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Impacts of eucalyptus (*Eucalyptus exserta*) plantation on sediment yield in Guangdong Province, Southern China—a kinetic energy approach

Guoyi Zhou [a], Xiaohua Wei [b,*], Junhua Yan [a]

[a] *South China Institute of Botany, Chinese Academy of Sciences, Wushan, Guangzhou, 510650, PR China*
[b] *Department of Earth and Environmental Science, Okanagan University College, 3333 College Way, Kelowna, British Columbia, V1V 1V7, Canada*

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Abstract

The relationship between the kinetic energy of waterdrops (rainfall and throughfall) and sediment yield (suspended solid (SS) and bed load (BL)) was studied in paired watersheds (one without vegetation and the other covered by an eucalyptus (*Eucalyptus exserta*) plantation) in Guangdong Province, Southern China. The results showed that there was a significant correlation between the kinetic energy of waterdrops and sediment yield in both watersheds. Sediment yield in the unvegetated watershed is significantly affected by the kinetic energy of atmospheric raindrops. Sediment yield in the plantation watershed, however, is significantly related to the kinetic energy of throughfall waterdrops, but not to the atmospheric rainfall intensity or the rainfall kinetic energy. When rainfall amount is greater than 5 mm, and their intensities are less than 20 mm h^{-1}, the single-layer eucalyptus plantations significantly increased the kinetic energy of waterdrops to the land surface, and consequently, accelerated soil erosion. However, these plantations do have positive impacts on the reduction of soil erosion for the rainfall events of larger intensities (particularly > 40 mm h^{-1}). Management implications of these results are discussed in the context of soil protection and ecosystem rehabilitation.

Keywords: Kinetic energy; Sediment yield; Soil erosion; Eucalyptus plantation

1. Introduction

Control of soil erosion in Southern China has long been an important resource management objective for sustainability of long-term site productivity and protection of

* Corresponding author. Tel.: +1-250-762-5445loc.7579; fax: +1-250-470-6005.
E-mail address: awei@ouc.bc.ca (X. Wei).

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aquatic ecosystems. In Guangdong Province, Southern China, recent attention is being focused on the selection of appropriate plantation species and structures for rehabilitation of highly eroded ecosystems. The provincial government is also seeking to develop prototypes on soil rehabilitation for large-scale demonstration in the province.

Impacts of forest plantations on soil erosion vary in Southern China. Studies from Guangdong Academy of Sciences (1991) and Zhang et al. (1994) showed that the presence of forest canopy and understory vegetation can significantly decrease the amount of water-contacting surface soil through canopy and understory vegetation interception, and thus, decrease the surface soil erosion. Studies from Zhou (1997, 1999), however, indicated that the single-layer plantation has a limited role in soil protection during early forest development, and some plantations may even accelerate soil erosion. Therefore, there is clearly a need to undertake investigations to identify the key mechanisms or factors contributing to soil erosion in plantation forests in Guangdong Province, Southern China.

Forest canopy can greatly influence soil surface erosion due to its rainfall interception. It alters both the rainfall magnitude and the kinetic energy reaching soil surface. Because of the presence of a canopy, the relationship between rainfall and surface soil erosion is different between forested and unvegetated lands. Comparable amounts of rainfall can cause significant differences in erosion between forested and unvegetated surfaces (Hoover and Hursh, 1943; Fletcher, 1952; Wischmeier and Smith, 1958; Lee, 1980; Ferreira, 1985; Zhang et al., 1994; Zhou, 1995a). This difference is more directly related to the difference in the kinetic energies of throughfall and atmospheric rainfall (Zhou, 1997, 1999). This clearly indicates that the impacts of plantation forests on soil erosion might be best evaluated through a kinetic energy approach.

Studies on the determination and application of appropriate rain erosivity indices for the evaluation of soil detachment or soil splash erosion are numerous. Quansah (1981) and Morgan et al. (1998) linked soil detachment with the kinetic energy of the rain. However, Park et al. (1983) showed that the rate of soil detachment per unit area depends more closely on the momentum than on kinetic energy. Govers (1991) obtained better estimates of splash loss with the product of kinetic energy and drop circumference. Salles et al. (2000) conducted laboratory experiments with the splash cup technique, and found that although all indices containing the mass of water (i.e., D^3) predicted splash detachment rates relatively well, the product of momentum and drop diameter (D^4V) was slightly superior in describing splash detachment. In this study, we consider the kinetic energy approach because our prime objective is to evaluate impacts of plantation on soil erosion.

Rainfall kinetic energy depends on rainfall physics such as diameters and velocities of raindrops. Recently, interest on the estimation of diameters of raindrops has been growing. Wischmeier and Smith (1958) developed the following equation to estimate the median size of raindrops (D_{50}, in cm) for various rainfall intensities (in cm h^{-1}): $D_{50}=0.188P^{0.182}$. Lee (1980) studied atmospheric raindrop energy and developed an experimental equation of raindrop diameter D_{50} (mm) with rainfall intensity P (mm h^{-1}): $D_{50}=1.238P^{0.182}$. Zhou (1997) studied the rainfall and throughfall energies in eucalyptus forests, and constructed an empirical equation for the estimation of the median size of raindrops $D_{\mathrm{mean\ or\ 50}}$ (mm): $D_{\mathrm{mean}}=1.33+0.32\ln P$ (P—rainfall intensities, in mm h^{-1}).

The study by Zhou (1997) also indicates that the variation of raindrop diameters with rainfall intensities can be described by a normal distribution: $N(1.33 + 0.32\ln P, 0.76 + 0.0022P)$. However, studies of the rainfall kinetic energy in relation to soil erosion in a forest are rare in Southern China (Zhou, 1997), and such studies must be conducted in order to identify suitable forest resource management strategies for soil protection and rehabilitation.

In this study, two small-scale neighboring watersheds [one completely without vegetation and the other with eucalyptus plantation (*Eucalyptus exserta*)] were used. Detailed description of these two watersheds will be presented in Section 2. The objectives of this study were to: (1) test if kinetic energy is a suitable indicator of soil erosion; (2) assess relationships among rainfall intensity, kinetic energy and soil erosion; (3) develop an approach for estimation of the kinetic energy; and (4) identify the key factors causing soil erosion. The management implications of our results are also discussed.

