8

Effects of various vegetation layers in an *Acacia auriculiformis* forest plantation on surface erosion in Java, Indonesia

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Vegetation protects soil against surface erosion in various ways:

► Rainfall interception decreases the quantity of water reaching the soil and alters the spatial distribution of that water through stemflow and throughfall with concentrated drip points.

► Leaves break the initial erosive power of rain. However, if waterdrops concentrate into larger drops and if the fall height between canopy and soil is great enough, these falling drops can obtain a new erosive power that may exceed their initial erosive power (*2*, *5*).

► Surface vegetation and litter protect the soil directly against the erosive force of falling waterdrops and surface runoff. By filtering splashed soil particles, vegetation and litter also prevent the clogging of soil pores, which would decrease infiltration and increase surface runoff (*7*, *12*).

► Decomposition of tree leaf litter increases the humus content in topsoil, creating optimal conditions for water permeability and good aggregate stability (*7*).

Thus, vegetation affects both the erosive agent, rainfall, and the medium being eroded, soil. It influences the properties of the two mediums independently, but operates as well at the level where these mediums interact, the soil surface.

In tropical regions these different effects have been documented independently in various degrees of detail. Jackson (*9*, *10*) summarized forest rainfall interception. De Castro (*4*) and Maene and associates (*13*) demonstrated increases in erosive power of throughfall drops under shade trees in Colombia and rubber trees in Malaysia, respectively. Douglas (*6*) observed washing away of litter and soil by stemflow in lowland tropical forests in Malaysia and Australia. Coster (3) illustrated the effect of litter in Indonesia, Yamamoto and Andersen (*16*) discussed the effect of forests on soil erodibility in Hawaii.

However, few data have been published on the interactions and relative importance of the different effects of various forest components. Only Coster (3)—more than 40 years ago—has studied the importance of various forest vegetation layers on erosion in Java. Coster used a black-box approach, measuring incident rainfall and sediment loss in forests from which different vegetation layers had been removed.

The purpose of my study was to compare Coster's results with those from a more integrated approach that accounted for the separate effects of various vegetation layers.

Site characteristics

The research site was in the Ubrug forest near Jatiluhur (West Java, Indonesia), on a clayey soil developed in a marly substrate. The original soil was classified as a Typic Tropaquept. Some artificial leveling had taken place. Consequently, soil depth varied from 25 to 100 cm. The erodibility factor K, as estimated from the nomograph, is 0.16 (metric units).

Average annual rainfall at Jatiluhur is 2,900 mm, with an average 8.8 wet months (rainfall more than 100 mm/month) and 2.1 dry months (rainfall less than 60 mm/month). Raindays average 150 each year. Estimated annual rainfall erosivity is 2,800 erosivity units (metric).

The experimental forest consisted of a 5-year-old *Acacia auriculiformis* A.Cunn. plantation with 650 trees/ha. Average tree height was 12.5 m; average diameter was 12.2 cm. Total tree biomass was 57,550 kg/ha, of which 6,220 kg consisted of leaves. Average canopy cover was 70 percent and the leaf area index was 6.8 m^2/m^2. Biomass of the undergrowth (grasses and herbs) totaled 800 kg/ha. Litter amounted to 4,800 kg/ha. Annual litter production was 10,690 kg/ha, of which 6,400 kg consisted of leaves; it took 16 months for 95 percent of freshly fallen litter to decompose. Only 3 percent of the soil surface was not covered by vegetative material.

Research methodology

Rainfall was measured 30 m outside the stand with a standard Hellman-type pluviograph and with two V-shaped, trough-type raingauges, 140 cm long and 10 cm wide. The latter were used for comparison with throughfall data in the forest.

Throughfall was measured by 12 randomly placed, V-shaped, trough-type raingauges. In this way, the standard error of mean throughfall per rainstorm was less than 5 percent. Stemflow was measured by attaching stemflow collars to a total of 10 trees in three 6- × 8-m plots.

Erosive power of falling waterdrops was measured by Ellison-type splashcups (*8, 11*) with a diameter of 8.5 cm, filled with sand of particle size 0.25 to 0.50 mm. Three splashcups were used outside the forest and 24 randomly placed splashcups were used inside the forest. The standard error of mean sandsplash for individual rainstorms inside the forest was 6.5 percent. Little variations were noted outside the forest.

