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Soil resistance to flowing water erosion as affected by tea planting age in Three Gorges Reservoir Area of China

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Abstract: Soil erosion resistance is influenced by intrinsic soil properties and multiple external factors. This study investigated the effect of tea planting age on soil resistance to flowing water erosion (reflected by rill erodibility (K_r) and critical shear stress (τ_c)) in Three Gorges Reservoir Area. One slope farmland (as the control) and five tea plantations cultivated for 3 to 34 years were selected for sampling sites. The results indicated that bulk density (BD), soil cohesion (Coh), water stable aggregate (WSA), mean weight diameter (MWD), soil organic carbon (SOC), litter density (LD), and root mass density (RMD) increased generally with tea planting age. Compared to the control, K_r of tea plantations reduced by 71.1%–85.3%. The temporal variation in soil erosion resistance was controlled greatly by the variations in most near-surface characteristics. K_r decreased with WSA, Coh, LD, RMD, and SOC following a power function ($P < 0.01$); τ_c increased with MWD, LD, RMD, and SOC as an exponential function, with BD a power function, and Coh a logarithmic function ($P < 0.01$). In this study, K_r could be simulated well by WSA and LD with a power function, and τ_c could be simulated well by MWD and RMD with an exponential function.

Keywords: critical shear stress; near-surface characteristics; rill erodibility; soil erosion resistance; tea cultivation age

Soil detachment is the initial stage of water erosion and it refers to the dislodgement of soil particles from the soil mass by raindrop impact or overland flow (Zhang et al. 2019a; Wang et al. 2022; Xiao et al. 2022). Soil detachment by overland flow, i.e., rill erosion, is quantitatively characterized by soil detachment capacity (D_c) and primarily controlled by soil erosion resistance under given flow hydrodynamic conditions (Zhang et al. 2020). D_c is the maximum rate at which the clear water detaching the soil and it is the basis for determining soil erosion resistance, such as in the representative Water Erosion Prediction Project (WEPP) model:

$$D_c = K_r(\tau - \tau_c) \quad (1)$$

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where:

D_c – soil detachment capacity (kg/m^2/s);

K_r – rill erodibility (s/m);

τ – flow shear stress (Pa);

τ_c – soil critical shear stress (Pa).

K_r and τ_c are soil erosion resistance parameters and could be derived via the linear regression between measured D_c and τ (Zhang et al. 2021). The ultimate aim of the study on soil detachment process is to analyze the spatio-temporal variation of soil erosion resistance as well as its dynamic mechanism using measured D_c, and to further construct the prediction model of soil erosion resistance.

Soil erosion resistance reflects the soil's ability to resist detachment by water flow (Moragoda et al. 2022), which is directly related to intrinsic soil properties and directly and/or indirectly affected by multiple extrinsic environmental factors driving the variations in soil properties (Zhang et al. 2020), such as plant community near-surface characteristics like litter, biological soil crust (biocrusts), and plant roots (Vannoppen et al. 2015; Sun et al. 2016; Wang et al. 2018a, 2022; Liu et al. 2020; Zhang et al. 2020, 2021; Liu et al. 2022b). Litter either covering on or incorporating into the topsoil could impact soil properties thereby soil erosion resistance, and this effect is also substantially associated with the litter morphological characteristics (Liu et al. 2020, 2022a). Previous studies indicated that K_r decreased exponentially and τ_c increased linearly with litter incorporation rate (Sun et al. 2016). It has been extensively confirmed in various bioclimatic regions that biocrusts played crucial roles in enhancing soil erosion resistance with which being influenced by successional stage, community composition and structure, and biocrust coverage (Liu et al. 2016, 2017; Zhang et al. 2020, 2021). K_r decreased exponentially with the increase of biocrust coverage, and moss biocrust played greater roles in enhancing soil erosion resistance than that of cyanobacteria biocrust (Knapen et al. 2007a; Liu et al. 2016). Numerous studies have highlighted the positive effects conferred by plant roots in promoting soil erosion resistance, with generally concluding the much superior effectiveness of fibrous root system to that of tap root system (Vannoppen et al. 2015; Hao et al. 2021; Xiao et al. 2022; Wang et al. 2021, 2022). Nevertheless, the optimal morphological parameter such as root length density (RLD), root mass density (RMD), root surface area density (RSAD), etc. that quantitatively depicting roots effects varied with study region, plant species, root architecture, and edaphic conditions (Vannoppen et al. 2017; Zhang et al. 2019a; Wang et al. 2021; Xiao et al. 2022).

Soil properties and near-surface characteristics exhibit obvious temporal variabilities, thus leading to the seasonal or interannual variations in soil erosion resistance. However, relevant studies in China mainly focused on the Loess Plateau. Wang et al. (2013) studied the temporal variations of soil erosion resistance in abandoned farmlands with different restored ages (3~37 years) and indicated that K_r gradually declined and tended to be stable after restored for 28 years; τ_c fell off within 18 years of restoration and then went up due to vegetation recovery and biocrust development. Zhang et al. (2019b) ascribed the temporal variation in soil erosion resistance to the seasonal variations in water stable aggregates (WSA), soil cohesion (Coh), and RMD. While for the slope farmland, the seasonal variation in soil erosion resistance was closely associated with the tillage disturbance and crop root growth (Yu et al. 2014).