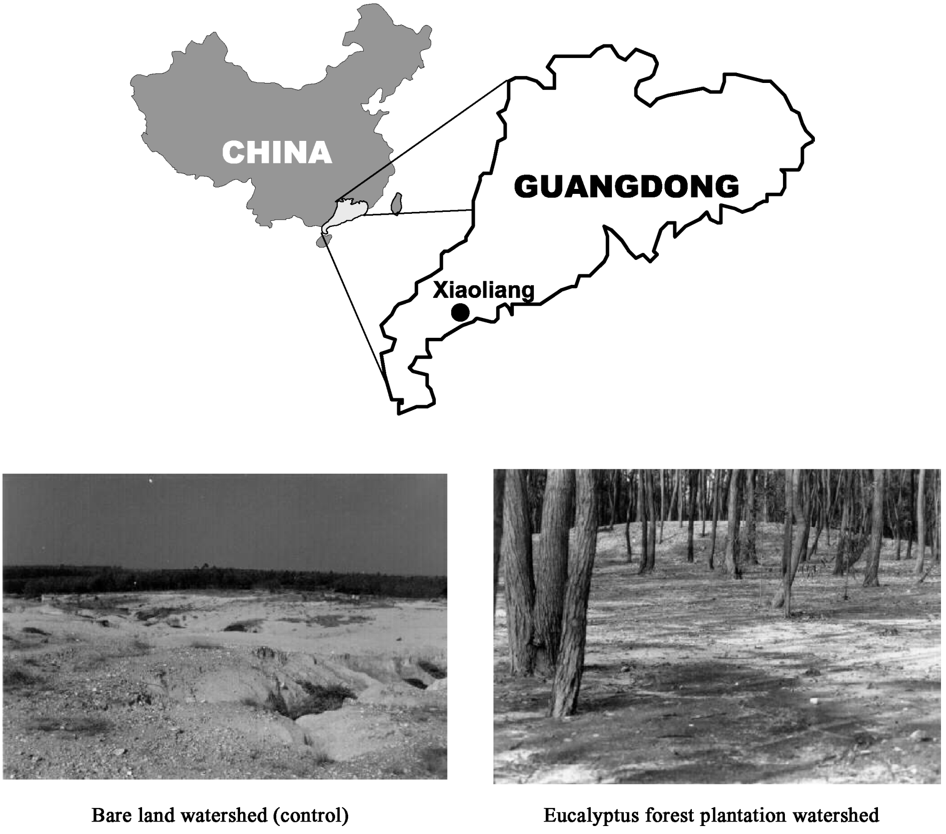

Fig. 1. The location of Xiaoliang ecological experimental station in China and views of the two studied watersheds.

2. Research sites

The two neighboring experimental watersheds studied belong to the Xiaoliang ecological experimental station located on the coastal highland of Dianbei County, Guangdong Province, China, northern border of the tropic zone (Fig. 1). Their geographic position is 110°54′ 18″E, 212°7′ 49″N. Mean annual rainfall was 1454.5 mm during 1981–1990. Dry (October to March) and wet (April to September) seasons are quite distinct. Total rainfall during the dry and wet seasons is 29% and 71% of the annual total, respectively. Rainfall is mainly associated with convective storms and typhoons, and the intensities (total rainfall divided by duration for each distinct rain event) usually exceed 16.0 mm h^{-1}. The annual average temperature is 23 °C.

The topography of these two watersheds is generally flat with similar altitude variations of 9–18 m. The bare soil watershed (3.73 ha) has been virtually devoid of vegetation at least for the last four decades because of severe soil erosion. The bare soil watershed is used as the control for this study. The eucalyptus forest watershed (3.78 ha) was established by the plantation in 1964. Prior to 1964, its surface was also totally bare and eroded, and its soil chemical and physical properties were not significantly different from those in the control watershed (Parham, 1993; Yu, 1994; Yu and Zhou, 1996) (Fig. 1). Since 1964, the forest has been devoid of any understory vegetation. During the periods of 1964 and 1979, the eucalyptus forest grew vigorously, particularly in 1970–1975. Since 1979, the forest has been growing slowly with little changes in the canopy height and density; only the stem diameter increased significantly. Based on measurements taken between 1981 and 1990, average canopy density (cover rate) and height were 0.76 and 6.0 m, respectively, and 90% of the trees was in the height range of 5.9–6.1 m.

The soil is a typically tropical laterite derived from granite (Yu and Zhou, 1996). For both the bare land watershed and eucalyptus forest watershed prior to 1964, most of the topsoil had been washed away by severe erosion and eroded to the depth of 100 cm. Surfaces were bare and covered by iron–manganese nuclei and quartz sand. Some of the soil physical properties in bare land and eucalyptus forest land prior to 1964 are shown in Table 1 (Yu and Wang, 1990).

Table 1
The soil physical characteristics of bare land and eucalyptus forest watershed prior to 1964

Depth (cm)	Bulk density (g cm^{-3})	Maximum capillary moisture holding capacity (%)	Saturated moisture (%)	Capillary porosity (%)	Noncapillary porosity (%)	Total porosity (%)
0–10	2.11	18.40	18.66	38.82	0.55	39.37
10–20	2.08	16.90	17.24	35.15	0.71	35.86
20–30	2.04	17.13	17.40	34.95	0.55	35.50
30–40	2.03	20.11	20.41	40.82	0.61	41.43
40–50	1.94	21.32	21.13	41.36	–	–
50–60	1.93	21.60	21.84	30.98	0.46	31.35
60–70	1.87	24.67	25.09	46.13	0.79	46.92
70–80	1.82	26.35	26.63	47.96	0.51	48.47

It is well known that a well-cemented soil will resist splashing erosion more readily than loose soils. Generally, splashing erosion increases with fraction of sand in the soil. Splashing erosion decreases with the percentage of water-stable aggregates. A soil whose individual grants do not tend to form aggregates will erode more readily than one in which aggregates are plentiful (Linsley et al., 1975). Soil physical properties on the two study sites prior to 1964 shown in Table 1 may indicate aggravation of soil erosion.

3. Methods

3.1. Calculations of rainfall and throughfall kinetic energy

For convenience, throughfall is divided into two parts, the "free throughfall" (FT) which is not intercepted by canopy and the "dripping throughfall" (DT) which is intercepted by canopy, with part of their intercepted water dripping to the soil. The characteristics of FT are the same as the atmospheric rainfall while those of DT are affected by atmospheric rainfall as well as forest canopy.

By definition, the total kinetic energy (E) of a population of waterdrops in a forest can be described as (Zhou, 1999, 1997):

$$E = \frac{n}{2}\sum m(D)[V(D,\ H)]^2 f(D) \tag{1}$$

where $m(D)$, the mass of waterdrop (kg) is a function of the diameter of waterdrop (D) ($m = \pi\rho_w D^3/6$, where ρ_w is the water density 1000 kg m^{-3}), n is the total number of waterdrops, H is the height (m) of the forest canopy from which DT comes, $V(D, H)$ is the velocity of waterdrops when they reach the soil surface (m s^{-1}), and $f(D)$ is the fraction of waterdrops with a diameter of D. $V(D, H)$ is a function of D and H.

The frequency distribution of the diameters of waterdrops can be satisfactorily described by the following normal distribution (Lee, 1980; Pei, 1985; Zhou, 1997, 1999):

$$f(D) = \frac{1}{b\sqrt{2\pi}} e^{-\frac{(D-a)^2}{2b^2}} \equiv N(a,\ b) \tag{2}$$

where $N(a, b)$ denotes a normal distribution with a mean of a and standard deviation of b.

We use m_i ($i = 1,2,\ldots n$) (kg) to denote raindrop mass in the range of $[D_{i-1}, D_i]$; $F(D_i)$ ($i = 1, 2, \ldots n$) is the probability of raindrop in the range of $[D_{i-1}, D_i]$, ($F(D_i) = \int_{D_{i-1}}^{D_i} f(D)\mathrm{d}D$); N is the total number of raindrops; and M is the total mass (kg) in rain. There would be:

$$m_1 = \frac{N}{6}\pi D_1^3 \rho_w \int_{D_0}^{D_1} f(D)\mathrm{d}D$$

$$m_2 = \frac{N}{6}\pi D_2^3 \rho_w \int_{D_1}^{D_2} f(D)\mathrm{d}D$$

……………………………

$$m_n = \frac{N}{6}\pi D_n^3 \rho_w \int_{D_{n-1}}^{D_n} f(D)\mathrm{d}D$$

By summing up the above equations, there would be:

$$M = \frac{N}{6}\pi\rho_\mathrm{w}\left\{ D_1^3 \int_{D_0}^{D_1} f(D)\mathrm{d}D + \cdots + D_n^3 \int_{D_{n-1}}^{D_n} f(D)\mathrm{d}D \right\} = \frac{N}{6}\pi\rho_\mathrm{w}\sum_{i=1}^{n} D_i^3 F(D_i) \tag{3}$$

Because M can be easily measured through rain gauges, Eq. (3) can be used to calculate the total number of waterdrops N in rain or throughfall (Zhou, 1997, 1999).

