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Spatial distribution of LAI and its relationship with throughfall kinetic energy of common tree species in a Chinese subtropical forest plantation

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ABSTRACT

The hilly red soil region in southern China is still facing serious soil erosion, even after long-term afforestation projects. This might result from structural shortcomings of the tree species chosen for afforestation. Within the Biodiversity and Ecosystem Functioning China project (BEF China), we used point cloud data from terrestrial laser scanners (TLS) and splash cups to analyze spatial leaf area index (LAI) and to predict the potential of splash erosion in subtropical forests. High LAI of *Lithocarpus glaber* and *Schima superba* was measured mainly at the middle and lower parts of the trees while for *Sapindus saponaria* it was found at the upper parts. LAI was decreasing from the tree stems to the edges of the canopy. Lognormal and exponential linear models were suitable to describe the vertical and horizontal LAI distribution of selected tree species, respectively. *Sapindus saponaria* generally had the highest values of throughfall kinetic energy (TKE) among the analyzed tree species and measured rainfall events. In the radial direction, higher LAI tended to produce lower TKE, whereas in the vertical direction, higher skewness of LAI distribution had higher TKE. LAI and its spatial distribution both were important for TKE. These findings can help to understand mechanisms of splash erosion in forest plantations related to unsuitable spatial LAI of tree species planted. It might further improve our knowledge how tree diversity may influence splash erosion by enriching the canopy layers in an early successional stage of subtropical forest plantations.

1. Introduction

Soil erosion is a serious environmental hazard of global scale (Lal, 2003) and vegetation cover of the soil surface is one key factor in controlling soil erosion (Stednick, 1996; Cao et al., 2008; Shi et al., 2009; Chen et al., 2011; Filoso et al., 2017; Feng et al., 2018). Forest vegetation cover affects splash erosion at the soil surface by intercepting rainfall and thus modifying rain patters, such as adapted drop size and speed, changing rainfall amount and spatial distribution (Nanko et al., 2006; Geißler et al., 2012b, 2013, 2015b). It is generally accepted that soil erosion is reduced under forests (Smith, 1914). However, research showed that high sediment delivery often occurred in forested catchments in subtropical regions (Marks, 1998; Molnar, 2004; Zhao, 2006). One reason is that effects of forest cover on splash erosion are dynamic in space as the structures of tree species differ. Hence, calculating an index that describes the ability of cover plants, especially trees, is essential to analyze the splash erosion risk under forest and can help to better understand the relationship between cover plants and splash erosion. Such an index can also serve in planning and management of afforestation as part of soil and water conservation approaches, e.g. in the hilly red soil region in southern China.

One well established index that describes the plant cover is the leaf area index (LAI, (Jordan, 1969)). It is defined as projected leaf area per unit ground area (Gower and Norman, 1991). As an important biophysical parameter, LAI is often used in quantitative analyses of processes related to vegetation dynamics such as rainfall interception (Maass et al., 1995), soil erosion modeling (Laflen et al., 1997; Zhou et al., 2008; Zhang et al., 2014), land surface process models (Chen et al., 2011; Tesemma et al., 2015) and global climate change (Claverie et al., 2016). In the subtropical part of China, studies showed that LAI has a significant effect on throughfall kinetic energy (TKE) in secondary forest (Geißler et al., 2012a), soil loss in 30-year afforestation (Sun et al., 2010; Zhang et al., 2011) and sediment discharge and TKE in young afforestation (Goebes et al., 2015a; Seitz et al., 2016). Further vegetation factors that are correlated with TKE in forests are crown cover, leaf traits, tree height and branch architecture (Cao et al., 2008;

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Geißler et al., 2010, 2012b; Goebes et al., 2015a, 2015b). Another important aspect is, that the process of free raindrops passing the tree canopies is dynamic (Nanko et al., 2006) and the canopy architecture can change the drop size and spatial distribution significantly at different positions and height of the tree canopy (Nanko et al., 2006; Goebes et al., 2015b). Hence, the relationship between general LAI values and splash erosion is questionable since it neglects the effects of spatial distributions of LAI. Also, most studies concentrate on mature forests (Cao et al., 2008; Geißler et al., 2013). Regarding afforestation measures on heavily eroded soils with a low structure stability and without shrubs or litter cover, like in the hilly red soil region in southern China (Zhao, 2006; Shi et al., 2009), the role of forests in their early stage of tree growth to protect the soil from erosion is of ample interest. Such research is still scarce.

Generally, there are several methods to estimate LAI, such as determination from satellite images (Knyazikhin et al., 1998; Deng et al., 2006; Xiao et al., 2014), instrumental measurements (Fassnacht et al., 1994; Chen et al., 1997; Gower et al., 1999), and direct acquisition from destructive measures (Gower et al., 1999; Nanko et al., 2006). As high-resolution, non-destructive and efficient tool, terrestrial laser scanners (TLS) are increasingly applied in forest inventory for reliable three-dimensional (3D) data acquisition and comparison (Clawges et al., 2007; Maas et al., 2008; Fleck et al., 2011; Lovell et al., 2011), especially for indexes of difficult acquisition using traditional methods (Moorthy et al., 2011; Li et al., 2014b). In addition, TLS is a useful tool for the retrieval of LAI (Hosoi and Omasa, 2006; Moorthy et al., 2008; Zheng and Moskal, 2012). Using TLS to measure LAI also allows to precisely calculate the radial and vertical distribution of LAI for individual trees over the whole crown area.

