smallest total runoff was in the first experiment on 8th May, which amounted to 143.90 dm^3 (Fig. 5). The runoff calculation result was quite varied due to changing rain intensity or non-uniform rainfall, with low precipitation of 50–150 mm.

The most massive amount of total sediment retained at the plaster was on the 1st experiment on 8th May, with total sediment of 44.88 kg. However, the smallest total sediment was in the third experiment on 11th May, which amounted to 19.36 kg (Fig. 6). The B drum bed load had the lowest sediment useful load from all the experiment and significantly different with B drum the suspended load. The highest sediment load was the drum A bed load; drum B suspended load, drum A suspended load, and lastly drum B bed load.

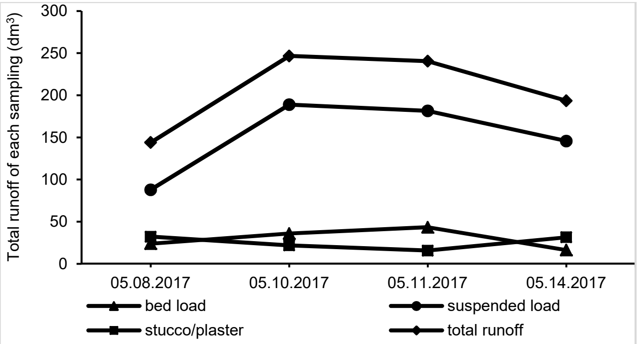

Fig. 5. Total runoff of each sampling from plot 1 (without sediment trapper) on different days; source: own study

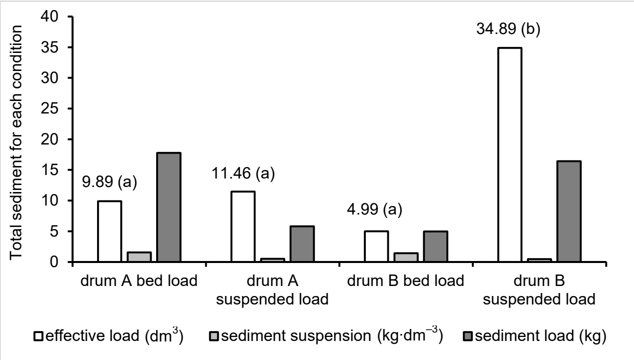

Fig. 6. Total sediment for each condition in plot 1 (without sediment trapper); each different letter means significantly differ at $p < 0.05$ based on two-way ANOVA followed by Tukey post hoc test; source: own study

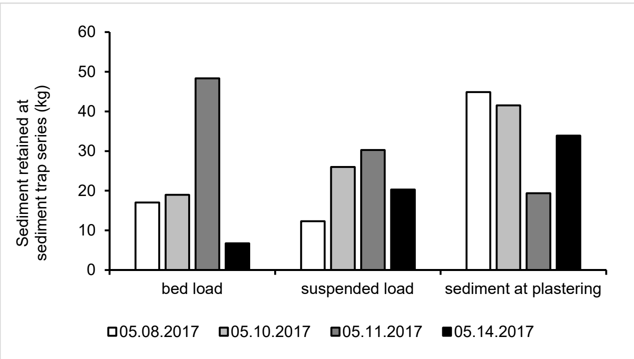

Fig. 7. Total erosion on different days sampling in plot 1 (without sediment trapper; source: own study

Total erosion is the sum of sediment at drum collectors A, B, both the result of suspended load and bed load samples, as well as the amount of sediment retained at the plastering (Fig. 7). The total erosion for each condition varied considerably, with the amount of erosion being between 60.94 and 97.96 kg. From the actual erosion, the percentage of sediment retained for each form of sediment trap can be calculated (Tab. 1).