Surface erosion was measured from 6- × 22-m plots with a slope of 9 percent. The eroded material was collected in a trough (6 m long, 27 cm wide, 25 cm deep). This method did not allow for sampling of all suspended material in the runoff, but checks revealed that the sediment traps normally caught more than 90 percent of all eroded material.

Three treatments were applied in two replications: forest with undisturbed undergrowth and litter, forest with undergrowth removed, and forest with undergrowth and litter removed.

Soil erodibility was measured both inside the plantation and on an adjacent grass-covered field by measuring aggregate stability using the wet-sieving and falling drop techniques and calculating various erodibility indices based on soil properties. Infiltration measurements with a double-ring infiltrometer also were made. Further details on the erodibility research methods were given by Ambar and Wiersum (*1*).

All measurements, except for erodibility, were made every 24 hours. They continued over nearly 5 months in the rainy season. During this period, 95 raindays produced total rainfall of 1,604 mm; the maximum 24-hour rainfall was 133 mm. In all, 48 erosion events occurred. The splashcup experiment lasted for a shorter period; 27 raindays were sampled; total rainfall was 402 mm.

The runoff experiment and interception measurements were repeated a second year during a period of 4 months with 90 raindays and 61 erosion events; total rainfall was 1,863 mm. In these trials the effects of the presence or absence of an undergrowth/litter soil cover and of stemflow was measured in a 2 × 2 factorial design with two replications.

Canopy effects on amount and erosive force of precipitation

Over the total period of rainfall measurements, throughfall within the forest was 80.4 percent of gross rainfall; stemflow was 7.8 percent. Thus, net rainfall in the forest was only 88.2 percent of the incident rainfall. For individual rainstorms, these percentages varied greatly, depending upon the amount and intensity of rainfall. Table 1 shows regression functions between gross rainfall and throughfall, stemflow, and net rainfall.

During the 27 raindays of splashcup measurements, the average amount of all sandsplash per individual splashcup was 213 g in the forest and 172 g outside the forest—an average increase of 24 percent in the erosive power of throughfall drops compared to raindrops. Because the total throughfall during this period was 79 percent of incident rainfall, erosive power per unit of precipitation falling on the splashcups increased 57 percent.

Although no detailed measurements of the drop-size distribution of rainfall and throughfall were made, observations of the imprints of waterdrops in the sand of the splashcups showed that many throughfall drops were distinctly larger than raindrops. The diameter of the 10 largest imprints in several splashcups that were measured indicated a twofold increase in diameter of throughfall drops compared to raindrops.

Table 1 also shows regression functions of sand-splash with gross rainfall and throughfall. These linear regressions had a better coefficient of determination than power functions; multiple regression functions increased the coefficient of determination by only a few percentage points. The positive value of the constant in the linear regression function is normal for splashcups. It is caused by the pushing of sandparticles over the edge of the cup when rain starts (*11*). The two regression functions were not significantly different at the 0.05 level. However, the Wilcoxon's test for paired plots indicated a statistically significant difference ($\partial = 0.01$) in sandsplash of individual rainstorms inside and outside the forest.

The amount of sand splashed from the cups correlated well with gross rainfall, throughfall, and total kinetic energy ($r^2 > 0.95$), but somewhat less well with such commonly used complex erosivity indices as EI_{30}, AI_m, and others ($r^2 \leq 0.87$). Sandsplash showed a better correlation with gross rainfall under the forest canopies than in the open. This indicates that the tree canopies eliminated various rainfall variables, which determine the erosive power of rainstorms.

In addition to throughfall, some precipitation reaches the forest floor as stemflow, causing a local concentration of water around stems. This could cause increased runoff rates and rill erosion. This effect, however, was not observed in the second-year trials. In plots where stemflow was allowed to reach the forest floor, erosion was 43 percent, 84 percent, 104 percent, and 151 percent of erosion in similarly treated plots without stemflow. No statistical difference in erosion between these plots was found. However, in the presence of both throughfall and stemflow, the amounts of erosion showed a better correlation with throughfall than with throughfall plus stemflow. This suggests that the concentration of stemflow water on very localized spots of the soil contributed irregularly to erosion.