The Three Gorges Reservoir Area (TGRA) is located at the upstream of Yangtze River of China. The inherent ecosystem vulnerability and strong anthropogenic disturbances have triggered serious soil erosion in this region, which has not only exacerbated the ecological environments, but also degraded the land productivity (Zhang et al. 2020). To reverse this situation, the Chinese government has implemented a series of ecological projects aimed at soil erosion control in the last several decades, e.g., Soil and Water Conservation Project in the Upper Reaches of the Yangtze River, the Natural Forest Protection Project, the "Grain for Green" project, and the Ecological Shelter Project of the TGRA (Zhang et al. 2020; Xu et al. 2020). To a great degree, these projects have generated favourable impacts on vegetation recovery and soil conservation thereby beneficial to the promotion of soil erosion resistance. Particularly, due to the implementation of these conservation projects, the small watershed dominated by farmlands has been converted into a mosaic pattern of multiple modes with tea plantations, orchards, forestlands and farmlands (Wang et al. 2016). Thereinto, a key practice in the TGRA was converting wastelands or farmlands to tea plantations or citrus orchard (Xu et al. 2020). In the tea plantation ecosystem, soil physicochemical properties will change considerably with tea planting age due to fertilization management, tea tree pruning and litter returning to soil as well as the accumula-

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tion of root exudates (Wang et al. 2019c, 2020c). As also corroborated in many previous researches, tea planting age rendered remarkable impacts on soil structure, physico-chemical properties, fertility level, relevant microbial biomass and activities (Wang et al. 2016, 2018c, 2019c, 2020b, c). Therefore, soil erosion resistance may well vary temporally due to the modifications in near-surface characteristics with tea planting age. However, studies in this respect are very scarce. How the chronological series of tea cultivation affect the dynamics of soil erosion resistance is still unclear. Therefore, the objectives of this study were to investigate the variations in soil erosion resistance with tea planting age and to further identify the dominant factors responsible for these variations. Our findings are conducive to a thorough comprehension of the dynamic mechanism of soil erosion in tea plantations thereby implementing soil and water conservation measures in TGRA, and also provide a useful reference for the sustainable development of tea plantations in other regions.

MATERIAL AND METHODS

Study area and sites selection. This work was conducted in Zhangjiachong small watershed (110°56'30''–110°57'45''E, 30°46'50''–30°47'40''N) of Zigui Soil and Water Conservation Station, Zigui County, Hubei Province (Figure 1). It locates in the head area of the TGRA and covers an area of 1.62 km^2 with the altitude ranging from 148 to 530 m. Subtropical monsoon climate is prevailing with a mean annual temperature of 16.8 °C. The annual mean precipitation is 1 221 mm, with 70% of which occurring from May to September. The soil developed from granite parent material and had a quartz sandy texture, thus is vulnerable to detachment. The vegetation is mainly subtropical evergreen or deciduous broad-leaf forest and mixed broadleaf-conifer forest, with tea, citrus and chestnut principally distributing in low mountain valley and semi-alpine area. "Yihong tea" is the main variety in this region and the cultivation ages of these tea plantations are different.

A space-for-time substitution method was adopted to investigate the variations in near-surface characteristics and D_c (Wang et al. 2020c). To avoid the potential spatio-temporal mixing effects between spatial variation of soil properties and the tea planting time, a chronological series of tea plantations (3, 8, 17, 25, and 34 years) cultivated with the identical variety (Yihong tea) were selected as the test sites. These tea plantations are distributed in close

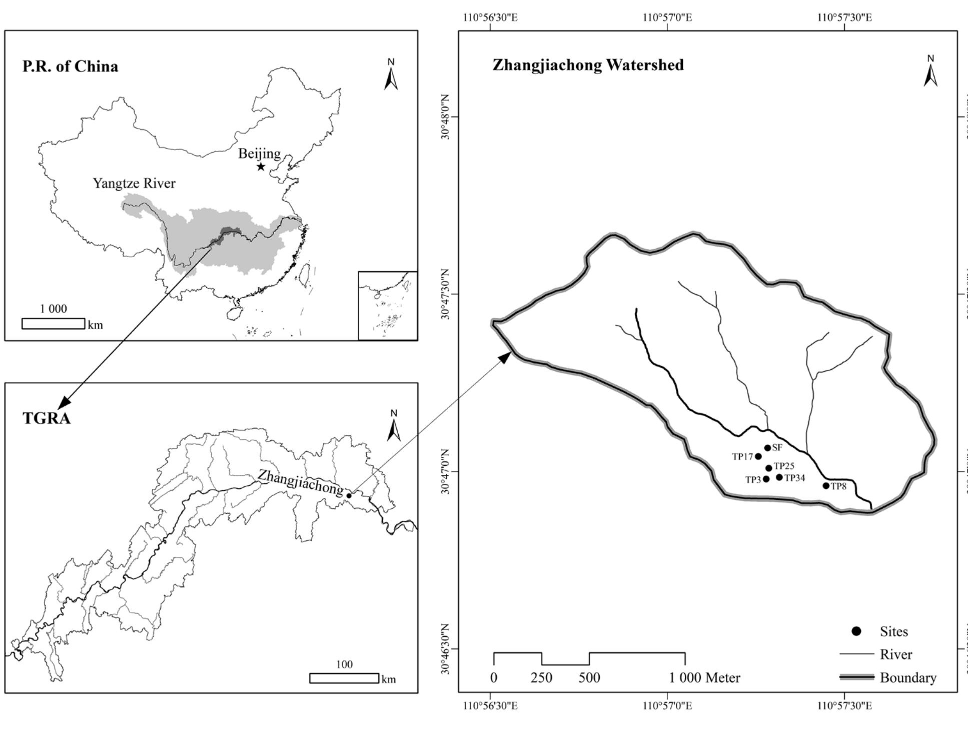

Figure 1. Location of the study area and sampling sites

SF – the slope farmland; TP – the tea plantation and the number is the age since tea cultivated; TGRA – Three Gorges Reservoir Area

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geomorphic units with similar soil parent material, slope gradient (10.45%–25.88%), and fertilizer application. Additionally, a slope farmland of soybean was selected as the reference.