The results of the experiment showed that the most effective design to withstand the sediment is the stratified form, which the average to withstand the sediment is 31.91% and statistically different with the other two sediment trap types. Based on single ANOVA test, it is evident that trapping model was significant. Further analysis shows that square and trapezoidal traps are the most effective followed by stratified trapping model. Different notation in each model indicates the considerable differences between trapping model (Fig. 8).

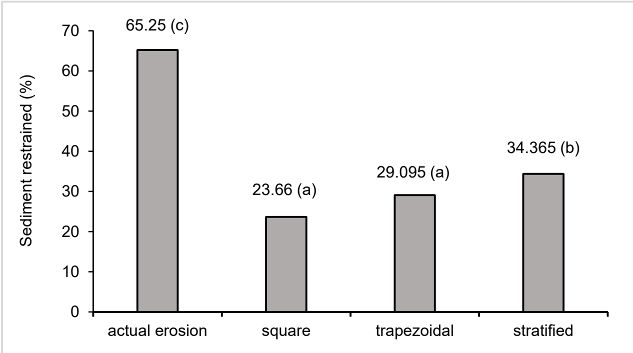

Fig. 8. Percentage of sediment restrained for each form; each different letter means significantly differ at $p < 0.05$ based on one-way ANOVA followed by Games–Howell post hoc test; source: own study

DISCUSSION

Erosion happens due to the forced movement of land mass to another place by the force of water, wind, or gravity. The humid and tropical climate in Indonesia elevate the risk of erosion caused by water. The degradation of land mainly happen in the mountainous and hilly area and primarily caused by rainfall [ARSYAD 2012]. Several other factors that contribute to water erosion is the rainfall, soil characteristics, slope, vegetation, and land use. The mountainous area has a higher risk to get water erosion due to the steep hill and high rainfall. The agricultural practice also increases the risk as it increases the soil sensitivity to erosion [MÜLLER-NEDEBOCK, VINCENT 2015; NOORWANTORO *et al*. 2014].

Continuous erosion will disturb the ecological balance and cause the eroded land to be in critical condition. The

Table 1. Percentage of sediment retained at sediment trap series in experiment 2017

No.	Date	Precipitation (mm)	Total bed load (kg)	Total sediment retained (kg)	Actual erosion	Erosion decreasing in plot with 2 pieces kg	2 pieces %	3 pieces kg	3 pieces %	4 pieces kg	4 pieces %
1	14.05–23.05	60	10.77	5.22	15.99	11.92	74.55	12.17	76.14	12.56	78.56
2	23.05–26.05	52	6.74	0.58	7.32	6.71	91.70	6.84	93.48	6.89	94.16
3	26.05–28.05	146	259.81	19.52	279.33	53.41	19.12	64.86	23.22	88.73	31.77
4	28.05–31.05	120	128.94	16.47	145.41	51.59	35.48	57.52	39.56	65.46	45.02

Source: own study.

critical land is defined as the land with low water absorption so the less water content can lead to drought during the dry season. The dryness can increase the risk of flood, landslide, and eventually decrease the soil fertility and its carrying capacity [SOEWANDITA, SUDIANA 2009].

The first stage of this study was to find out the amount of erosion caused by runoff by using a multiplying factor from sediment levels previously obtained from laboratory tests. Because not all sediment was deposited on the drum, but some were retained at plastering (serves as a barrier and direct runoff to the container drum), the total runoff maintained at the plaster, and the sediment level can also be calculated. By multiplying sufficient volume with sediment suspension data obtained from the experimental results, the sediment load for each condition on each drum was obtained.

The result of sediment retained at the plaster tended to be similar. But there is one data point that is entirely different in the third experiment on May 11th (sediment deposited on the drum is much less than that retained at the plaster/stucco) in contrast to the three other data points, which may be caused by longer rainfall duration than the other three times during the experiment. It would mean that the amount of runoff is not directly proportional to the amount of sediment but instead depends on the weather.

