Estimation of Soil Erosion Rates in Oil Palm Plantation with Different Land Cover

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Abstract: Soil losses from hill slopes in oil palm plantation in Sedenak Estate, Johor were measured using runoff plot and rainfall simulator. The plot was designed to be removable but the size was fixed at 0.8 x 3.75m. Four types of surface covers were investigated for the plots, i.e. half bare soil and half grass cover (HGC), half bare soil and half dry frond (HDF), fully grass cover (FG), and fully bare soil (BS). The influence of initial soil moisture, saturated hydraulics conductivity, Ks, bulk density and slope on rates of soil loss were also evaluated. The rainfall simulator produced rainfall intensities between 90 and 160 mm/hr with durations from 45 to 60 min per run. BS plot exhibited the highest Ks value among all plots but the percentage of initial soil moisture on this surface was low. BS plot recorded the highest runoff coefficient (C) and soil loss values of 73.6 ± 4 percent and 5.26 ± 3.2 t/ha respectively, while the lowest was from plot FG with 41.7 ± 5.7 percent and soil loss of 2.85 ± 2.1 t/ha. Meanwhile, the results suggested that the ground cover had the ability to reduce soil loss by 67% and 17%, respectively for plots BS-HGC and BS-HDF. Overall, soil erosion control such as surface is effective measures in reducing level of runoff and soil erosion.

Keywords: Rainfall simulator, soil loss, soil erosion plot, surface cover, saturated hydraulic conductivity.

1. Introduction

Erosion and sedimentation are the major issues when it comes to managing water quality and constitute the largest portion of non-point source pollution in the tropical region [1,2,3]. High soil erosion rate often leads to river constriction, increased flood frequency and magnitude, threatened aquatic habitats, increased rate of nutrients losses and interference with recreation opportunities. Sediment would absorb nutrients and thus increase rate of nutrient losses[4,5]. Studies on erosion and sedimentation in the past have mostly been confined to forestry related activities and urban catchments [6,7,8]. Activities associated with oil palm plantation, especially during land preparation or replanting, could have significant impact on soil health both in terms of quality and quantity.

Lord and Clay [9] stated that soil erosion is the major cause of soil degradation through increased leaching of reducing nutrients and organic matter, at the same time modifying the physical properties such as bulk density and infiltration rates. Soil losses from oil palm plantation during its development to maturity stage could be as high as 4 ton/ha/yr [10]. The rapid expansions of oil palm cultivation have put this crop as commercial cultivation after slow growth in 1917. Even so, after 50 years have passed, agricultural growth continues to involve massive investments from the government. Besides Malaysia known as a major producer of rubber crops and also cocoa, oil palm has also significantly contributed to the country's agricultural industry. This has given massive job opportunities for Malaysians when FELDA was first established on July 1, 1956 when the Land Development Act (1956) was enforced [11].

Soil erosion in oil palm plantations has caused water pollution in local rivers where turbidity and total solids are suspended high in the area. This may cause adverse impact on life which cannot live in such conditions. If precautions are not taken seriously, it will affect the supply of fresh water resources. The highest rate of erosion and sedimentation from oil palm plantation mostly occur during land preparation, involving forest clearance or replanting [12,13]. Malaysia's climate with frequent rainfall will worsen this situation. In matured oil palm plantations, soil erosion losses chiefly depending on the slope and soil management practices, including maintenance of unpaved roads and the harvesting paths. The degree of erosion rates is highly spatial in major landscape units such as harvesting paths and less disturbed surfaces, even after the trees have become established. Hartemink [14] reported that erosion rates in matured oil palm plantations in Malaysia range from 7.7 to 14 t/ha/yr. However, a quantitative estimate of erosion rates in oil palm plantation is still very scarce. Therefore, the objective of this paper is to quantify runoff and erosion from four types of surface covers in oil palm plantation on harvesting path and less disturbed area using rainfall simulator

Study Area

The study was carried out in an oil palm plantation at Sedenak Estate (01° 43' 35" N and 103° 32' 42"). The estate is managed by Mahamurni Plantation Sdn.Bhd, a wholly owned subsidiary of Kulim (M) Bhd. The oil palms at time of investigation were 10 years old. The palms are of PAMA/FELDA clone, planted with density of 143 stands per hectare arranged in an equilateral triangle with 9 m gap, alternating North-South rows. The catchment's topography is undulating and the soil belongs to Renggam series [15]. Renggam series are characterized by deep profile with sandy clay texture and in brownish yellow colour. The soil is well drained and suitable for oil palm, cocoa, rubber, coconut and fruit plantation [15].