As indicated previously, the waterdrops reaching the soil surface in the forest watershed consist of FT and DT. Therefore, the amount of DT, M_DT, can be estimated from:

$$M_\mathrm{DT} = \alpha R - I - P_\mathrm{s} \tag{4}$$

where α is the fraction of ground covered by the forest canopy, R is the atmospheric rainfall (mm), I is the canopy interception (mm) and P_s is the stemflow (mm).

When calculating the kinetic energy of DT by Eq. (1), M in Eq. (3) should be replaced by M_DT. We used E_o (J m^{-2}) to denote the kinetic energy of raindrops of atmospheric rainfall onto the open ground in the control watershed or the above-canopy layer in the plantation watershed, and E_c (J m^{-2}) for the kinetic energy of the waterdrops of DT in the plantation watershed. The total kinetic energy of waterdrops on forested land E_l (J m^{-2}) can then be written as:

$$E_\mathrm{l} = E_\mathrm{c} + (1-\alpha)E_\mathrm{o} \tag{5}$$

Based on Eq. (1), Eqs. (6) and (7) would be as follows:

$$E_\mathrm{o} = \frac{n_\mathrm{o}}{2}\sum_{n_\mathrm{o}} m_\mathrm{o}(D_\mathrm{o})[V_\mathrm{o}(D_\mathrm{o},\ H)]^2 f(D_\mathrm{o}) \tag{6}$$

$$E_\mathrm{c} = \frac{n_\mathrm{c}}{2}\sum_{n_\mathrm{c}} m_\mathrm{c}(D_\mathrm{c})[V_\mathrm{c}(D_\mathrm{c},\ H)]^2 f(D_\mathrm{c}) \tag{7}$$

where n_o and n_c are the total number of waterdrops of atmospheric rainfall and DT, respectively; $m_\mathrm{o}(D_\mathrm{o})$ and $m_\mathrm{c}(D_\mathrm{c})$ are the mass of atmospheric rainfall and DT, respectively; $V_\mathrm{o}(D_\mathrm{o}, H)$ is the velocity of waterdrops of atmospheric rainfall when they reach the open soil surface and $V_\mathrm{c}(D_\mathrm{c}, H)$ is the velocity of waterdrops of DT when they reach the soil surface in the forest. $f(D_\mathrm{o})$ and $f(D_\mathrm{c})$ are similar to the above.

The ratio (l) of the kinetic energy of waterdrops onto the soil surface in the forest to that onto the open ground is a useful indicator for the evaluation of impacts of forest canopy on the rainfall kinetic energy. It can be calculated through the following formula, based on Eq. (5):

$$l = \frac{E_c + (1-\alpha)E_o}{E_o} \tag{8}$$

In order to estimate l, $V_o(D_o, H)$ and $V_c(D_c, H)$ must be calculated. The detailed calculations of $V_o(D_o, H)$ and $V_c(D_c, H)$ are presented in the following sections.

3.1.1. Stable velocity of atmospheric raindrops

The motion of a falling raindrop is affected by two forces: gravity and the resistance force during its fall. The gravity can be described as $F_g = mg = 1/6\pi D^3 \rho_w g$, and the total resistance force as $F_r = K\pi DV^3$ (Pei, 1985).

The falling velocity of a waterdrop becomes constant when two forces are equal, that is:

$$\frac{1}{6}\pi\rho_w D^3 g = K\pi D V_\infty^3$$

therefore

$$V_\infty = \left(\frac{D^2\rho_w g}{6K}\right)^{1/3} \tag{9}$$

where g is acceleration by gravity ($=9.8$ m s^{-2}), K is the constant in the certain range of D (kg s m^{-3}), ρ_w is the raindrop or waterdrop density ($=1000$ kg m^{-3}) (Zhou, 1997), and V_∞ is the steady velocity of a falling raindrop (m s^{-1}).

In general, the falling distance of atmospheric raindrops is long enough to make the velocity constant before they reach the open soil surface. Therefore, $V(D, H)$ in Eq. (1) can be written as $V(D)$ for atmospheric rainfall. Correspondingly, $V_o(D_o, H)$ can be expressed as $V_o(D_o)$. Therefore, $V_o(D_o, H) = V_o(D_o) = V_\infty$. Eq. (9) also indicates that $V_o(D_o)$ is a function of D only.

The calculated stable or terminal velocities from this study are consistent with the experimental results from Laws (1941) and Gunn and Kinzer (1949) (Table 2). They are also in accordance with the calculated terminal velocities from Epema and Riezebos (1983).

3.1.2. Velocity of DT waterdrops on the soil surface

Because the FT has the same physical properties as atmospheric raindrops, it is necessary for us to consider, here, DT only.

A falling waterdrop of DT cannot usually reach its stable velocity before reaching the ground due to the limit of canopy height, and hence, we need to utilize the equation of motion from the Newton's Second Law. The motion of a falling DT waterdrop obeys the following equations:

$$\frac{dV}{dt} = \frac{F_g - F_r}{m} = \frac{mg - K\pi DV^3}{m} \tag{10}$$

Table 2
Fall velocities of waterdrops of various sizes after different fall heights

Waterdrop diameters (mm)													
Height of fall (m)	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7
0.5	2.91	3.02	3.07	3.09	3.1	3.1	3.1	3.1	3.11	3.11	3.11	3.11	3.11
1	3.69	4.05	4.19	4.25	4.3	4.31	4.32	4.33	4.33	4.33	4.33	4.34	4.35
1.5	4.02	4.62	4.91	5.05	5.13	5.16	5.19	5.2	5.21	5.21	5.22	5.22	5.22
2	4.29	4.98	5.41	5.64	5.75	5.82	5.85	5.88	5.9	5.9	5.91	5.91	5.92
3	4.29	5.34	6.02	6.4	6.62	6.74	6.82	6.86	6.89	6.91	6.92	6.93	6.93
4	4.29	5.48	6.32	6.85	7.16	7.35	7.45	7.52	7.57	7.6	7.61	7.63	7.64
5	4.29	5.54	6.48	7.12	7.51	7.74	7.89	7.98	8.04	8.08	8.1	8.12	8.13
6	4.29	5.57	6.56	7.27	7.73	8.01	8.18	8.29	8.37	8.41	8.44	8.46	8.48
7	4.29	5.57	6.65	7.36	7.87	8.18	8.38	8.51	8.6	8.65	8.68	8.71	8.73
8	4.29	5.57	6.65	7.42	7.96	8.3	8.52	8.66	8.76	8.82	8.86	8.89	8.91
9	4.29	5.57	6.65	7.5	8.02	8.38	8.61	8.77	8.87	8.94	8.98	9.01	9.03
10	4.29	5.57	6.65	7.5	8.06	8.43	8.68	8.84	8.95	9.03	9.07	9.1	9.12
11	4.29	5.57	6.65	7.5	8.1	8.48	8.72	8.89	9.01	9.09	9.13	9.16	9.19
12	4.29	5.57	6.65	7.5	8.12	8.51	8.75	8.93	9.05	9.13	9.17	9.21	9.23
13	4.29	5.57	6.65	7.5	8.12	8.54	8.77	8.96	9.07	9.16	9.2	9.24	9.27
14	4.29	5.57	6.65	7.5	8.12	8.54	8.79	8.97	9.09	9.18	9.23	9.26	9.29
15	4.29	5.57	6.65	7.5	8.12	8.54	8.8	8.99	9.11	9.19	9.24	9.28	9.31
[a]	4.29	5.57	6.65	7.5	8.12	8.54	8.82	9	9.14	9.23	9.28	9.32	9.35
[b]			6.58	7.41	8.06	8.52	8.86	9.1	9.25	9.3	9.3		
[c]			6.49	7.42	8.06	8.52	8.83	9.00	9.09	9.15			
[d]			6.68	7.41	7.99	8.46	8.75	8.96	9.08	9.13	9.24		

