Mechanisms of Soil Erosion in Subtropical Forests of China - Effects of Biodiversity, Species identity, Tree architecture and Spatial variability on Erosivity

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Philipp Goebes

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1. Berichterstatter	Prof. Dr. Thomas Scholten
2. Berichterstatter	Prof. Dr. Johannes Ries
3. Berichterstatter	*Prof. Dr. Wim Cornelis*

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List of Abbreviations

AIC	Akaike Information Criterion
CART	classification and regression tree
CBH	crown base height
GD	ground diameter
KE	kinetic energy
LA	leaf area
LAI	leaf area index
M	momentum
NILEx	New Integrated Litter Experiment
PE	polyethylene
RF	Random Forest
ROP	runoff plot
SLA	specific leaf area
TKE	throughfall kinetic energy

1 Summary

Soil erosion is a major threat to ecosystems and agricultural land worldwide. To overcome severe soil loss, afforestation is used as a common tool. However, the mechanisms of soil erosion in forests are understood rarely up to now. There is still a knowledge gap to what extent biodiversity and tree species identity affect soil erosion in early successional forest stands, which tree architectural and leaf traits account for these effects and which of these traits are important for the spatial variability of soil erosion.

Therefore, this thesis investigated the influence of tree species richness (as a measure of biodiversity) and tree species identity on rainfall erosivity (measured as throughfall kinetic energy; TKE). Furthermore, this thesis concentrated on the spatial variability of TKE. Importance and influence of five tree architectural and nine leaf traits on these TKE properties were evaluated. In addition, the influence of leaf litter diversity and soil meso- and macrofauna on initial soil erosion was investigated. The experiments were carried out in a young subtropical forest of southern China in the framework of the BEF-China (Biodiversity and Ecosystem Functioning) project.

Tree species richness effects on TKE were found only at the local neighborhood scale while plot-level effects of tree species richness on TKE were not found. This effect was attributed to the young age of the forest plantation. Crown cover, canopy layering or tree heights have not yet fully developed and thus only effects at a local neighborhood scale can be seen. Neighborhood effects on TKE were due to larger crown areas and taller tree heights in more diverse neighborhoods thus increasing TKE.

TKE was highly species-specific. TKE below *Choerospondias axillaris* and *Sapindus saponaria* were higher and TKE below *Schima superba* was lower than the mean TKE of all other eight species. Species-specific effects of TKE occurred due to differences in tree architecture and leaf traits. By far, leaf habit, leaf area and tree height were most important in inducing species-specific TKE differences by changing rain drop velocity and drop size.

Furthermore, TKE was spatially variable. Below the first branch of a tree individual

TKE was lowest due to low rain drop velocities and small drop sizes. In contrast, TKE was highest in the middle of four tree individuals due to a low interception by a low LAI resulting in higher throughfall amounts.

In addition, this thesis provides a ranking of abiotic and biotic factors according to their importance for predicting TKE. Leaf area, leaf area index, throughfall and tree height were the most important variables. These findings emphasize the interplay between abiotic factors as well as tree architectural and leaf traits for a successful TKE prediction.

Considering soil erosion management, the erosive potential of TKE in the experimental forest plantation can be mitigated by smaller leaf areas than 70 cm^2, lower tree heights than 290 cm, lower crown base heights than 60 cm, smaller leaf area index than 1, more than 47 branches per tree individual and by using single tree species neighborhoods.

Initial soil erosion (measured as sediment discharge) was not influenced by leaf litter diversity, but positively affected by the presence of soil meso- and macrofauna. This faunal effect arises mainly from arthropods slackening and processing the soil surface and only marginally from fauna taking part in the decomposition of leaves leading to less coverage. Nevertheless, leaf litter coverage highly negatively influenced the occurrence of initial erosion.

Summarizing, biodiversity effects on soil erosion were neither present by investigating tree species richness at plot-level nor by investigating leaf litter diversity. However, a positive effect on TKE at the local neighborhood indicates that this can change with a full-grown and dense tree canopy with further succession of the forest. It can be concluded that in young successional forest stands tree architecture, leaf traits, species identity and abiotic factors are more important in influencing the erosive potential of rain than biodiversity.