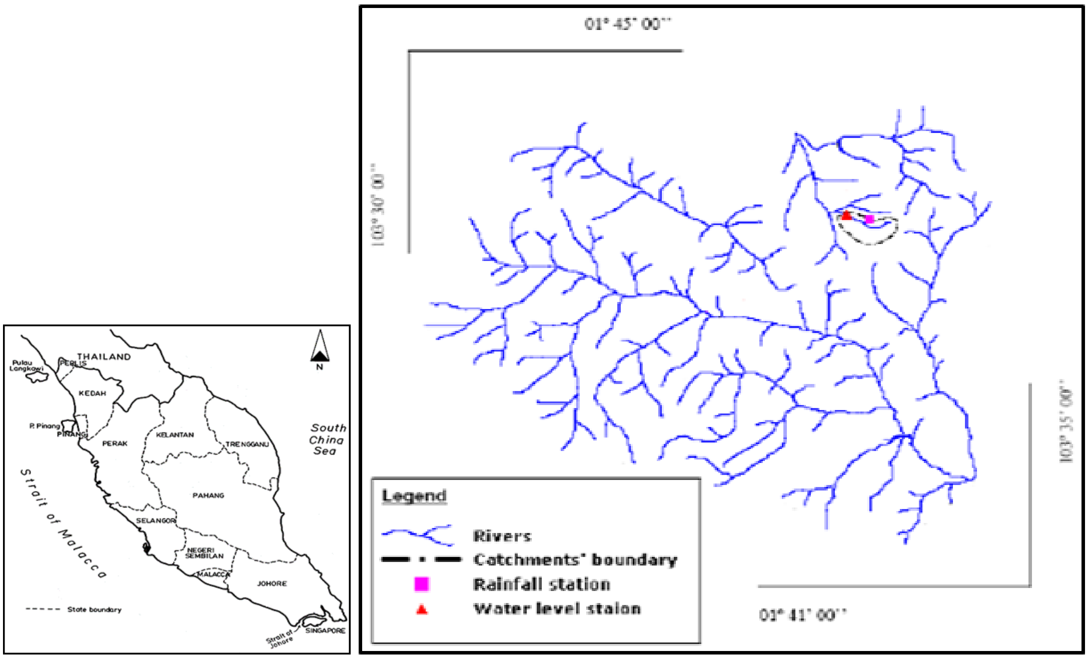


Figure 1. Location of the study area.

2. Methodology

2.1 Simulation Treatments

The rainfall simulator was run 15 times on harvesting path and less disturbed from February to May 2011. The harvesting paths consist of grass of 0.1 to 0.15 m height at the time of fieldwork. Prior to simulation, the harvesting path was less disturbed by farm workers. The oil palms were harvested every two weeks, during this time surface were disturbed by harvesting machines and workers footsteps. This will interfere with the structure of soil surface in terms of compaction and infiltration [16]. Harvesting machine may lead to the formation of tyre ruts on soil surface and could enhance the generation of Horton overland flow, HOF [17]. The four types of surface are function as runoff plots to measure erosion rates on that particular surface. The criteria for the surface selection were based on slope, surface cover and proximity to water resources and each plot is close to each other's. Table 1 shows the plot dimension, surface description and types of surface cover.

Table 1. Description of four erosion plots [18].

Surface Type	No. of Simulation	Surface Description	Ground Cover (%) and Type of Grass Cover
Bare Soil	4	100% harvesting path	Null
Fully Grass Cover	4	100% harvesting path	100% *Paspatum Conjugtum and Centotheca Lappacea*
Half Grass Cover	3	50 % undisturbed area	50% *Centotheca Lappacea*
Half Dry Frond Cover	3	100% harvesting path	50% Dry Frond

2.2 Measurement of physical properties

Prior to rainfall simulation, the soil physical properties for each plot were determined. Information of soil physical properties are important to determine the characteristics of the soil condition. Surface bulk density (ρb) and soil moisture was determined by sampling the upper 5 cm with 110 cm3 soil ring sample. Core sample was oven dried for 24 hours at 105°C. The plot slopes were determined by an Abney level. Saturated hydraulic conductivities (Ks) were estimated from infiltration measurements taken in situ using model 2800 K1 Guelph Permeameter.