Table 1. Regression functions between various interception components and gross rainfall.

	n	r^2
$Th = 0.851\ R_g - 0.068$*	86	0.998
$St = 0.083\ R_g - 0.006$	86	0.903
$R_n = 0.948\ R_g - 0.090$	86	0.998
$Sp_r = 3.485\ R_g + 1.179$	27	0.833
$Sp_{th} = 4.192\ R_g + 1.667$	27	0.923

*Th = throughfall (mm), R_g = gross rainfall (mm), St = stemflow (mm), R_n = net rainfall (mm), Sp_r = erosive force rainfall (g sandsplash/cup), Sp_{th} = erosive force throughfall (g sandsplash/cup).

Table 2. Regression functions between erosion in runoff plots and rainfall parameters.

Treatment	*Single Regression Function*	*n*	r^2
Bare soil	$E = 5.501\ R_g - 3.281$*	95	0.850
Litter-covered soil	$E = 0.360\ R_g - 0.212$	95	0.684
Litter/herb covered soil	$E = 0.132\ R_g - 0.069$	95	0.570
	Multiple regression function		
Bare soil	$E = 3.227\ Th - 0.070\ Sp_{th} - 0.733$	26	0.751
Litter-covered soil	$E = 0.041\ Th + 0.021\ Sp_{th} - 0.061$	26	0.632
Litter/herb covered soil	$E = 0.013\ Th + 0.004\ Sp_{th} - 0.001$	26	0.528

*E = erosion (kg/plot), R_g = gross rainfall (mm), Th = throughfall (mm), Sp_{th} = erosive force throughfall (g sandsplash/cup).

Undergrowth and litter effects on erosion

During the first year of the runoff plot trial, total erosion in the two plots with bare soil was 2.04 and 6.84 kg/m²; in plots with soil covered by litter, 0.25 and 0.33 kg/m²; and in plots with soil covered by litter and undergrowth, 0.13 and 0.10 kg/m². Table 2 gives linear regressions of gross rainfall with average erosion in the variously treated plots. An analysis of variance of these regressions indicated a statistically significant difference ($\partial = 0.01$) in erosion between plots with bare soil and plots with soil covered by litter. The difference in erosion between plots covered by litter only or by litter plus undergrowth was significant at the 0.05 level. This indicates that litter was the most important soil protection agent and that the undergrowth added little extra protection.

In contrast to the splashcups, erosion in the runoff plots correlated well with commonly used erosivity indices. Highest correlations ($r^2 \pm 0.95$) were obtained on bare soil plots; plots with only litter showed somewhat lower correlations ($r^2 \pm 0.85$); and plots with both litter and undergrowth produced the lowest correlations ($r^2 \pm 0.75$). Simple rainfall parameters gave correlation values of about 0.1 less. Erosion on the runoff plots was caused by the combined erosive forces of waterdrops and runoff, while sandsplash from splashcups was caused only by the erosive force of falling waterdrops. Thus, the simple erosivity indices reflect the erosive force of the waterdrops, while the complex erosivity indices reflect the combined effect of raindrop impact and runoff. Furthermore, the differences in correlations between erosion and erosivity indices in the variously treated plots indicated that precipitation's direct influence on erosion becomes less important as the number of protective layers increase.

The effect of the litter on decreasing soil erodibility by enriching the soil humus content as a result of decomposition could not be ascertained in the present trial (*1*). The erodibility measurements inside and outside the still young forest stand did not show significant differences. Apparently this effect needs more time to be developed.

Combined effect of various vegetation layers on erosion

The data indicate that in the *Acacia* stand tree canopies decreased rainfall water reaching the soil by 11.8 percent, but increased the erosive power by 24.2 percent. Litter reduced erosion by as much as 9.5 percent in comparison with bare soil, and the presence of undergrowth decreased erosion by another 3.7 percent. Although these data refer to different aspects of the erosion process and cannot be compared directly, they do suggest that litter (and undergrowth) protects soil more than tree canopies do.