[a] Terminal velocities calculated from this study.
[b] Terminal velocities after Laws (1941).
[c] Terminal velocities after Gunn and Kinzer (1949).
[d] Terminal velocities calculated from Epema and Riezebos (1983).

with boundary conditions of $V=0$ when $t=0$ and

$$\int_0^T \mathrm{d}V = H$$

where t is the falling time of DT waterdrop(s), T is the falling time of the waterdrop(s) when it reaches ground surface(s) and H is the canopy height (m).

Considering $m=\pi\rho_\mathrm{w}D^3/6$, Eq. (10) can be changed into:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = g - \frac{6KV^3}{D^2\rho_\mathrm{w}} \tag{11}$$

Noticing $V_\mathrm{o}=V_\mathrm{o}(D_\mathrm{o})=V_\infty=(D^2\pi_\mathrm{w}g/6K)^{1/3}$ as stated above, Eq. (11) could be transformed into:

$$\frac{V_\mathrm{o}^3\mathrm{d}V}{V_\mathrm{o}^3 - V^3} = g\mathrm{d}t \tag{12}$$

Integrating Eq. (12) with the first boundary condition, we have

$$-\frac{V_o}{3}\ln(V_o - V) - 0.3023V_o + \frac{V_o}{6}\ln(V^2 + V_oV + V_o^2)$$
$$+\frac{V_o}{\sqrt{3}}\arctan\frac{2V + V_o}{\sqrt{3}V_o} = gt \qquad (V_o > V) \tag{13}$$

Eq. (13) is an implicit function relating V to t. It is the time course of the velocity of a falling waterdrop. The explicit form of Eq. (13) can be written as $V = V(t)$. We then use the second boundary condition to obtain the value of T, and the velocity of a waterdrop at time T can be expressed as:

$$V_c = V(T) \tag{14}$$

The value of T depends on the canopy height and the diameter of waterdrop(s). V_c is a non-steady velocity, and is usually less than V_o, that is, $V_c = V_c(D_c, H)$. Based on Eq. (13), Zhou (1997) estimated that the velocity of raindrops as large as 7 mm in diameter could increase to steady velocity from a height of 23 m (Fig. 2). This further supports that an atmospheric raindrop can usually reach its stable or terminal velocity before descending to the open ground or the above-canopy layer. Because the average eucalyptus canopy height is 6.0 m, much less than the calculated height (23 m), the velocities of falling DT waterdrops of diameters larger than 3 mm are not stable.

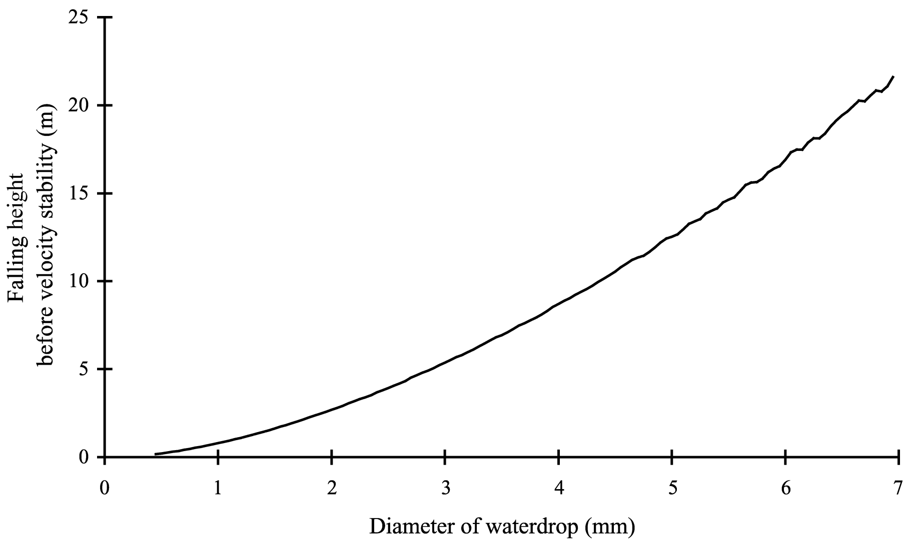

Fig. 2. Height required for stable velocity for different diameters of waterdrops.

3.1.3. Diameters of waterdrops and their distribution with rainfall intensities and forest canopy structures

For both the atmospheric rainfall and DT waterdrops, the frequency distribution of the diameters can be described by Eq. (2). For raindrops, the medium size (a) and standard deviation (b) of the frequency distribution of the diameters are affected by rainfall intensities (Wischmeier and Smith, 1958; Lee, 1980; Chen and Black, 1991; Chen and Wang, 1992; Zhou, 1997). Zhou (1997) showed the following quantitative relations for raindrops:

$$a = 1.33 + 0.32\ln P \tag{15}$$

$$b = 0.76 + 0.0022P \tag{16}$$

For DT waterdrops, however, Zhou (1997, 1999) found that a and b values were not affected by atmospheric rainfall intensities. They were influenced only by tree species and canopy structures, including leaf direction and canopy shape. Those parameters are listed in Table 3. The waterdrop diameter of DT for the eucalyptus plantation follows the normal distribution of $N(3.9,\ 1.09)$.

3.2. Field measurement

The two watersheds were instrumented in 1959 for a long-term research. One of the watersheds was then planted with eucalyptus (*E. exserta*) trees in 1964. Hence, data were collected for 4 years from the two watersheds prior to plantation, and measurement was continued until 1990. This paper is based on the measurements taken between 1981 and 1990.

Table 3
Waterdrop diameter distribution parameters (a, b) of dripping throughfall in several artificial mono-forests, the subtropics area, China (based on 20 observations)

Forest name and description	Diameter class (mm)	Percentage (%)	a	b
Cunninghamia lanceolata	less than 2.5	11	3.7	0.98
(20 years old, canopy density 0.85)	2.5–4.5	68		
	larger than 4.5	21		
Pinus massoniana	less than 2.2	9	3.5	0.97
(18 years old, canopy density 0.85)	2.2–4.4	73		
	larger than 4.4	18		
Sassafras tzumu	less than 3.3	23	4.1	1.14
(17 years old, canopy density 0.78)	3.3–5.1	57		
	larger than 5.1	20		
Eucalyptus exserta	less than 2.7	13	3.9	1.09
(12 years old, canopy density 0.75)	2.7–4.7	63		
	larger than 4.7	24		
Acacia mangium	less than 2.8	16	3.8	1.06
(12 years old, canopy density 0.80)	2.8–4.7	63		
	larger than 4.7	21		

a: Mean of the normal distribution.
b: Standard deviation of the normal distribution.