Soil sampling and index measurement. Soil sampling was performed in August 2020. Within each tea plantation, we randomly established a sample plot of 15 × 15 m that was at least 15 m from the tea plantation edge. Thereafter, all the sampling and measurements were proceeded in an 'S'-shaped pattern in each plot. Before soil sampling, 5 quadrats of 0.5 × 0.5 m were designed to collect the litter samples on soil surface into the plastic bags, which were subsequently transported into the laboratory to measure litter density (LD, g/m^2) by oven-drying under 60 °C to a constant weight. For D_c measurement, undisturbed soil samples were taken from 0–5 cm soil layer at each plot utilizing steel rings (5 cm in height,10 cm in diameter). When sampling, a flat soil surface nearby the tea plants between 2 adjacent rows was selected and all the litter was cleared carefully. The steel ring was then pressed into the soil until it is fully filled and its upper rim was flush with the soil surface. The details of the sampling procedure can be referred in studies by Zhang et al. (2020, 2021) and Xiao et al. (2022). Around the sampling points in each plot, eight soil cores were collected with cutting rings (5 cm in height and 100 cm^3 in volume) from 0–5 cm soil layer for measuring soil water content and BD via oven-drying. Mean soil water content was then used to determine the original dry weight of soil samples for D_c measurement. Soil cohesion of each plot was determined onsite with a portable shear vane (Durham Geoenterprise, Inc., Durham, UK) for 10 replications. Simultaneously, six topsoil (0–5 cm layer) samples were collected with a shovel and mixed homogeneously, then sieving through a 2 mm mesh to analyze particle size distribution (Mastersizer 2000, Malvern, UK), soil organic carbon (potassium dichromate colorimetric method), and WSA (wet-sieving method) for three replications. The stability of soil aggregates was evaluated by mean weight diameter (MWD, mm) as follows:

$$\text{MWD} = \sum_{i=1}^{n}(x_i w_i) \tag{2}$$

where:
x_i – mean diameter of two adjacent sieves (mm);
w_i – aggregate proportion remaining on i^{th} sieve.

Flume experiments. D_c was measured in a flume of 4.0 m in length and 0.4 m in width. The flume slope could be adjusted in the range of 0–60%. Flow discharge was controlled by valves and measured at the flume outlet with collecting barrels. When the flow became steady, dye-tracer method was employed to measure the surface flow velocity with 15 replicates, which was then multiplied by a correction coefficient to get the mean flow velocity. Flow depth (h, m) was computed as:

$$h = \frac{Q}{BV} \tag{3}$$

where:
Q – flow discharge (m^3/s);
B – flume width (0.4 m);
V – mean flow velocity (m/s).

Then, the flow shear stress (τ, Pa) was computed as:

$$\tau = \rho g h S \tag{4}$$

where:
ρ – water density (kg/m^3);
g – gravity constant (m/s^2);
S – slope gradient (m/m).

In this study, six different shear stresses of 4.94, 7.15, 11.39, 13.36, 16.27, and 19.17 Pa were applied through six combinations of flow discharge (0.0005–0.0013 m^3/s) and flume slope (17.4%–42.3%).

Soil samples were pre-saturated for 8 h in a container and then drained for 12 h to eliminate the impacts of soil moisture regime on the testing process. When testing, adjust the flow discharge and flume slope gradient to the designed values and then set the prepared soil sample into a circular chamber (0.5 m from the lower end of flume) on the flume bed. To uniformize the boundary effect, the scouring test ended when approximate 2 cm scouring depth was attained and the test duration was recorded. After the flume tests, the scoured samples were oven-dried and weighed to determine the final dry soil mass. D_c for each sample was calculated by the following equation:

$$D_c = \frac{M_b\text{-}M_a}{At} \tag{5}$$

where:
M_b – initial dry weight of the soil sample before scouring (kg);
M_a – final dry weight of the soil sample after scouring (kg);
A – scouring area of the soil sample (m^2);
t – test duration (s).

https://doi.org/10.17221/157/2022-SWR

Five samples were tested for each flow shear stress and the mean was regarded as the D_c for that flow shear stress, 30 samples were needed for each sampling plot and a total of 180 samples were thus tested. When the flume tests finished, the plant roots within each soil sample were rinsed out and weighed after oven-drying (65 °C, 24 h). Root mass density (RMD, kg/m^3) was computed via dividing the dry root mass to the steel ring volume. Finally, soil erosion resistance (K_r and τ_c), was estimated for each plot by Equation (1).

Statistical analyses. One-way variance analysis (ANOVA) was used to detect the effects of tea planting age on near-surface characteristics and D_c, with the least significant difference (LSD) test being performed for post hoc multiple comparisons (α = 0.05). The single relationships between soil erosion resistance and near-surface characteristics were fitted via simple regression analysis. Pearson correlation analysis (α = 0.05) was adopted to test the correlation between soil erosion resistance and the potential influencing factors. All statistical analyses were executed with SPSS 20.0 and Origin Pro 2019b.

RESULTS

Variations in near soil surface characteristics. ANOVA showed that near-surface characteristics were appreciably ($P < 0.05$) influenced by tea planting age. As shown in Table 1, BD, Coh, WSA, MWD, SOC, LD, and RMD increased generally with the increase of tea planting age. In comparison with the control, BD, Coh, WSA, and MWD increased on average by 3.8%, 36.0%, 40.7%, and 6.7%, and means of SOC, LD, and RMD were 2.3, 6.0, and 12.0 times of that for the tea plantations, respectively (Table 1). In this study, significant differences in the soil particle contents have not been detected among the six sampling sites.

Soil detachment capacity and soil erosion resistance. D_c exhibited great variations among the sampling sites, ranging from 0.049 to 2.361 kg/m^2/s (Figure 2). Mean D_c of the slope farmland (1.327 kg per m^2/s) was remarkably higher than that of tea plantations, with the former being 3.4 to 7.2 times greater than that of the latter. Compared with the control, D_c for tea plantations was reduced by 70.8% to 86.1%. Regression analysis revealed a negatively exponential relationship between D_c and the tea planting age (T_a):

$$D_c = 1.088\exp(-0.643T_a) + 0.238; \quad R^2 = 0.979; P < 0.01 \tag{6}$$

Table 1. Near-surface characteristics for each test site (mean ± SD)