The relative importance of the various influences was further investigated through a multiple regression model. Because forest canopies affect both the amount and erosive power of precipitation, surface erosion in the different treatments was expressed as a function of these two variables. Throughfall was used as an indicator of the precipitation reaching the soil; the amount of sandsplash from the splashcups served as the value for the erosive power of precipitation (Table 2). In general, these multiple regressions explained the variation in erosion as much as single regressions using gross rainfall, if the same data base for 26 rainfall events was used. Further analysis using stepwise inclusion of several other rainfall parameters indicated that other variables increased the explained variation in erosion by less than 1 percent.

Although the multiple regression approach did not explain the variation in erosion better, it did indicate notable differences between bare soil plots and those with a direct soil cover. In the latter case, erosion increased with constant throughfall and an increase in erosive power. On bare soil plots, erosion decreased under such conditions. Also, in plots with a direct soil cover, the effects of precipitation and erosive power were of a much more similar order of magnitude than on bare soil plots.

Here, precipitation's effect was most important.

The multiple regressions could also be used as a basis for theoretical calculations of the combined effects of the canopy and the direct soil cover. The effect of the presence or absence of the canopy could be modelled by using the regressions related to the conditions inside and outside the forest (Table 1). Substitution of precipitation falling on the soil and its erosive power by their respective linear regression functions with incident rainfall resulted in six theoretical relations between surface erosion and gross rainfall under different conditions of canopy and forest floor (Figure 1). In plots with both litter and undergrowth, the difference in relations with or without tree canopy were so small that they were entered as one in the figure.

Discussion

The presence of a direct soil cover is the single most important vegetation factor protecting the soil (Figure 1). The sustained presence of litter is ensured by the litter production capacity of the tree canopies. This litter decomposes gradually, resulting in increased humus in forest soils and decreased erodibility. As the data indicated, this vegetation effect on erodibility does take much longer to develop than the effect of producing a protective layer on the soil surface.

The additional protective value of herbal undergrowth is relatively small. The direct canopy effect is even smaller. The latter is the combined effect of an increase in erosive power causing increased hazard for splash erosion, but a decrease in the amount of water reaching the forest floor resulting in decreased hazard for runoff and rill erosion. Under the trial conditions, these opposite effects caused a variable result, depending upon soil surface conditions.

On bare soils, with constant amounts of throughfall, a negative relation existed between erosion and erosive power of precipitation. This surprising result might be explained by the nature of the soil. The soil at the experimental site is susceptible to slaking. Consequently, splash erosion results quickly in a crust, which is relatively resistant to erosion. Here, the combined effects of increased slaking hazard and decreased runoff hazard resulted in a positive influence by the forest canopy.

In plots with a protective soil cover, such erosion crusts form less easily because splashed soil particles are partially filtered by the litter. Under such conditions, the decreased runoff hazard is offset by the increased splash erosion hazard. Thus, the combined influence of the canopy effects resulted in an increased erosion hazard.

Rainfall interception by tree canopies also results in an uneven distribution of precipitation reaching the soil. Stemflow especially concentrates water on the forest floor. In this study, this process did not influence the overall erosion hazard, although stemflow amounts were considerable. There were indications that stemflow contributed irregularly to erosion. The concentrated amounts of water may cause runoff to occur earlier than similar amounts of throughfall. But the significance of this early runoff on the transport of soil particles depended upon the microrelief around the tree.

My findings on the relative importance of various vegetation layers to erosion support those of Coster (*3*). Table 3 shows that his measurements also indicated that in forests any vegetation layer in addition to litter is of minor importance to erosion suppression. His data also suggested that, in the absence of a protective direct soil cover, the presence of tree canopies might even increase erosion. More recently, in Japan, Tsukamoto (*15*) found that throughfall drops have a higher erosive power than rainfall drops and that removal of forest litter increased erosion rates.