Surface runoff and soil erosion data were collected automatically from a hydrological measurement weir. Soil erosion was quantified by the amount of suspended solid and bed load (Singh, 1988; Zhou, 1995a,b).

Every rainfall event was measured with a standard rain gauge in the control watershed and above the eucalyptus forest canopy in the plantation watershed. Because both sites are flat and the forest canopy was uniform, only two replicates were used (Bren, 1980, 1997; Bren and Papworth, 1991).

Throughfall was collected by a plate (trough), with a horizontal area of 10 m^2, and the water gathered by the trough was channeled to the V-shaped outlet of the case. A fluviograph was installed to record the water level in the outlet channel. Because the eucalyptus trees were evenly planted, and the forest canopy was uniform, two replicates with a total horizontal area of 20 m^2, which is much larger than the throughfall-sampled area of other studies (Gash, 1978; Vertessy et al., 1993), were sufficient to sample throughfall of the whole forested watershed.

Stemflow was collected by a polyvinyl chloride (PVC) tube twisting round the stem, and led to a standard automatic rain gauge. Ten trees adjacent to each site where throughfall was monitored were selected for stemflow measurement (Gash, 1978; Lee, 1980).

Between 1981 and 1990, the intensity and duration of 850 rainfall events, and associated throughfall, stemflow, surface flow, suspended solid (SS) and bed load (BL) were measured in each watershed. The intensities of 98% rainfall events were less than 50 mm h^{-1}. Rainfall events were separated into 25 classes at 2-mm h^{-1} interval. For each class of rainfall events, we calculated the average SS and BL per unit rainfall (kg mm^{-1}) (Chen and Wang, 1992; Dietrich et al., 1992; Yu, 1994; Zhang et al., 1994; Yu and Zhou, 1996).

In order to measure the diameters of waterdrops (including raindrop and throughfall waterdrop), we used a 1-m^2 plate on which peanut oil of 1-cm depth was laid. The diameters of waterdrops were measured by a series of rules mounted on the bottom of the plate. This plate was left in rain and throughfall for a very short time, and the numbers of waterdrops within different diameter ranges were counted (Lee, 1980; Zhou, 1997, 1999). This method was tested prior to this study, and can give satisfactory results. The measurement must be undertaken many times according to different rainfall intensities. We used an umbrella to control the time of raindrop onto the plate. Three diameter classes including (< 1, 1–3, >3 mm) and (< 2.5, 2.5–4.5, >4.5 mm) were assigned for raindrops and waterdrops, respectively.

The interception of rainfall by the forest canopy (I, mm) is closely related to the atmospheric rainfall (R, mm), the best-fit regression equation is: $I = 0.6470R^{0.5481}$ ($n = 378$ and $r^2 = 0.96$). The stemflow (P_s in mm) is also closely related to atmospheric rainfall, and the best-fit regression equation is: $P_s = 0.0831R - 0.0464$ ($n = 266$ and $r^2 = 0.92$).

4. Results and discussion

4.1. Factors affecting sediment yield

Fig. 3 shows that both the SS and BL per unit rainfall (kg mm^{-1}) in the control watershed are significantly correlated with atmospheric rainfall intensity. The correlation

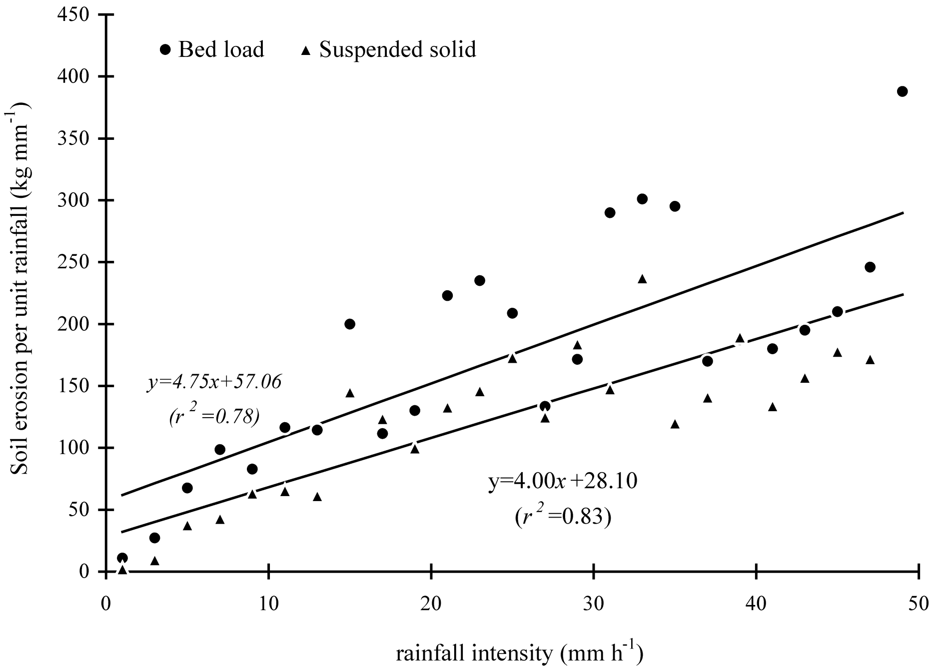

Fig. 3. Relationship between atmospheric rainfall intensity and soil erosion (bed load and suspended solid) for the control watershed.

coefficients are 0.833 and 0.779 for SS and BL, respectively, which indicate that splashing of raindrops is the main cause of soil erosion. Linsley et al. (1975) demonstrated theoretically that erosion may be viewed as starting with the detachment of soil particles by the impact of raindrops, and the kinetic energy of the drops can splash soil particles into the air. Guangdong Academy of Sciences (1991) showed by experiment that different simulated rainfall intensities resulted in different soil erosion despite same total rainfall amounts. Zhang et al. (1994) summarized the related research results and came up with the same conclusion as that of Linsley et al. (1975).

There is also a significant correlation between SS or BL and the kinetic energy per unit rainfall for the control watershed as shown in Fig. 4. This suggests that the kinetic energy of atmospheric rainfall is also a direct, sensitive factor affecting soil erosion or stream sediment yield in the control watershed.

For the plantation watershed, both SS and BL were significantly related to the kinetic energy of total waterdrops (FT and DT), but not to the atmospheric rainfall energy or intensity (Table 4). This demonstrates that the kinetic energy of FT and DT is the key factor influencing sediment yield in the plantation watershed.