Site	BD (g/cm^3)	Sand	Silt)	Clay	Coh (kPa)	WSA (%) < 0.25 mm	MWD	SOC (g/kg)	LD (g/m^2)	RMD (kg/m^3)
			(%)							
SF	1.24 ± 0.01^{a}	65.21 ± 1.12^{a}	210.86 ± 0.82^{a}	12.93 ± 0.30^{a}	6.72 ± 1.03^{a}	20.87 ± 2.01^{a}	1.16 ± 0.22^{b}	7.31 ± 1.17^{a}	83.72 ± 5.20^{a}	0.39 ± 0.30^{a}
TP3	1.27 ± 0.04^{ab}	65.01 ± 1.46^{a}	21.72 ± 0.29^{a}	13.27 ± 0.57^{a}	7.16 ± 0.79^{ab}	23.23 ± 1.43^{b}	1.10 ± 0.24^{a}	10.61 ± 0.49^{b}	305.73 ± 19.63^{b}	0.95 ± 0.43^{b}
TP8	1.25 ± 0.03^{a}	65.18 ± 0.49^{a}	23.27 ± 0.33^{a}	11.55 ± 1.16^{a}	7.86 ± 1.43^{b}	26.71 ± 2.23^{c}	1.14 ± 0.17^{ab}	14.03 ± 0.75^{c}	378.08 ± 34.15^{c}	1.85 ± 0.56^{c}
TP17	1.29 ± 0.10^{bc}	66.40 ± 1.30^{a}	20.91 ± 0.87^{a}	12.69 ± 0.44^{a}	9.00 ± 1.59^{c}	27.41 ± 1.57^{c}	1.27 ± 0.14^{c}	17.66 ± 0.78^{d}	580.29 ± 28.85^{d}	4.70 ± 0.96^{d}
TP25	1.31 ± 0.02^{c}	64.19 ± 2.39^{a}	23.75 ± 0.29^{a}	12.06 ± 1.10^{a}	9.72 ± 2.11^{c}	30.60 ± 1.29^{d}	1.37 ± 0.21^{d}	20.71 ± 0.51^{e}	670.33 ± 21.93^{e}	6.81 ± 1.82^{e}
TP34	1.32 ± 0.03^{c}	64.74 ± 1.27^{a}	22.85 ± 0.51^{a}	12.41 ± 0.87^{a}	11.94 ± 1.68^{d}	38.91 ± 0.96^{e}	1.31 ± 0.09^{cd}	22.82 ± 0.24^{f}	600.34 ± 28.53^{d}	9.13 ± 2.59^{f}

SF – slope farmland; TP –tea plantation and the number is the tea planting age in years; BD – bulk density; Coh – soil cohesion; WSA – water stable aggregate; MWD – mean weight diameter; SOC – soil organic carbon; LD – litter density; RMD – root mass density; SD – standared deviation; different lowercase letters in a column indicate significant differences among the planting ages at $P < 0.05$

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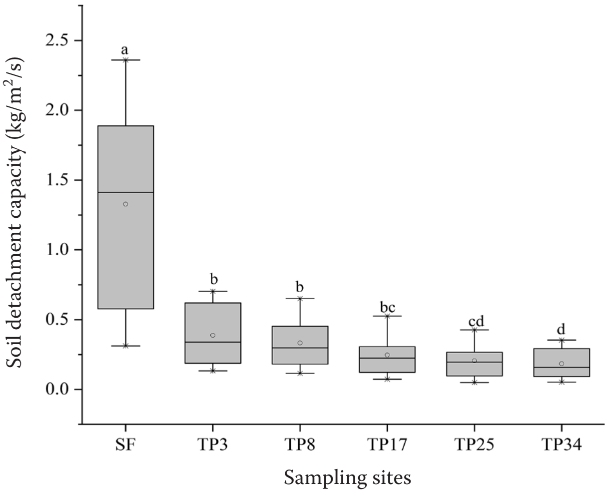

Figure 2. Soil detachment capacity of different tea plantations
SF – slope farmland, TP – tea plantation and the number is the age since tea cultivated; the same letter indicates differences are not significant at $P < 0.05$

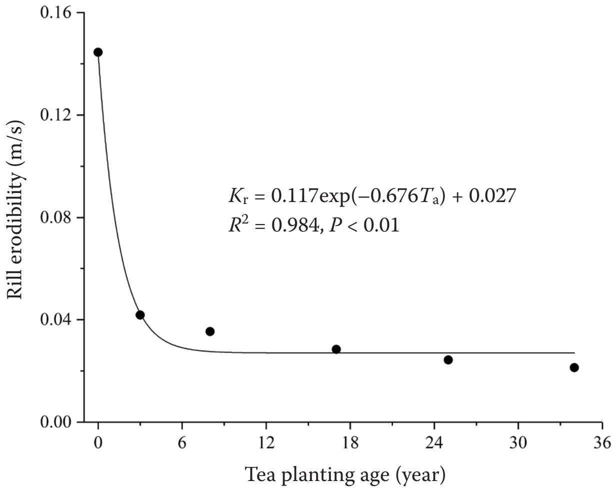

Figure 3. Variations in rill erodibility with tea planting age
K_r – rill erodibility; T_a – tea planting age

Soil erosion resistance parameters (K_r and τ_c) was derived by Equation (1) and shown in Table 2. Similar to D_c, K_r differed evidently as well among the six sampling sites. The maximum K_r was also observed in slope farmland (0.1445 s/m), which was 3.4 to 6.8 times of that in tea plantations (0.0213–0.0418 s/m). Compared to the control, K_r of tea plantations reduced by 71.1% to 85.3%. Regression analysis displayed an exponential decline in K_r with T_a (Figure 3):

$$K_r = 0.117\exp(-0.676T_a) + 0.027; \quad R^2 = 0.984; P < 0.01 \tag{7}$$

The fitted τ_c in slope farmland was 2.866 Pa, while τ_c in tea plantations varied from 2.644 to 3.597 Pa (Table 2). A positively exponential relationship between τ_c and T_a was detected by regression analysis (Figure 4):

$$\tau_c = 2.758\exp(0.007T_a); R^2 = 0.665, P < 0.01 \tag{8}$$

Table 2. Rill erodibility (K_r) and critical shear stress (τ_c) for each sampling site

Site	Regression equation	K_r (s/m)	τ_c (Pa)	R^2
SF	$D_c = 0.1445\tau - 0.4141$	0.1445	2.866	0.997
TP3	$D_c = 0.0418\tau - 0.1166$	0.0418	2.789	0.951
TP8	$D_c = 0.0354\tau - 0.0936$	0.0354	2.644	0.939
TP17	$D_c = 0.0284\tau - 0.0955$	0.0284	3.363	0.904
TP25	$D_c = 0.0243\tau - 0.0874$	0.0243	3.597	0.944
TP34	$D_c = 0.0213\tau - 0.0719$	0.0213	3.376	0.948