The stratified form of sediment traps was observed to be the most effective in dealing with the erosion of agricultural land with very steep slopes. However, the small capacity for storage due to a small drainage section meant that the stratified form of sediment traps is not yet efficient. Differences were also detected between the square and trapezoidal designs, caused by differences in the number and dimensions of bamboo. It obtained that the tighter the bamboo sequence, the more sediment was caught. With the average erosion of 80 kg per 340 m^2 per rain event (i.e., per plot) or 0.235 kg per m^2 per rain event, within less than one month in the wet season, a sediment trap will be full.

The percentage range of withstanding sediment was 19% as the lowest and 94% as the highest. In the third and fourth rain events, the most downstream sediment trap was in a fully charged condition. It shows that the container becomes full after one rainfall. In experiments with different sediment trap contents, each plot showed that the effect of runoff did not affect the amount of sediment retained. It is because the experimental grounds are perceived to be less extensive than the total area of existing land and sediment retaining structures that are less proportional to the area of the experimental area so that the stuffing mixed the sediment in the container because the runoff is huge.

With the same calculation procedure as the first experiment, a second experiment conducted to increase the efficiency of sediment traps by increasing the number of sediment traps. In this experiment, different numbers of the stratified form in each plot showed that the effect of runoff influenced the amount of sediment retained. In contrast to the first experiment, the amount of runoff tended to be constant in this experiment, and there was the various intensity of rain so that the data range was wider than the first one. In series of the stratified form of sediment traps of more than two pieces, the additional traps had no significant effect on direct runoff caused by the land becoming increasingly steeper at higher elevations. The higher the elevation of the stratified form of sediment trap the less sediment was retained. Based on our result, the stratified form can elevate the sediment trapping until 90%, when compared to the previous study, which had the trap capacity around 60–80% [PIMENTEL *et al*. 1995; SHIBATA *et al*. 2002; TAKAMATSU *et al*. 1997; ZHOU *et al*. 2005].

CONCLUSIONS

The calculation results of runoff in the study area were quite varied, i.e., between 143.90 and 246.66 dm^3. It is because the intensity of rainfall is not similar. Meanwhile, from four experiments that were conducted, the total erosion for each condition varied greatly between 60.94 and 97.96 kg. From the actual erosion, the most efficient sediment trap was the stratified form, with an efficiency of 31.91%. Moreover, the most efficient number of stratified forms of sediment traps was two pieces placed in series with efficiency number more than 90%. In series of the stratified form of sediment traps of more than two pieces, the addition of more traps had no significant effect. Therefore, this stratified form of sediment traps is useful in dealing with the erosion of agricultural land in the study area, which has very steep slopes. In the future, this research will be developed with different plot conditions to determine in more detail the level of effectiveness of the sediment trap. Moreover, the further analysis is required to determine the most effective stuffing of sediment traps.

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Test skuteczności modelu przyjaznej środowisku pułapki osadów do ograniczenia erozji na terenach rolniczych

STRESZCZENIE

Pułapka z bambusu do wychwytywania osadów może być używana na terenach rolniczych do ograniczenia erozji jako jedna z alternatywnych technologii przyjaznych środowisku. Miejscem badań była wieś Tulungrejo, Batu w Indonezji. W badaniach terenowych podjęto próbę określenia najbardziej efektywnej pułapki spośród trzech form: kwadratowej, trapezoidalnej i warstwowej. Najlepsza okazała się pułapka warstwowa o skuteczności 31,91%, zdolna zatrzymać osad o masie 25,02 kg. Zestawienie dwóch takich pułapek dało skuteczność 91,70%. Warstwowa forma pułapek jest więc skuteczna w zapobieganiu erozji z terenów rolniczych na obszarze prowadzonych badań. W przyszłych pracach należy przeprowadzić podobne testy na innych obszarach o bardziej zróżnicowanej rzeźbie terenu.

Słowa kluczowe: *bioinżynieria, degradacja ziemi, ograniczenie erozji, pułapki osadowe*