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Throughfall kinetic energy and its spatial characteristics under rubber-based agroforestry systems

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ABSTRACT

Rubber is usually grown as a monoculture but there have been recent attempts to encourage rubber-based agroforestry systems to reduce adverse environmental impacts, including the reduction of soil erosion in Xishuangbanna, SW China. To estimate the influence of different types of rubber-based agroforestry systems on soil erosion processes, we measured the throughfall kinetic energy (TKE) under different vegetation types by using 640 sand-filled Tübingen splash cups. This study was conducted in Xishuangbanna Tropical Botanical Gardens under natural rainfall conditions. Our results indicated that in both rubber-based agroforestry systems and rubber monocultures, a significant linear positive correlation exists between TKE and rainfall amount. Rainfall amount is a critical factor that contributes to soil detachment in rubber plantations in this region. TKE under rubber plantation conditions was found to be notably higher than under open field conditions (ranging from 1.84 to 2.32 times greater). However, there was no significant difference under multiple canopies compared to monoculture. TKE values under the different rubber-based agroforestry systems were closely related to the canopy structure, and TKE and leaf area index were significantly negatively correlated. The spatial variability of TKE was higher in rubber-based agroforestry systems than in rubber monocultures. In addition, TKE was usually concentrated in 3–4 m bands that did not have the protection of a sub-canopy. The fact that the erosion by TKE under rubber-based agroforestry was still high highlights the importance of selecting intercrops when constructing rubber-based agroforestry systems and of improving planting patterns.

1. Introduction

Due to economic demands, rubber monoculture plantations have undergone substantial expansion and have replaced primary tropical forest in Xishuangbanna, SW China. It is commonly recognized that the change in vegetation to rubber monoculture may result in significant soil erosion (Liu et al., 2015, 2011) and a loss of soil organic matter (Li et al., 2012), posing a major threat to regional water quality (Zhou et al., 2014). Therefore, there is clearly a need to identify the key mechanisms or factors that contribute to soil erosion in rubber plantation forests.

In forests, throughfall kinetic energy (TKE) is a widely used indicator to express the potential of rainfall erosivity and predict soil erosion rates (Goebes et al., 2015a, 2015b; Morgan, 2009; Zhou et al., 2002). Many studies have confirmed that monoculture plantations significantly increased TKE and accelerated soil erosion (Mosley, 1982; Nanko et al., 2008; Zhou et al., 2002). Therefore, TKE might be one of the best indices of the impacts of rubber plantation forests on soil erosion. On the other hand, the rainfall erosivity factor (R), in terms of the widely used methodology for soil loss estimation USLE/RUSLE (Renard et al., 1997; Wischmeier and Smith, 1978), is defined as a product of the rainfall kinetic energy (KE) and the maximum 30-min rainfall intensity (I_{30}). Direct measurements of rainfall kinetic energy are very rare (Mikoš et al., 2006); therefore, an alternative approach is to estimate kinetic energy from widely available rainfall intensity (I) data by implementing empirical kinetic energy-rainfall intensity relationships. Although, this relationship has been used in many locations with different climate conditions, it should be justified prior its implementation in a climatically different environment, such as the rubber plantations in Xishuangbanna.

In recent years, the Xishuangbanna local government has proposed building rubber-based agroforestry systems that aim to reduce water and soil losses. With the different canopy layers, they could increase rainfall interception and reduce TKE (Feng, 2007). In particular, TKE is mainly influenced by forest crown architecture and tree species richness (Geißler et al., 2012, 2010; Goebes et al., 2015a; Hall and Calder, 1993;

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Nanko et al., 2006; Seitz et al., 2015; Wainwright et al., 1999; Wakiyama et al., 2010). Crown cover, plant morphology (Xu et al., 2009), leaf area index (Park and Cameron, 2008) and branch traits (Nanko et al., 2008) are all thought to influence TKE in various ways. In Japan, Nanko et al. (2008, 2011) conducted numerous experiments and observed that decreasing the canopy thickness resulted in increased TKE. Geißler et al. (2010, 2012, 2013) also emphasized the importance of shrubs and herbs in forest ecosystems as protection against soil erosion. Therefore, whether the rubber-based agroforestry system is effective in reducing TKE and soil erosion needs to be studied, but thus far, relatively few studies have investigated this topic (Liu et al., 2016; Zhu et al., 2014).

In addition, compared with the spatial variability of throughfall, TKE has also been demonstrated to have spatial variability (Goebes et al., 2015b; Nanko et al., 2011). TKE variability has important implications for sampling strategies and has important effects on soil physical properties such as bulk density, soil aggregates size, crust thickness and infiltration rate (Cerdà, 2000; Vaezi et al., 2017). Therefore, research on TKE and its spatial variability is a key factor in understanding the hydrological, hydrosedimentological and ecological cycles (Ramon et al., 2017). However, the spatial variability of TKE has rarely been studied. Nanko et al. (2011) showed a distance-to-stem effect, where TKE below a single Japanese cypress (*Chamaecyparis obtusa*) increased as the distance to the stem increased. Goebes et al. (2015b) examined the spatial variability of TKE in mixed-species forest stands and found that TKE showed distinct spatial variability, influenced primarily by neighbourhood tree species richness. By studying the spatial variability of TKE in the rubber-based agroforestry systems, we can analyse the spatial characteristics of splashing in the forest. Such knowledge would provide a reference for the construction of rubber-based agroforestry systems.