The objectives of this study were (1) to assess the differences in the spatial distribution of LAI among different common tree species and along the tree stem and height of single species and (2) to explore the relationship between spatial distribution of LAI and TKE for different rainfall events.

2. Materials and methods

2.1. Study area

The field experiment was conducted in the context of the joint Sino–German–Swiss Research Unit "BEF China" (BEF, biodiversity and ecosystem functioning) (Bruelheide et al., 2011). The BEF China project is located in Xingangshan Town, Dexing City, Jiangxi Province, PR China (29.08°–29.11° N, 117.90°–117.93° E). The climate of the area is dominated by subtropical monsoon, with mean annual temperature of 17.4 °C and mean annual precipitation of 1821 mm (Yang et al., 2013). The subtropical summer monsoon starts from May to July (Goebes et al., 2015a; Seitz et al., 2016). The area is hilly with mean elevations of 189 m a.s.l. (site A) and 137 m a.s.l. (site B) (Scholten et al., 2017). Soils in the region are mainly Cambisols, Acrisols and Ferralsols (Scholten et al., 2017). The BEF China project is a forest experiment on approximately 50 ha and includes two parallel sites, A and B, planted in 2009 and 2010, respectively. These two sites were established by transplanting seedlings of 40 local trees and shrubs after logging of the original secondary forest (Bruelheide et al., 2014).

2.2. Sample selection and data collection

2.2.1. Tree parameters retrieval

In this study, three subtropical tree species were selected, including evergreen broadleaved species (*Lithocarpus glaber* and *Schima superba*) and a deciduous broadleaved species (*Sapindus saponaria)*. These three species are recommended species for afforestation projects regarding water and soil conservation in the subtropical region of China (China, 2013). For each tree species, three tree individuals were randomly selected. LAI measurements were carried out in October 2013 and point cloud data for each tree was obtained using a Terrestrial Laser Scanner (RIEGL VZ-400, Horn, Austria). For each tree, 3–5 measurement positions were set at different directions with a horizontal distance ranging from 1.5 to 8 m. The view zenith angle from the center of the scanner to the canopy was set to 60°. Before the measurement, high reflectance sheets were stuck on pegs around the trees at various distances, heights and directions, to guarantee that more than 6 common sheets were scanned for each two adjacent stations, which provided reference points to convert all data in the same coordinate. The scanning angle resolution of the TLS was 0.01°and measurement rate was 122,000 points s^{-1}.

2.2.2. TKE measurements

TKE was measured using Tübingen Splash Cups (T-Cup, (Scholten et al., 2011)). The cup has a diameter of 4.6 cm and a height of 4 cm (Scholten et al., 2011). It is filled with uniform fine sand (0.125 mm). The detached sand is calculated by the weight difference between the dry sand in the filled up splash cup before measurements and the dry sand inside the cup after the rainfall event. Then kinetic energy of rainfall (KE_{rf}) is calculated by the detached sand (*ds*) per splash cup (*sc*) using the equation (Eq. (1)) below with a modified slope and standardization to 1 m^2 (Goebes et al., 2015b).

$$KE_{rf}\,(\mathrm{Jm^{-2}}) = ds_{sc}\,(\mathrm{g}) \times 0.1455 \times \{1000(\mathrm{cm}^2)/\pi r_{sc}^2\} \quad (1)$$

Its application was approved in field studies in subtropical China (Geißler et al., 2012a, 2012b; Goebes et al., 2015b). Five monoculture plots of *Lithocarpus glaber* (1 plot), *Schima superba* (2 plots) and *Sapindus saponaria* (2 plots) were selected to install splash cups under different tree individuals using the design of (Goebes et al., 2015b). The cup positions were 15 cm, 30 cm, 45 cm, 60 cm, 75 cm, and 95 cm from the stem respectively (Fig. 1, six splash cups per plot). Five rainfall events from May to July in 2013 were measured (Table 1). In total, data from 150 splash cups were collected.

2.3. Data analysis

LAI was estimated using a volume element model from the point cloud data (Hosoi and Omasa, 2006; Zheng and Moskal, 2012) and was

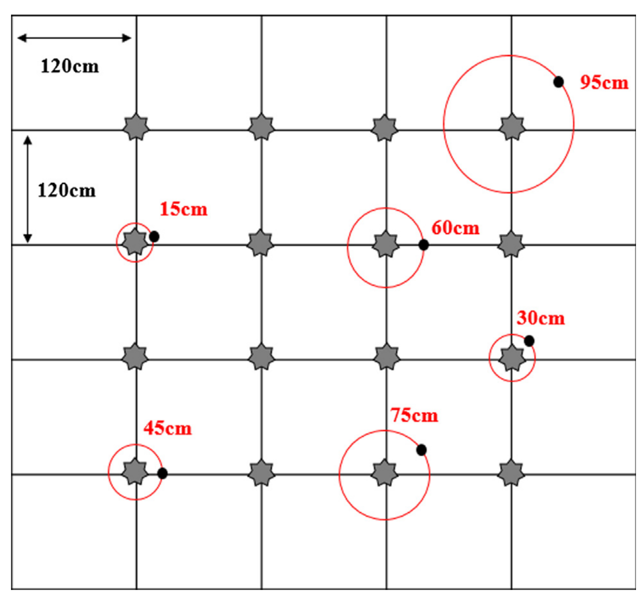

Fig. 1. Splash cup measurement design with six positions according to Goebes et al. (2015b). Gray stars, black dots and red circle lines represent tree individuals, splash cup position and radius around tree stems, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)