2.3 Rainfall simulator and plot design

The rainfall simulator consists of 4 vertical steel rods with 4.3 m high to mount two 60° full cone nozzles with 70µm orifice diameter (Figure 2). Water was pumped from a storage container of 2000L to the simulator through 2.5 cm diameter PVC hose by two units of 750 W centrifugal pumps with pressure head of 172 kPa (25psi). The storage container is refilled by pumping water from a nearby river. This operating pressure produces rainfall energy flux densities (EFD) of 1000 to 1900 Jm-2h-1. Steel plates were erected to form rectangular. Runoff was sampled at the lower end of the plot. The simulated rainfall was measured for 45 and 60 minutes with manual gauges placed on the ground using 8 small cups with surface diameter of 6.3 cm. The volumes of water collected were measured every 5 min. EFD of the simulated rainfall was using formula (1) [19].

$$EFD = \frac{R_i m v^2}{2V_{D_{50}}} \quad (1)$$

Where Ri is event rainfall intensity (mh-1), VD50 is volume (m3) of the median-diameter (D50) raindrop and m for mass (kg). In equation 1, m is the mass (kg) of the D50 drop, which is estimated as

$$V_{D_{50}} = \frac{4\pi D_{50}}{6} \quad (2)$$

$$m = (\rho_w - \rho_{air})V_{D_{50}} \quad (3)$$

where ρw (1000kg m-3) and ρair (1.29 kg m-3). Factor v in Equation 1 is the fall velocity (m s-1) of the D50 drop, determined by the equation[19],

$$\nu = V_{max}\left(1 - e^{-\frac{D_{50}}{b}}\right) \quad (4)$$

where Vmax = 9.5 (m s-1), b = 1.77 and β = 1.147 [16]. D50 = 1.024 mm ((Median drop size was estimated from nozzle manufacturer engineering data). Natural rainfall and artificial rainfall obviously have different terminal velocity and drop size distribution. Therefore, artificial rainfall energy was calculated using those equations. Ziegler [19] emphasised that same value of rainfall intensity from different simulator architecture will cause different EFDs.

(a) (b)

Figure 2. (a) Half Dry Frond surface (b) Rainfall simulation design with water flow from the nozzle into trenches at the plot outlet

2.4 Simulation data collection

For each plot, the simulations were replicated for dry and wet conditions. Wet simulation was performed one day following the dry simulations. Instantaneous discharge and sediment output during each experiment were measured at time to runoff (TTRO). Discharge was determined by dividing the volume of a collecting bucket (30 litres) with the time to fill up the bucket. Suspended solids sediment concentration was determined by decanting 100 ml of runoff and followed by oven dried at 105˚C for 24 hours. Instantaneous discharge and sediment output values were adjusted to rates per unit area. Cumulative discharge (Q_{cum}) was calculated as total runoff volume prior to any time t, divided by EFD since TTRO contribute differently to sub processes controlling runoff generation and sediment transport. At the beginning of rainfall, sediment is detached by raindrop impact and material is transported downslope via rainsplash. In essence, energy prior to TTRO contributes to the sediment supply that will be transported throughout the event after runoff commences.

3. Results and Discussions

As mentioned before, simulations were run on different day; therefore giving different values of soil moisture contents. Table 2 shows that FG recorded the highest value of soil moisture content followed by HGC. This could affect the infiltration of the water into the soil surface [20]. Bulk density was measured during each simulation exercise from the soil sample taken from the plots. HDF recorded the highest value of bulk density (see Table 2). BS and surface type like HGC had almost similar bulk density but slightly higher for HGC. Of all the plots, FG had the lowest bulk density. Meanwhile, Ks was the highest on the BS and lowest for FG. Besides BS having the highest Ks, it also had the highest value of bulk density. According to Penna [20], the increase in Ks can lead to increase in bulk density. Moisture content and soil properties can also indirectly affect on Ks.