D_c – soil detachment capacity; τ – flow shear stress

Factors affecting soil erosion resistance. Table 3 showed the correlations between soil erosion resistance (K_r and τ_c) and near-surface characteristics. No prominent correlations were detected between K_r and BD, soil texture (sand, silt and clay), and MWD. K_r was in negative associations with WSA, Coh, LD, RMD, and SOC ($P < 0.01$). τ_c was significantly correlated with BD, MWD, Coh, LD, RMD, and SOC ($P<0.01$). Regression analysis indicated that K_r decreased significantly with WSA, Coh, LD, RMD, and SOC as power functions; τ_c increased logarithmically with Coh, exponentially with LD, RMD, and SOC, while with BD as a power function (Figure 5–10).

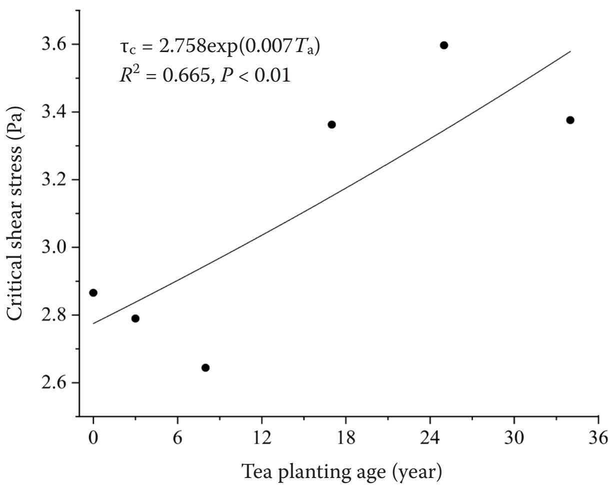

Figure 4. Variations in critical shear stress with tea planting age
τ_c – soil critical shear stress; T_a – tea planting age

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Table 3. Pearson coefficients between soil erosion resistance (K_r and τ_c) and near-surface characteristics

Items	BD	Sand	Silt	Clay	WSA	MWD	Coh	LD	RMD	SOC
K_r	–0.308	0.372	–0.378	–0.477	–0.656**	–0.435	–0.631**	–0.861**	–0.626**	–0.781**
τ_c	0.876**	–0.478	0.505	0.492	0.641**	0.964**	0.750**	0.810**	0.848**	0.802**

BD – bulk density; Coh – soil cohesion; WSA – water stable aggregate; MWD – mean weight diameter; SOC – soil organic carbon; LD – litter density; RMD – root mass density

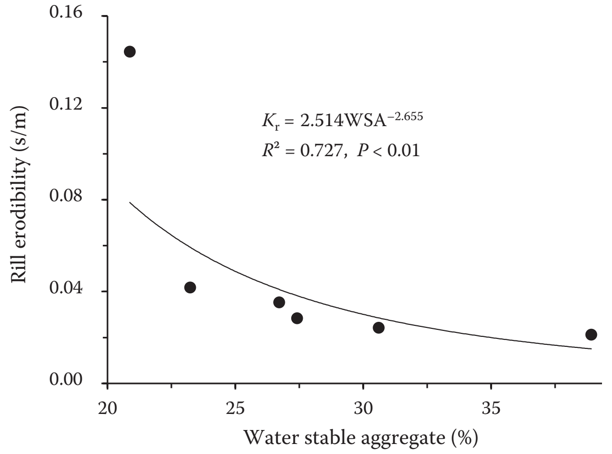

Figure 5. Fitting function between rill erodibility (K_r) and water stable aggregate (WSA)

DISCUSSION

Effect of tea cultivation on near-surface characteristics. Bulk density (BD) is strongly associated with soil hydraulic properties and penetration resistance (Wang et al. 2018b, 2022). Soil cohesion (Coh) is also another variable commonly representing soil erosion resistance (Moragoda et al. 2022). Generally, Coh increases with the increase of BD and the soil gets much harder to be detached by the external erosive force (Wang et al. 2022). In this study, both BD and Coh in tea plantations increased with the cultivation age and then gradually levelled off after 17 years. Compared with the control, BD and Coh of tea plantations averagely increased by 3.8% and 36.0%. Our result is inconsistent with Wang et al. (2018c), who found a gradual decline in BD with natural recovery age for abandoned farmlands. This may be connected with the difference of vegetation restoration strategies (artificial planting or natural succession) or land-use conversion modes (Wang et al. 2014, 2019a).

Aggregates are the elementary unit of soil structure and serve as the assemblages of organic and mineral particles (Wang et al. 2019c, 2020c). Aggregate stability is also another variable used to define soil erosion resistance (Moragoda et al. 2022). Both WSA and MWD increased significantly with tea planting age in this study, which accords with many existing findings (Wang et al. 2016, 2020c). This result implied that rill erodibility reduced with tea planting age as the result of the promoted ability of soil resisting overland flow and disaggregating aggregate.

Soil organic carbon (SOC) had strong impact on soil erodibility or soil erosion resistance, mostly owning