The kinetic energy of waterdrops is the integration of their velocity, size and magnitude. Because velocity, size and magnitude can all individually affect soil erosion, it is expected that their combination, kinetic energy, can be better used to indicate soil erosion. The results from this study confirm our expectation. They are also consistent with conclusions

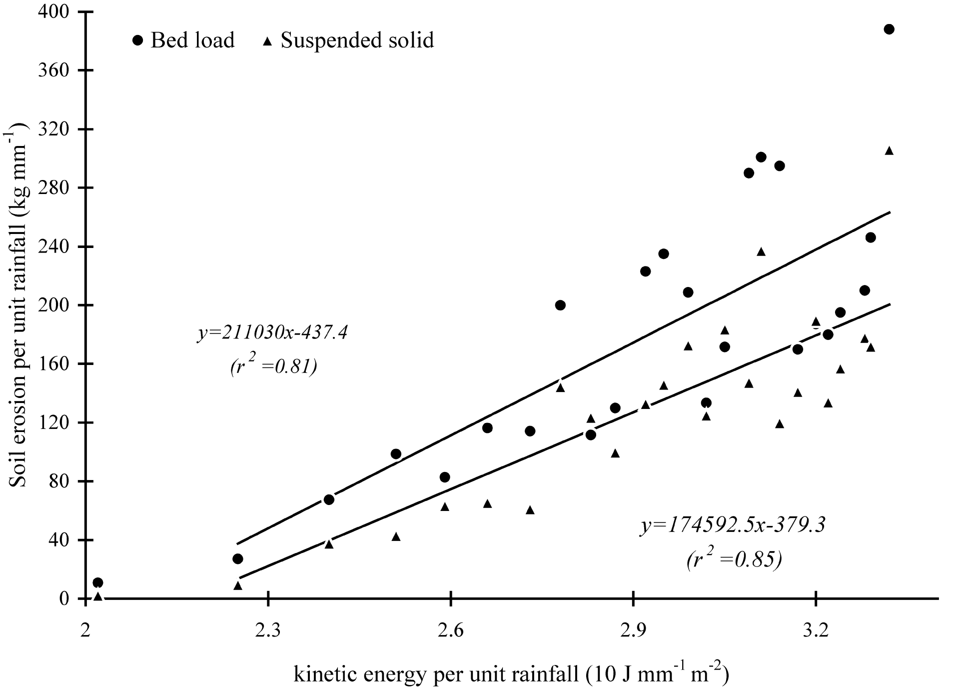

Fig. 4. Relationship between raindrop kinetic energy per unit rainfall and soil erosion (bed load and suspended solid) for the control watershed.

from Wischmeier and Smith (1958), Gilley and Finkner (1985) and Salles et al. (2000). Salles et al. (2000) identified a critical kinetic energy to indicate the initiation of soil detachment, and this threshold energy equals 5 μJ for the fine sand and 12 μJ for the silt loam soils.

Lack of significant correlation between SS, BL and rainfall intensity or kinetic energy in the plantation watershed indicates that rainfall intensity or energy is not an appropriate indicator for the evaluation of soil erosion in the eucalyptus plantation forests. It also implies that forest canopy may have an important role in altering rainfall physics and energies.

Table 4
Correlation coefficients (r^2) and ANOVA tests between stream sediment and various waterdrop kinetic energy for the plantation watershed

Types of sediment (kg mm^{-1})	Atmospheric rainfall intensity (mm h^{-1})	Atmospheric rainfall energy (J mm^{-1} cm^{-2})	Throughfall waterdrop kinetic energy (J mm^{-1} cm^{-2})
Suspended solid (SS)	$r^2 < 0.1$, insignificant[a]	$r^2 < 0.22$, insignificant	$r^2 = 0.74$, significant
Bed load (BL)	$r^2 < 0.1$, insignificant	$r^2 < 0.25$, insignificant	$r^2 = 0.63$, significant

[a] Use α (confidence level) = 0.005.

4.2. Factors affecting kinetic energy of waterdrops under a forest canopy

4.2.1. The frequency distribution of rainfall intensity

The ratio (l) of waterdrop kinetic energy on forested land to raindrop kinetic energy on an open place is greatly affected by rainfall intensity and the presence of a forest canopy. Therefore, it is necessary to analyze the characteristics of rain events in the studied watersheds.

Fig. 5 shows that the percentage of rainfall with intensities less than 2.5 mm h^{-1}, between 2.5 and 8 mm h^{-1}, between 8 and 16 mm h^{-1} and greater than 16 mm h^{-1} to the total amount of rainfall are 5.53%, 31.57%, 28.9% and 34.0%, respectively. Most rainfall, in this region, was brought by rainfall events having larger than 2.5 mm h^{-1} rainfall intensity. The rainfall events with small to medium intensities of 2.5–16 mm h^{-1} contribute to 77.8% of the total number of rainfall events.

4.2.2. The ratios (l) for atmospheric rainfall intensities

Fig. 6 shows the simulated relationship between l and rainfall for each rainfall intensity classes for the canopy of 6 m in height and 0.76 in density or cover rate.

Because the ratio l is affected by both rainfall and rainfall intensity for a given canopy height and density, it is necessary to separate the rainfall intensities into different classes as shown in Fig. 5 in order to identify the influence of rainfall on l. For each class, we simulated the relationship of l and rainfall.

When rainfall is small (less than 5 mm), l is less than 1 for all intensities. This is due to more rainfall interception by the canopy. Therefore, the presence of the canopy can reduce the splashing of waterdrops from small rainfall events on the forested land, which can decrease soil erosion.

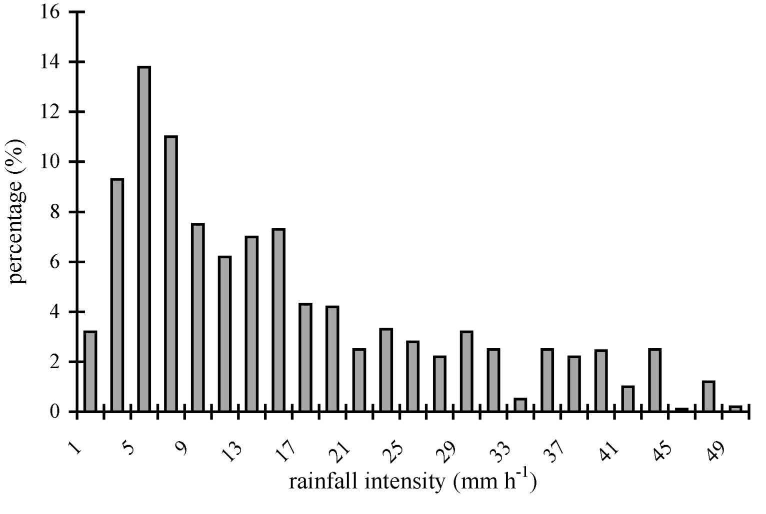

Fig. 5. Distribution of rainfall intensities (total rainfall divided by duration for each distinct rain event) in the studied watershed.

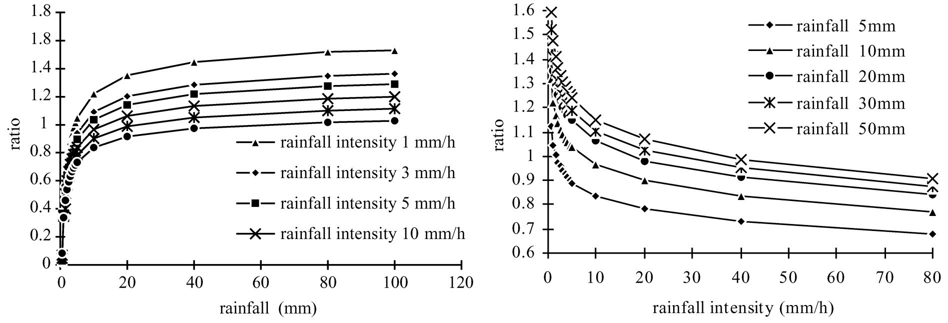

Fig. 6. The ratios (l) for various rainfall amounts and intensities.