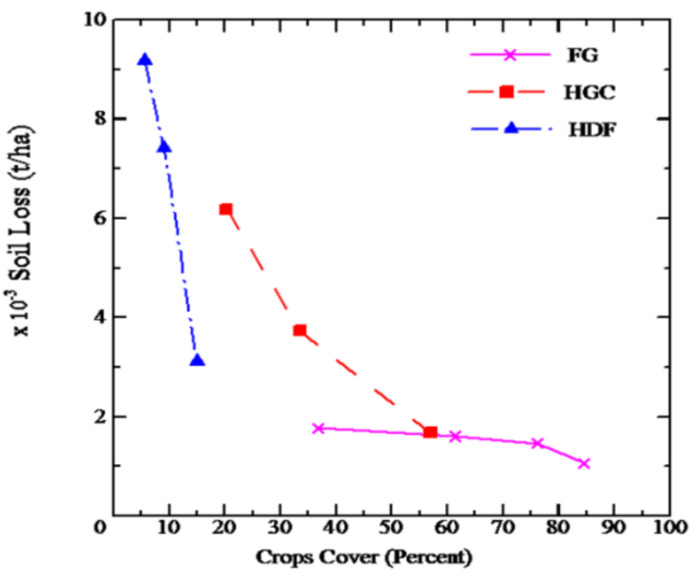
Table 2. Soil and Rainfall Characteristics of the four erosion plots [18].

Surface Type	Slope (°)	Rainfall Intensities (mm/hr)	Soil Moisture (%)	Bulk Density (gcm^{-3})	K_s (mm/hr)	EFD ($Jm^{-2}h^{-1}$)
Bare Soil (BS)	23	103 ± 52	31.8 ± 7.2	1.34 ± 0.1	7.3	1010
Full Grass Cover (FG)	15	90 ± 45	48.7 ± 12.1	1.01 ± 0.1	1.4	1880
Half Grass Cover (HGC)	12	85± 50	36.2 ± 10.9	1.36 ± 0.1	3.0	1860
Half Dry Frond (HDF)	23	81 ± 48	40.1 ± 15.3	1.61 ± 0.2	7.3	1332

Note: values are mean ± standard deviation; EFD is energy flux density of rainfall intensities

3.1 Effect of Crops Cover

The ability of crops cover in reducing soil loss can be seen in Figure 3 which shows substantial reduction in soil loss with increasing undergrowth cover. Nevertheless, different levels of crop cover produced different situation. A fully covered plot (FG) recorded the lowest soil loss of 51.9 x 10-3 t/ha compared to BS plot with 96.9 x 10-3 t/ha. Meanwhile, runoff plot with half surface cover (HGC) recorded 0.002 t/ha to 0.006 t/ha soil loss, which was two times higher than at FG plot. Whilst the surface slope on FG plot was higher (Table 2) compared to HGC plot, the crops cover played a major role in controlling soil erosion. Besides intercepting soil particles, the root held the soil particles and stabilized the soil structure from the effect of raindrops and overland flow. Among the three runoff plots, HDF was the least effective in reducing erosion and recorded between 0.009 t/ha to 0.03 t/ha soil loss, or two to four times higher compared with FG and HGC.



3.2 Runoff Coefficient (C)

Runoff coefficient (C) generally increases with the increase of soil moisture (Figure 4), except for plot HGC, which remained steady with 60% of rainfall appeared as runoff. Among the four surfaces, BS plot recorded the highest C due to higher rainfall and higher Ks value (see Table 2) and bare surface condition. Furthermore, it had steeper slope. Other factor that contributed to higher C readings for BS plot was EFD. According to Dalen et al. [21] and [22], rainfall kinetic energy was found to influence the soil surface structure during storm events. A lower kinetic energy has a lower capacity to reduce the detachment of soil particles by raindrops which reduce erosion rates. The C value for FG plot was higher compared to HGC and HDF plots even though this surface was fully covered by grasses.