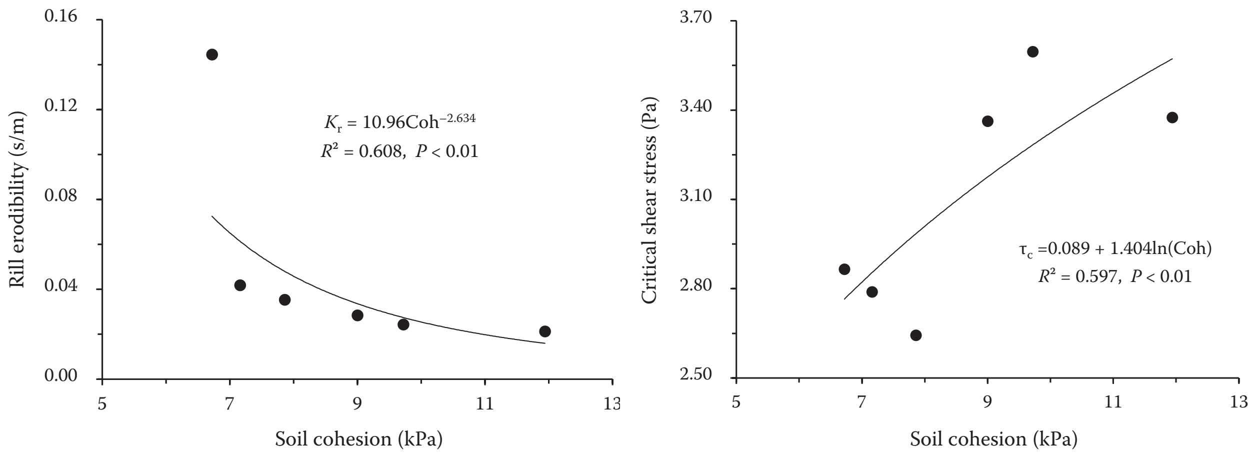

Figure 6. Fitting functions between soil erosion resistance and soil cohesion
K_r – rill erodibility; τ_c – soil critical shear stress; Coh – soil cohesion

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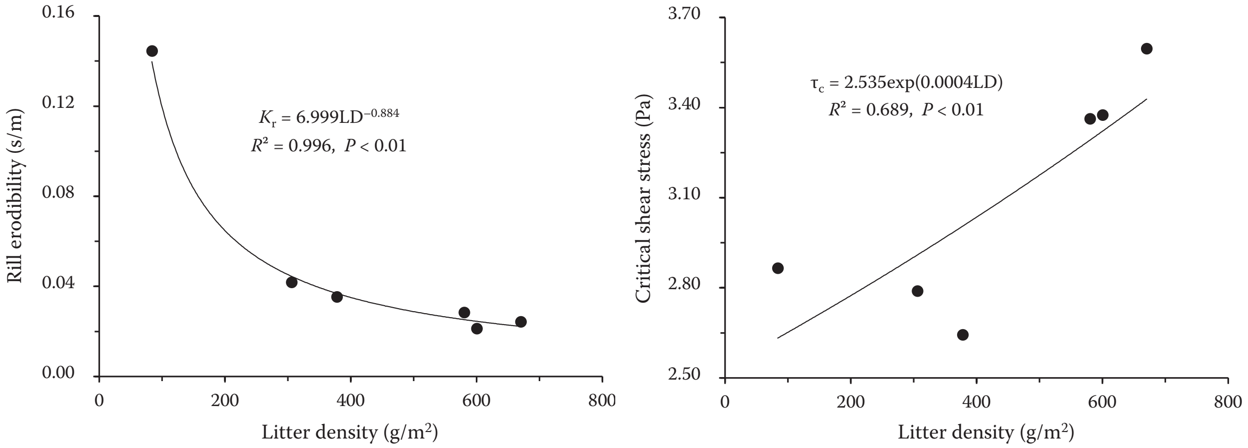

Figure 7. Fitting functions between soil erosion resistance and litter density
K_r – rill erodibility; τ_c – soil critical shear stress; LD – litter density

to its benefit to soil infiltration and structure stability (Wang et al. 2019b). In our study, SOC increased with tea planting age, which agreed with Wang et al. (2018b, 2019c, 2020c) who found a gradual increase in SOC with tea planting age in the hilly area of western Sichuan and southern Guangxi, China.

Plant litter had an important effect on soil properties, hence may well potentially effects on soil's resistance to erosion (Sun et al. 2016; Liu et al. 2020). LD in slope farmland was 83.72 g/m^2 (Table 1) and in tea plantations cultivated for 3 to 34 years increased significantly by 2.6 to 7.0 times. Tea plantation cultivated for 25 years had the highest LD but the differences between those cultivated for 17 and 34 years were non-significant ($P > 0.05$). Though litter distribution on soil surface was very extensive in tea plantations, their impacts on soil erodibility/soil erosion resistance during tea cultivation were seldom concerned.

RMD is usually used to quantitatively interpret the linkages between soil erosion and root traits. RMD of slope farmland was 0.39 kg/m^3, and that of tea plantations increased continuously with cultivation age, varying between 0.95 and 9.13 kg/m^3 (Table 1). The difference in RMD may be connected with the land uses and tillage practices, plant community type, root architecture, and growth stage (Vannoppen et al. 2017; Yao et al. 2022).

Relationship between soil erosion resistance and near-surface characteristics. Soil detachment occurs at the water-soil interface; hence soil properties tremendously affect soil erosion resistance. K_r decreased with progressive tea planting age

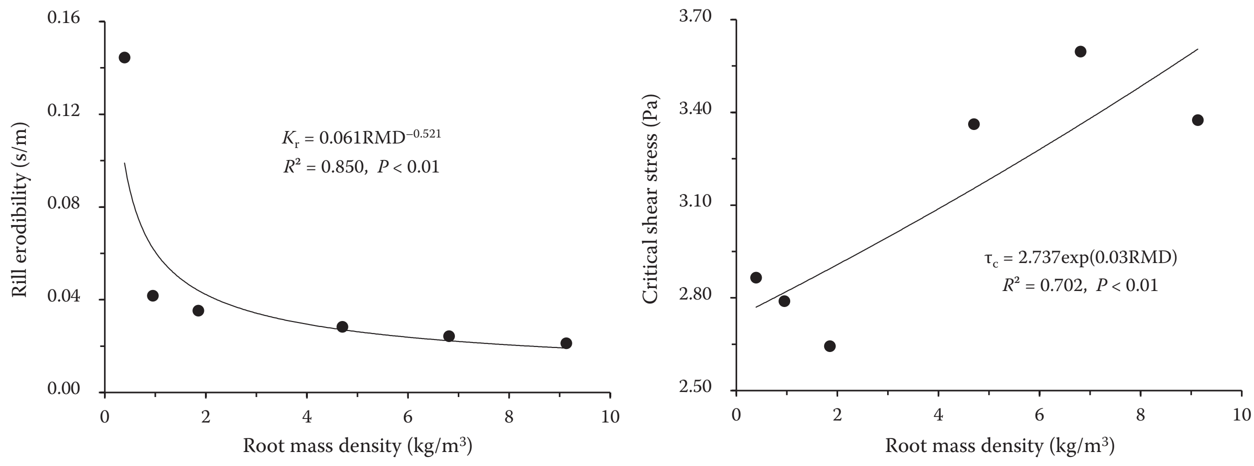

Figure 8. Fitting functions between soil erosion resistance and root mass density
K_r – rill erodibility; τ_c – soil critical shear stress; RMD – root mass density