When rainfall is greater than 5 mm, l values increase (Fig. 6). However, the magnitude of increase varies for different rainfall intensities (Fig. 6). For the rainfall intensity less than 20 mm h^{-1}, all l values are greater than 1. This indicates that when rainfall is >5 mm and intensity is <20 mm h^{-1}, the presence of canopy can increase the waterdrop kinetic energy on the plantation sites, which means acceleration of soil erosion. However, the canopy does have positive impacts on reduction of soil erosion when rainfall intensities are >40 mm h^{-1}, because the l values for this intensity class are less than 1 (Fig. 6).

The unexpected higher l values (>1, when rainfall amount is >5 mm and intensity is <20 mm h^{-1}) indicate that the total kinetic energy is increased after rainfall passes through the forest canopy. There are two factors contributing to this. Firstly, the forest canopy redistributes rainfall amount and sizes, and usually increases waterdrop sizes in throughfall. Because of increasing waterdrop sizes, there is less energy loss from air friction in the forest throughfall as compared with those on open land or above forest canopy. Secondly, due to increasing throughfall waterdrop sizes, their velocities are also higher than those above forest canopy or on open land. The higher velocities result in a much higher kinetic energy because kinetic energy is associated with the square of velocity.

As shown in Eq. (2), the diameters of both raindrop and waterdrop follow the normal distribution $N(a, b)$. The parameters a and b increase with rainfall intensities according to Eqs. (15) and (16) for raindrops. However, for waterdrops of DT, a and b are 3.90 and 1.09, respectively, and they are not affected by rainfall intensities. Because the medium diameters of DT waterdrops will be much larger than that of raindrops, the ratio l varies inversely with rainfall intensities.

Fig. 7 is based on the field measurements in the plantation and control watersheds. It shows that the ratios (l) continuously decreased with rainfall intensities under the circumstance of average rainfall. This supports the above simulation results.

Based on Fig. 6, we can define the critical rainfall for different rainfall intensities and the critical rainfall intensities for different rainfall in the condition of $l = 1$ (shown in A and B of Fig. 8, respectively). The l values are greater (less) than 1 for the lower (upper) part of the line in Fig. 8A and the upper (lower) part in Fig. 8B.

Integrating the results from Figs. 5, 7, and 8), we find that the eucalyptus canopy does not reduce the waterdrop kinetic energy. Soil erosion from the plantation watershed

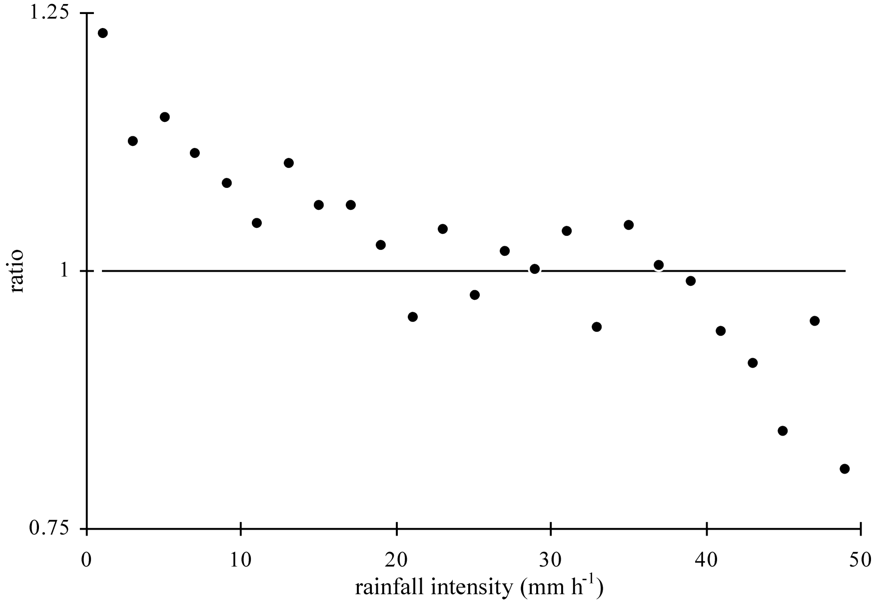

Fig. 7. The ratios (l) for measured rainfall intensities.

remains higher under many rainfall conditions (about 65% rain events) compared with the control watershed, particularly for light rain with long duration.

4.2.3. The ratio (l) for various canopy heights

Fig. 9 shows the simulation results of the influences of forest canopy height on the ratio. The canopy density was assumed to be 0.75. The influence of canopy height (H) on the ratio is related to rainfall intensity and quantity. With the increase of canopy height, l increases in S shape. When H is less than 2 m and more than 7 m, l has little change. When H is 2–7 m, l changes dramatically. Therefore, the canopy has a significant impact on l values in the heights of 2–7 m.

Fig. 9 also shows that l is greater than 1 when canopy heights are >7 m, and less than 1 when canopy heights are <5 m. This suggests that lower vegetation layers such as understory vegetation play an important role in protecting soil from erosion. Such lower layers should be maintained particularly when main canopy height is more than 7 m in the study area.

4.3. The characteristics of rainfall and soil erosion for the control and plantation watersheds

4.3.1. Comparison of the total soil erosion and kinetic energy between two watersheds

Between 1981 and 1990, the total kinetic energy of raindrops (247 811 J m^{-2}) in the control watershed was less than that (265 554 J m^{-2}) on the plantation watershed. This is due to the domination of rainfall intensities of 2.5–16 mm h^{-1} in the study area. The l

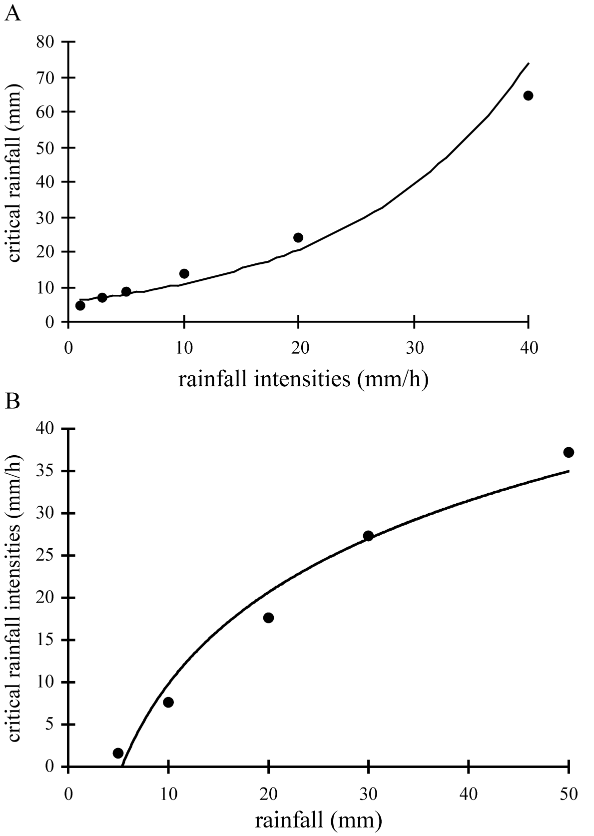

Fig. 8. The critical rainfall and rainfall intensities in the condition of $l = 1$.

values are generally greater than 1 for those rainfall intensities. Therefore, the forest canopy had increased the splashing impact of waterdrops on the soil of the plantation watershed.

Fig. 10 was based on field measurements. All the rain events were separated into different groups according to rainfall intensity. The kinetic energies in both watersheds were then calculated for each group, and total kinetic energy of each group was divided by the corresponding total rainfall.