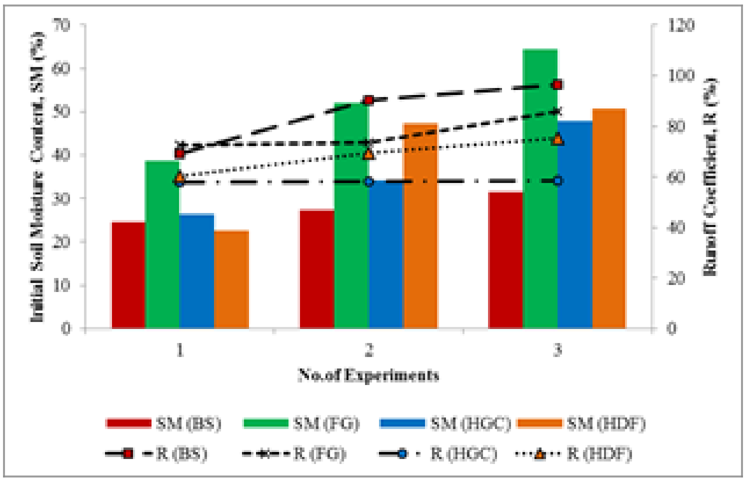


Figure 4. Runoff Coefficient (line) and initial soil moisture (bar) for all plots

3.3 Influence of Runoff Coefficient (C) on Soil Loss

Table 3 shows the means C and soil loss for all plots and the correlation between these variables. BS plot recorded the highest C value and soil loss of 73.6±4 percent and 5.26±3.2 t/ha respectively, while the lowest was from FG plot with average C of 41.7±5.7 percent and soil loss of 2.85±2.1 t/ha. The effectiveness of grass in FG plot was evident when the erosion rate reduced by 83% compared to value for plot BS. FG plot was located underneath the oil palm trees and could have higher content of organic matter. According to Ariza [23] organic matter can improve the structure of the soil. Meanwhile, between BS-HGC and BS-HDF plots, the results suggested that the ground cover had the ability to reduce soil loss by 67% and 17% respectively. The soil loss reduction was higher for HGC plot compared to HDF plot. Again this shows that grass and its root system are effective in reducing surface erosion [24]. Although runoff is important for transporting sediment, in this study, its correlation against soil loss was not significant ($p > 0.05$) with low Pearson coefficient values (0.01 to 0.45). This was rather unexpected as soil loss is the product of sediment concentration and runoff volume. However, it is still possible to argue in term of dilution of sediment concentration with time while the runoff rate is relatively constant. This may happen due to i) limited particle on the slope surface and ii) ponding effect due to much higher rainfall intensity compared to the infiltration capacity of the soil moisture. Moreover, the rainfall was the second highest (Table 2).

Table 3. Soil Loss and Runoff Properties for different plots.

Plot	BS	FG	HGC	HDF
Runoff Coefficient (%)				
Mean	73.6	41.7	45.6	53.4
Standard Deviation	4.7	5.7	18.7	18.8
Soil Loss (x10^{-3} t/ha)				
Mean	5.26	2.85	3.12	4.48
Standard Deviation	3.2	2.1	1.4	2.6
Pearson coefficient (*r*)	0.01	0.45	0.15	0.23
***p*-value**	0.43	0.312	0.46	0.29

Figure 5 shows the soil loss response to runoff for the four plots. Error bars are also given at 95% Figure 5 shows the soil loss response to runoff for the four plots. Error bars are also given at 95% confident interval. It was evident that despite a relatively constant runoff in BS and FG plots, the soil loss showed a gradual reduction. Such condition could occur due to water ponding which covered the soil surface from direct rain drop impacts. Under such high rainfall intensity, a bare surface could generate less erosion compared to vegetated surface. As such, the erosion rate from bare surface could be lower compared to partially covered surface. The mean runoff from BS plot and HDF plot were 4.20 mm and 2.98 mm respectively (Table 4). It was observed that dry frond was able to reduce sediment loss by 41%. HDF and HDF plots are not recorded readings for runoff in the fifth minute due to time to runoff (TTRO) is more than five minutes.

Soil loss from FG plot decreased gradually with time except for a small peak at 65 minute due to sudden increase in runoff. Nevertheless, compared to other runoff plots, FG still had the lowest mean soil loss of 3.71 x 10-3 t/ha. Munoz et al. [25] found that a reduction in soil loss from vegetated surfaces associated with increasing hydraulic resistance by the vegetation which helps to slow down the runoff velocity. As such, larger soil particles tend to be redeposited along its journey from hill-slope to water course. The runoff from FG and HGC plots were quite uneven. According to Fox et al. [26], low infiltration can cause higher ponding depth that lead to the re-deposition of soil particles.