In this study, we focused on TKE under different types of rubber-based agroforestry systems and rubber monoculture. Specifically, we investigated (1) how rainfall characteristics and canopy architecture affect TKE and (2) what are the spatial variability features of TKE.

2. Materials and methods

2.1. Study area

The study site was located in the Xishuangbanna Tropical Botanical Gardens (XTBG, 21°55′39″ N, 101°15′55″ E), Yunnan Province, SW China. Observations were conducted in a small catchment (19.3 ha) that consisted of rubber monoculture and different types of rubber-based agroforestry systems. The elevation of the small catchment ranged from 550 m to 680 m with an average slope of 15°. The local climate is dominated by tropical southern monsoons from the Indian Ocean between May and October and by subtropical jet streams between November and April (Zhang, 1988). Therefore, the two apparent seasons in this area are the rainy season (May to October) and the dry season (November to April). Climate records over the past 40 years showed that the mean annual air temperature was 21.7 °C and that the mean annual rainfall was 1487 mm. Most of the precipitation (87%) occurred between May and October, with very little precipitation (13%) occurring between November and April (Fig. 1) (Liu et al., 2015).

Rubber trees in this catchment were intercropped in the following four planting patterns: rubber (*H. brasiliensis*) monoculture (R), rubber-cocoa (*T. cacao*) agroforestry system (RC), rubber-*F. macrophylla* agroforestry system (RF), and rubber-tea (*C. sinensis*)-orange (*C. reticulata*) agroforestry system (RTO). We selected these four planting patterns to conduct the field experiments and an area without trees to measure rainfall kinetic energy for comparison. In the rubber plantation, rubber trees were planted in a traditional spatial arrangement: double rows spaced 2 m apart on level bench terraces. Within the rows, the trees were spaced 4 m apart, and each set of double rows was separated by a 12 m-wide gap. The intercrops were planted in the 12 m-wide gaps, and there was no understory vegetation in the rubber monoculture (Fig. 2d).

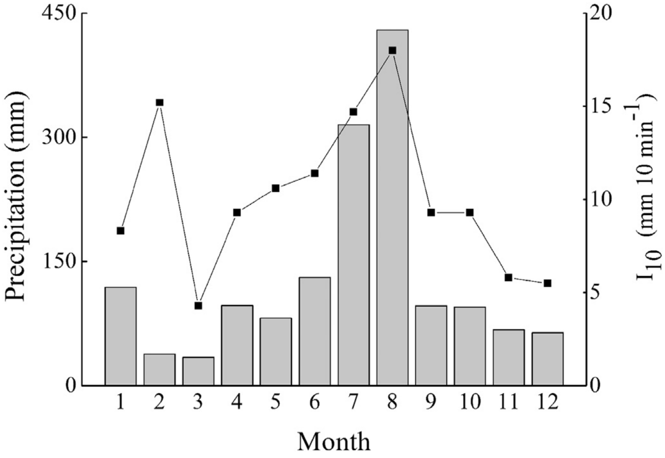

Fig. 1. Monthly precipitation distribution (grey bar) and monthly maximum 10 min rainfall intensity (I_{10}, black square) during 2015.

In RF, the *F. macrophylla* was planted in seven rows, each spaced 1 m apart and with 0.7 m between the plants in each row (Fig. 2a). In RC, the cocoa trees were planted in four rows, each spaced 3 m apart and with 1.5 m between the plants in each row (Fig. 2b). In RTO, the intercropping system was planted with two species: the tea trees were planted in two rows, and the orange trees were planted in one row between tea trees, each spaced 2 m apart and with 0.5 m between the tea trees plants in each row. The spacing between the orange and tea trees was 4 m, with 2 m between orange trees (Fig. 2c). The planting strategies of the intercrops were designed based on prior planting experience and on the suitability of the terrain for the growth of the intercrops (Feng, 2007). The crown heights of the rubber trees ranged between 11 and 18 m above the ground. The mean diameters of the rubber trees at breasted height in the RF, RC, RTO and R systems were 32.47 ± 5.23 cm, 30.77 ± 5.81 cm, 24.89 ± 4.18 cm, and 22.56 ± 3.33 cm (mean ± SD), respectively. The distance between the rubber monoculture and the three rubber-based agroforestry systems was approximately 500 m; consequently, there was no significant difference in rainfall characteristics or geological properties.

2.2. Experimental design

A total of four plots were used for TKE measurements during the rainy season in 2015: one in the rubber monoculture, and the other three in the various rubber-based agroforestry systems. The plots were sampled in the inter-rows. Each plot's area was 108 m^2, which was divided into nine sections (3 m × 4 m grids). In the nine sections, each corner was located at a specified TKE measurement, and rain gauges were placed in the centre of each section (Fig. 2). Each plot included sixteen TKE measurement positions and nine rain gauges. The splash cup positions remained constant during the experiment. To collect reference measurements under open field conditions, a set of five splash cups was positioned in a pentagonal shape at equal distances of 60 cm from the rain gauge. The 60-cm distance was sufficient to avoid interference between the splash cups (Geißler et al., 2012). All the splash cups were firmly attached to steel stakes inserted vertically into the ground, and their rims were level with the ground surface. After each sampling rainfall event, all cups were replaced.

TKE was measured using Tübingen splash cups (4.6 cm in diameter) designed by Scholten et al. (2011). In general, splash cups allow a high number of replications at low cost and are easy to handle in the field. Previous experiments indicated that TKE can be easily and accurately estimated in the field using this type of sand-filled splash cup (Geißler et al., 2012). The splash cups used in our investigation consisted of a