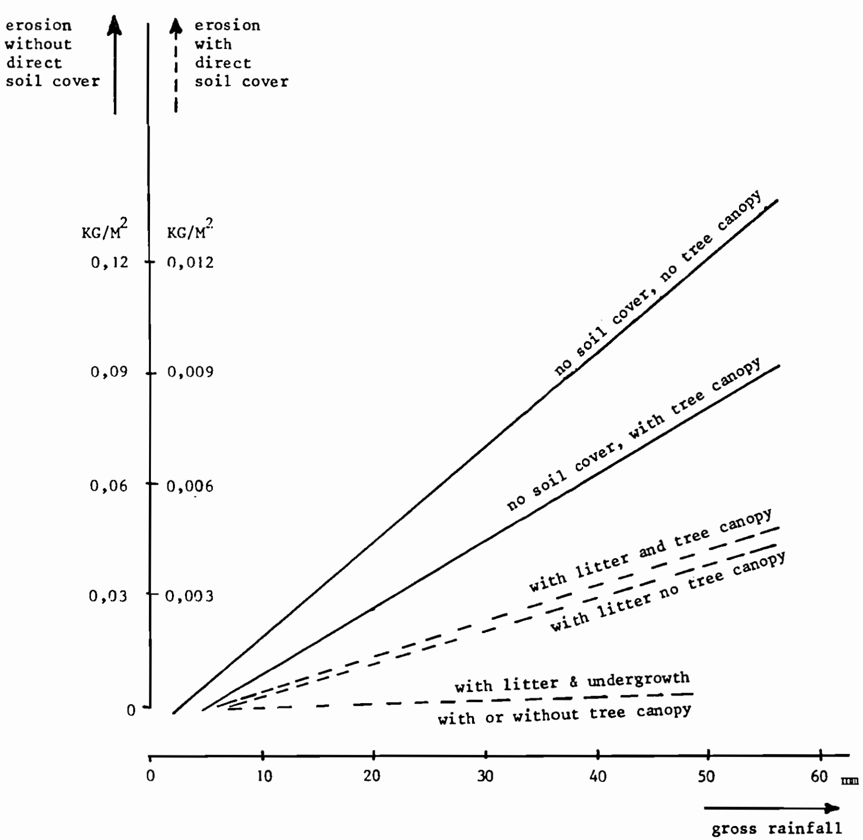

Figure 1. Theoretical relations between erosion and 24-hour rainfall, depending upon the presence of various vegetation layers.

Table 3. Erosion (kg/m²/yr) in a montane forest, Java, Indonesia (3).

	Number of Observations (plot years)	*Measured Erosion*	*Erosion Adjusted for Equivalent Slope and Rainfall*
Undisturbed forest	2	0.03	0.01
Trees removed	5	0.04	0.03
Undergrowth removed	4	0.06	0.05
Trees and undergrowth removed	1	0.08	0.02
Undergrowth and litter removed	10	4.32	2.61
Trees, undergrowth, and litter removed	2	1.59	0.44
Shrub vegetation	4	0.00	0.00
Shrubs removed	3	0.20	0.23

Lowdermilk (*12*) recognized the importance of litter for preventing erosion as early as 1930. Chapman (*2*) also indicated the greater importance of litter over tree canopies. Packer (*14*) demonstrated that not only the percentage cover of litter is important but also the maximum size of bare spots. These and similar findings should receive more attention in many practical soil conservation activities. Too often, trees are planted on eroding lands without ensuring the development of a protective litter layer. In erosion control programs, continued agricultural cropping sometimes is allowed between widely planted trees, resulting in the removal of litter during tillage. Also, if trees are planted on heavily eroding badlands, without any runoff-reduction effort, all litter can be washed away by the continued surface flow. Such erosion control efforts are based on the wrong impression, that trees protect the soil from erosion by reducing the erosive power of rain in their canopies.

Also, many people believe roots play an important role in soil protection by binding soil particles together. However, it should be realized that the majority of tree roots are not situated at the soil surface. Roots exposed at the surface are mostly the result of past erosion. This effect could well be observed in the trials. However, this exposure did not seem to diminish erosion. On one bare soil plot where measurements were repeated in a second year, linear regression functions between rainfall and erosion were similar for both years. Thus, the exposed roots did not reduce the erosion rate in the second year. Longer periods of erosion, however, might cause so much exposure of the roots that they provide some protection against raindrop impact and splash and rill erosion (*15*).

Conclusion

My study indicated that the protective influence of forest vegetation on surface erosion depends mostly upon the vegetation's influence on the interface between erosive agent and the eroded medium, rather than on its direct influence on these two properties. The effect of trees on the rainfall has a variable and often negative effect, while the positive effect of humus incorporation on the soil will be developed over longer periods. It is the proper functioning of the forest ecosystem rather than the presence of trees that is important for erosion control.

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