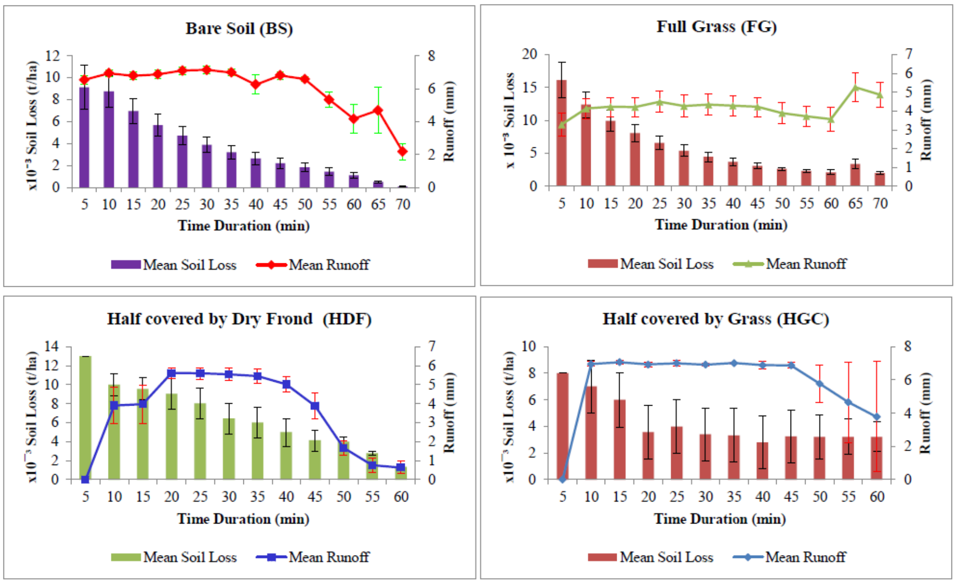


Figure 5. Relation between Soil Loss (t/ha) and Runoff (mm) against time.

Table 4. Statistics for analysis of variance on runoff and soil loss.

Variables	BS	FG	HGC	HDF
Runoff (mm)				
Mean	4.20	6.02	3.50	2.98
Standard Deviation	0.50	0.84	1.37	0.50
Confidence Level (95.0%)	0.29	0.84	1.37	0.50
p -Value between group	3.1962E-06			
Soil Loss (t/ha) x 10^{-3}				
Mean	5.88	3.71	3.64	6.93
Standard Deviation	4.32	2.95	2.22	3.57
Confidence Level (95%)	2.49	1.70	1.28	2.06
p -Value between group	0.027			

4. Conclusions

The study shows that areas with no protection from cover crops are exposed to high rates of soil erosion. This condition usually occurs during site clearing and dry season when soil becomes loose and less compact. When rain falls, there is no protection for the surface against raindrops and will cause the soil particles to be easily to wash away by runoff. Raindrops rupture the soil surface, causing the soil particles to detach and then splashed to short distance. Continuous high intensity rainfall with slope surface conditions makes this situation worse. Slopes are known to produce high runoff velocity.

Energy generated by high flow velocity can easily erode the soil surface. In addition, areas with low saturated hydraulic conductivity generate runoff on bare surface more quickly. Sediment transport on bare soil surface is initially high but declines over time when the loose soil particles on the soil become depletes. Cover crops such as grass could reduce the rate of soil erosion by 67%, whereas 17% dried fronds. Dried fronds can be used as surface flow breakers and to lower down the velocity of surface runoff. The arrangement of the dried frond also plays an important role in intercepting soil loss. Dried fronds layout position perpendicular to the groundwater surface flow is a better method to intercept soil loss compared to arrangement in parallel position. Therefore, it is important to ensure that the cover crops always thrives in agricultural areas, particularly at oil palm plantation and to stack dried frond with good arrangement for reducing the risk of soil erosion.

Acknowledgement

This research is funded by the Ministry of Agricultural of Malaysia (Science Fund Project, Grant no. 05-01-06-SF0418 (79328)). We are grateful to Associate Prof. Ziegler A.D from National University of Singapore (NUS) for his kind guidance in our fieldwork and technicians in Hydrology Laboratory from University Teknologi Malaysia (UTM) for their help in completing this project research

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