Fig. 10 demonstrates that the kinetic energy in the plantation watershed was more than that in the control watershed when rainfall intensity is less than 24.3 mm h^{-1}, which indicates higher soil erosion in the plantation watershed. When rainfall intensity is greater than 24.3 mm h^{-1}, the impact was opposite. As previously indicated, percentage of rainfall with intensities less than 16 mm h^{-1} to the total accounts for 66% in amount and 78% in number. The domination of small to medium rainfall intensities in the study area contributes to higher soil erosion in the plantation watershed, compared with the control watershed.

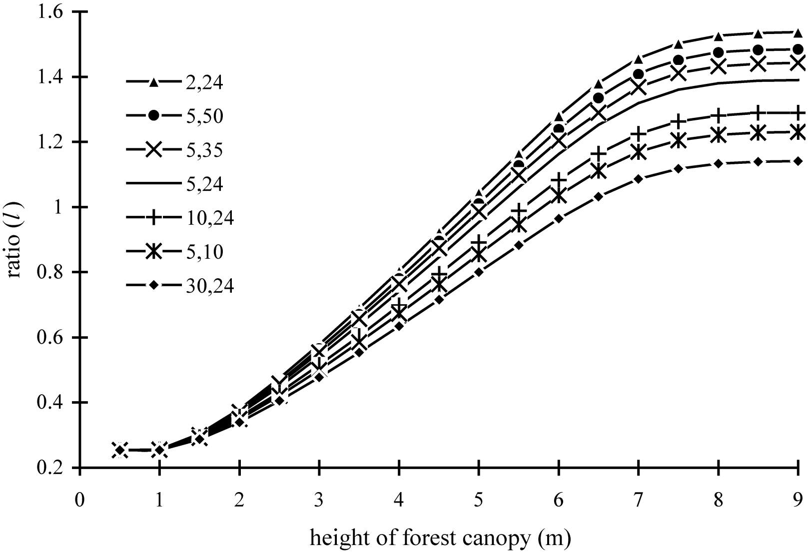

Fig. 9. The ratios (*l*) for canopy heights for the combination of rainfall quantity (mm) and intensity (mm h^{-1}).

Our results suggest that in order to successfully restore degraded ecosystems, we must take an integrated approach considering tree species, canopy height, canopy structure and rainfall characteristics.

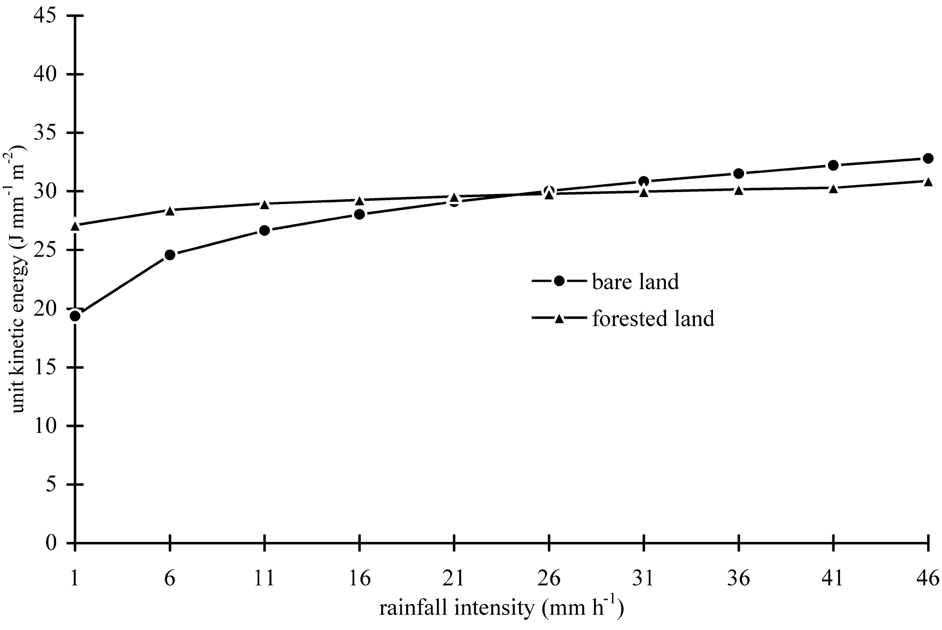

Fig. 10. Comparison of unit kinetic energy at various rainfall intensities in the two studied watersheds.

Table 5
Percentages of soil erosion at different rainfall intensities to the total soil erosion in the unvegetated (control) and plantation watersheds

Rainfall intensity class (mm h^{-1})	Watershed types	Suspended solid	Bed load	Total erosion	Sample size (*n*)
0–2.5	control	0.4 ± 0.1[a]	0.9 ± 0.2	0.7 ± 0.2	65
	plantation	1.8 ± 0.3	1.3 ± 0.2	1.4 ± 0.1	75
2.5–8	control	14.2 ± 1.1	19.3 ± 1.8	17.3 ± 1.3	352
	plantation	17.5 ± 1.2	68.1 ± 5.1	50.3 ± 4.3	342
8–16	control	32.8 ± 2.1	43.8 ± 3.0	39.5 ± 2.3	210
	plantation	32.1 ± 2.7	14.0 ± 2.2	20.4 ± 3.1	205
>16	control	52.6 ± 4.8	36.0 ± 3.2	42.5 ± 3.4	223
	plantation	48.7 ± 3.9	16.6 ± 2.7	27.9 ± 2.9	228

[a] Standard deviation.

4.3.2. Comparison of soil erosion characteristics of these two watersheds

Data on soil erosion at different rainfall intensities for both watersheds are summarized in Table 5. The results indicated that the percentages of soil erosion caused by rainfall with small- to medium-sized intensities to the total in the plantation watershed were much higher than those in the control watershed. However, the percentages of soil erosion caused by rainfall with high intensities to the total in the plantation watershed were much lower than those in the control. Therefore, the forest canopy increased the soil erosion on the plantation land when the rainfall intensity is less than 10 mm h^{-1}, otherwise, there is a decreased in soil erosion in the plantation watershed.

5. Conclusions

Erosion may be viewed as starting with the detachment of soil particles by the impact of raindrops (Ellison, 1944). The kinetic energy of the drops can splash soil particles into the air. Linsley et al. (1975) qualitatively confirmed that raindrop splashing is the original driving force of soil erosion. This study supports those findings.

Studies on how forest canopy affects DT diameters, kinetic energy and sediment yield are rare. From this study, we have the following conclusions. The sediment yield per unit rainfall depends on the kinetic energy of waterdrops falling onto the land surface. For the control watershed, the waterdrops are rainfall, but for the eucalyptus plantation watershed, the waterdrops are throughfall. Our results suggest that the kinetic energy of waterdrops is an appropriate and sensitive indicator of soil erosion.

The role of a single-layer eucalyptus plantation in soil protection is largely dependent on rainfall intensities and canopy heights. The plantation has a positive impact on the reduction of soil erosion when rainfall is less than 5 mm or intensities are greater than 40 mm h^{-1}, otherwise, the plantation increases soil erosion in the study area. The positive relationship between canopy height and kinetic energy suggests that understory vegetation should be maintained as part of the plantation.

Soil characteristic is also an important factor in determining soil erosion. How this factor affects soil erosion in the study area, particularly from a kinetic energy approach, remains unexamined.

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