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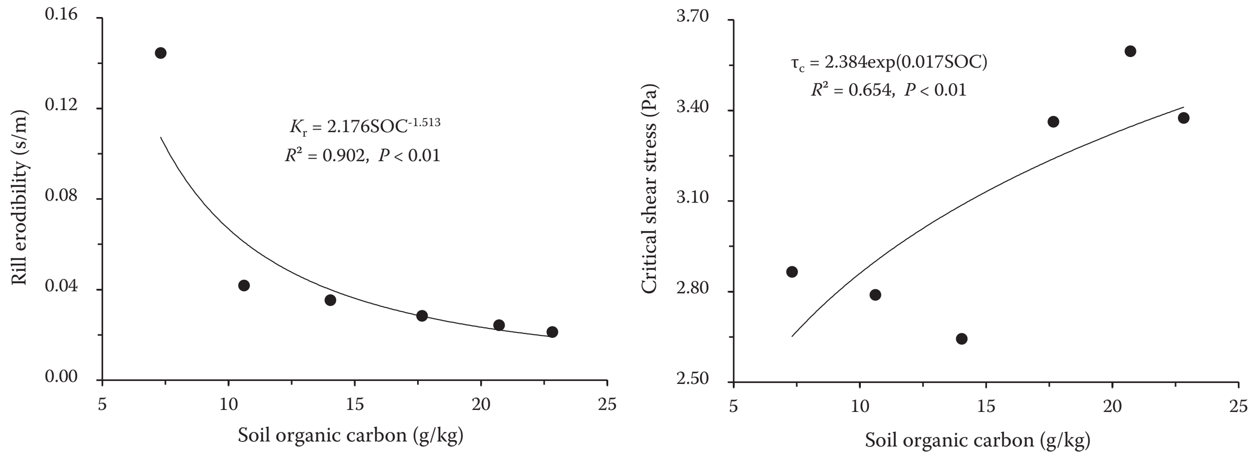

Figure 9. Fitting functions between soil erosion resistance and soil organic carbon
K_r – rill erodibility; τ_c – soil critical shear stress; SOC – soil organic carbon

in this study (Figure 3), whereas the τ_c presented a opposite trend (Figure 4). These variations were aroused to a large extent by the dynamic changes of near-surface characteristics, e.g., soil properties, plant litter and roots in topsoil layer. Soil texture is one of the most fundamental properties affecting soil erosion resistance (Hao et al. 2021). However, no obvious relationships were identified between them in this study (Table 3), probably due to the non-significant differences in soil particle compositions among the test sites. Though research showed that the temporal variation in K_r was connected with the seasonal variation in BD (Knapen et al. 2007b), no pronounced correlation was identified between them in this study; while τ_c was found increasing with BD as a power function (Figure 10).

In this study, both K_r and τ_c were clearly related to Coh (Table 3), and a positively power function and negatively logarithmic function with Coh were fitted, respectively (Figure 6). Though K_r was found to be notably related to WSA (Table 3), no significant relation was obtained between τ_c and WSA, while it increased exponentially with MWD (Figure 9). Furthermore, Pearson correlation analysis also found that K_r and τ_c were negatively and positively linked to SOC, LD, and RMD, respectively (Table 3). Regression analysis indicated that K_r decreased with SOC, LD, and RMD as power functions (P < 0.01), and τ_c increased with these three indicators as exponential functions (Figure 7–9).

As discussed above, soil conditions improved with long-term tea cultivation due to the accumulation

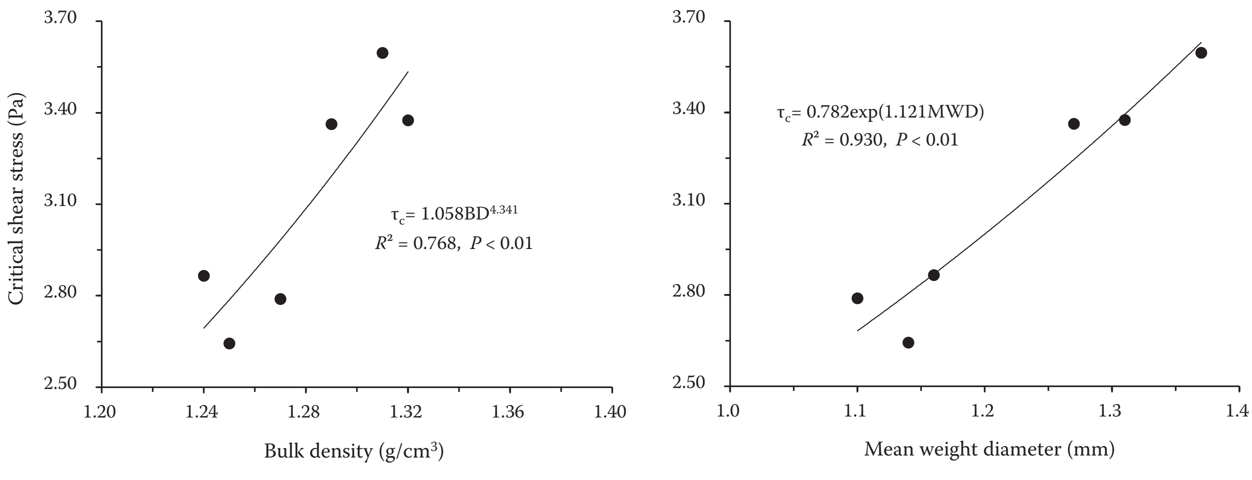

Figure 10. Fitting functions between critical shear stress and bulk density as well as mean weight diameter
τ_c – soil critical shear stress; BD – bulk density; MWD – mean weight diameter

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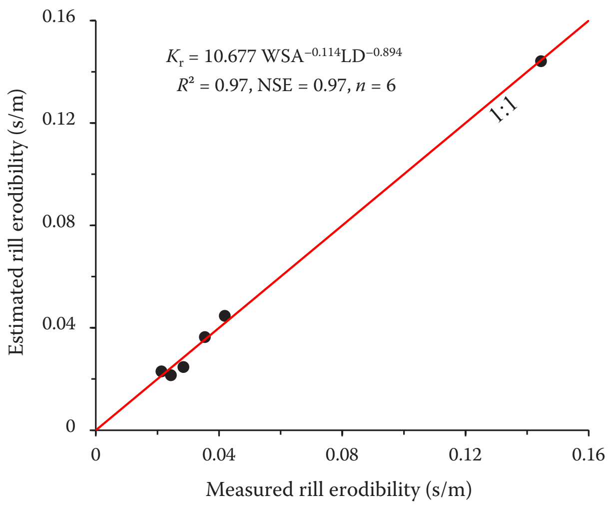

Figure 11. Comparison between the measured and estimated rill erodibility

K_r – rill erodibility; WSA – water stable aggregate; LD – litter density; NSE – Nash-Sutcliffe efficiency

of aboveground litter on soil surface and the development of belowground roots. Consequently, soil was difficult to be detached and K_r declined (Wang et al. 2018b, 2020a, 2021, 2022). These results concurred with research on the Chinese Loess Plateau that K_r decreased and τ_c increased appreciably with WSA, Coh, LD, and RMD (Zhang et al. 2019a, b; Wang et al. 2020a).

Soil erosion resistance estimation. Soil erosion resistance is calibrated by relating D_c to flow shear stress, and cannot be directly measured in the field. Therefore, it is quite necessary to estimate soil erosion resistance using some measurable or available candidate indicators of soil properties and near-surface characteristics. In this study, nonlinear regression revealed that K_r could be simulated by WSA and LD as a power function (Equation (9)); and τ_c could be simulated by MWD and RMD as an exponential function (Equation (10)).

$$K_r = 10.677\mathrm{WSA}^{-0.114}\mathrm{LD}^{-0.894};\quad R^2=0.97,\ \mathrm{NSE} = 0.97,\ P < 0.01 \tag{9}$$

$$\tau_c = 0.696\exp(1.202\mathrm{MWD} + 0.002\mathrm{RMD});\quad R^2 = 0.89,\ \mathrm{NSE} = 0.89,\ P < 0.01 \tag{10}$$

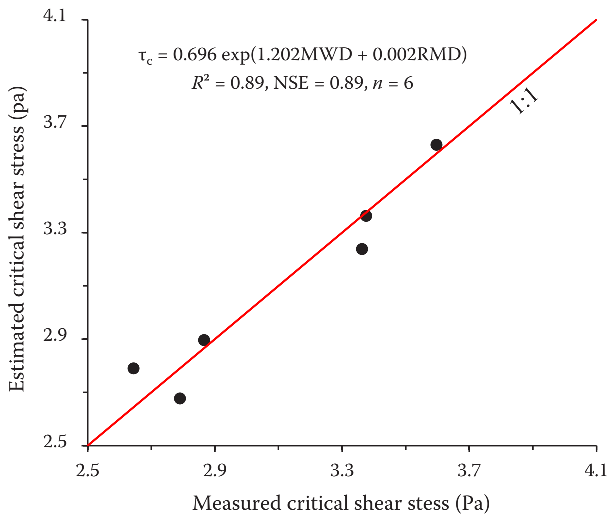

Figure 12. Comparison between the measured and estimated critical shear stress

τ_c – soil critical shear stress; MWD – mean weight diameter; RMD – root mass density; NSE – Nash-Sutcliffe efficiency

As can be seen from Figure 11, the estimated and measured K_r fitted well. The performance of Eq. (9) was very satisfactory, with both R^2 and Nash-Sutcliffe efficiency (NSE) being 0.97. Whereas, the simulated τ_c by Equation (10) did not nicely match the measured ones, with discrete points appearing though totally 6 data points were included (Figure 12). Theoretically, the variation trend of K_r and τ_c with soil properties should be opposite. For example, when the soil changes from clay texture to sandy texture, K_r increases while τ_c decreases, and vice versa. However, this ideal situation has rarely been reported in literature. In general, K_r reflects the soil erosion resistance much better and is more closely associated with soil properties, while the change of τ_c is much uncertain (Knapen et al. 2007b). Future research is still required to verify or optimize the obtained models for soil erosion resistance estimation.

CONCLUSION

The study quantified the effects of tea planting age on soil erosion resistance (reflected by K_r and τ_c) in TGRA of China. The results demonstrated that BD, Coh, WSA, MWD, SOC, LD, and RMD increased significantly with tea planting age, while long-term tea cultivation did not cause remarkable variations in soil particle composition. Compared to the control, BD, Coh, WSA, MWD increased by 3.8%, 36.0%, 40.7%, 6.7%, and SOC, LD, RMD were 2.3, 6.0, 12.0 times greater for tea plantations. Both D_c and K_r gradually declined with the progress of tea planting age and relatively levelled off after 17 years. Mean D_c and K_r of tea plantations reduced by 70.8%–86.1% and 71.1%–85.3% than those of the farmland, respectively. D_c and K_r decreased exponentially, whereas τ_c in-

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creased exponentially with the tea planting age. The temporal variations in soil erosion resistance were connected with the variations in most near-surface characteristics. K_r decreased with WSA, Coh, LD, RMD, and SOC following a power function. τ_c increased with MWD, LD, RMD, and SOC following an exponential function, while with Coh a logarithmic function and with BD a power function. K_r could be simulated by WSA and LD with a power function, and τ_c could be simulated by MWD and RMD with an exponential function. Our findings would shed more light on soil conservation and ecological function maintenance in the tea plantation ecosystems.

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