2 Zusammenfassung

Bodenerosion stellt weltweit eine enorme Bedrohung für Ökosysteme und landwirtschaftlich genutzte Flächen dar. Aufforstung wird dabei als gebräuchliche Methode verwendet, um großflächigen Bodenabtrag zu vermeiden. Allerdings sind die Mechanismen der Bodenerosion unter Wald bisher kaum tiefgründig verstanden. Es bestehen immer noch Unklarheiten darüber, ob und bis zu welchem Grad die Baumartenvielfalt und einzelne Baumarten Bodenerosionsprozesse in jungen Wäldern beeinflussen, welche Baumstruktur- und Blatteigenschaften diese Effekte hervorrufen und welche dieser Eigenschaften für das räumlich unterschiedliche Auftreten von Bodenerosion verantwortlich sind.

Diese Arbeit untersucht den Einfluss der Baumartenvielfalt (als Maß für die Biodiversität) und einzelner Baumarten auf die Regenerosivität (in dieser Arbeit als kinetische Energie des Bestandsniederschlags gemessen; TKE). Außerdem analysiert diese Arbeit die räumliche Variabilität der TKE und zeigt variabilität-beeinflussende Faktoren auf. Die Wichtigkeit und der generelle Einfluss von fünf Baumstruktur- und neun Blatteigenschaften auf die Eigenschaften der TKE werden zusätzlich untersucht. Der Einfluss der Blattstreudiversität und der Bodenmeso- und makrofauna auf initiale Bodenerosionsprozesse wird in einem abschließenden Experiment untersucht. Alle Experimente wurden in einem jungen subtropischen Wald im südlichen China im Rahmen des BEF-China (Biodiversität und Ökosystemfunktionen) Projektes durchgeführt.

Die Baumartenvielfalt beeinflusste die TKE nur in der direkten Nachbarschaft, während großräumige Effekte der Baumartenvielfalt nicht gezeigt werden konnten. Dies ist dem jungen Alter des Waldes geschuldet. Da die Kronendachfläche sowie deren Schichtung noch nicht vollständig entwickelt sind, wirken sie sich nur in der direkten Nachbarschaft auf die TKE aus. Die Experimente haben gezeigt, dass die Nachbarschaftseffekte aufgrund erhöhten Kronenschlusses und größerer Baumhöhen in diverseren Nachbarschaften die TKE positiv beeinflussen.

Des Weiteren konnte gezeigt werden, dass die TKE stark artenspezifisch ist. Die

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TKE unter *Choerospondias axillaris* und *Sapindus saponaria* war größer und die TKE unter *Schima superba* war geringer als das Mittel der verbleibenden acht Baumarten. Artenspezifische TKE Unterschiede konnten auf Baumstruktur- und Blatteigenschaften zurückgeführt werden. Als wichtigste Steuergrößen für die artenunterschiedliche TKE können Blatthabitus, Blattgröße und Baumhöhe angeführt werden, indem diese Faktoren die Tropfengeschwindigkeit und -größe des Bestandsniederschlags beeinflussen.

Außerdem zeigte sich die TKE räumlich hoch variabel. Direkt unter dem ersten Ast eines Baumindividuums wurde die niedrigste TKE beobachtet, was sich auf langsame und kleine Regentropfen zurückführen lässt. Dagegen war die TKE in der Mitte zwischen vier Baumindividuen am größten. Hier beeinflusste ein sehr kleiner Blattflächenindex die Interzeption und erhöhte dadurch den Bestandsniederschlag, der sich positiv auf die KE auswirkte.

Zusätzlich zeigt die vorliegende Arbeit eine Gewichtung von abiotischen und biotischen Einflussfaktoren für die TKE Modellierung. Dabei waren Blattgröße, Blattflächenindex, Bestandsniederschlagsmenge sowie die Baumhöhe die wichtigsten Faktoren. Dies bestärkt das Zusammenspiel zwischen abiotischen Faktoren und Baumstruktur- und Blatteigenschaften für eine erfolgreiche TKE-Modellierung.

Bei Betrachtungen zur Verringerung der Bodenerosion kann das erosive Potential der TKE durch Blattflächen kleiner als 70 cm^2, niedrigere Baumhöhen als 290 cm, niedrigere Kronendachhöhen als 60 cm, kleinere Blattflächenindexe als 1, mehr als 47 Äste pro Baumindividuum sowie durch die Verwendung von gleichen Baumarten in der Nachbarschaft begrenzt werden.

Die initiale Bodenerosion (gemessen durch den Sedimentabtrag) wird nicht durch die Blattstreudiversität beeinflusst, jedoch durch das Auftreten der Bodenmeso- und makrofauna. Der positive Faunaeffekt kann hauptsächlich der Bearbeitung der Bodenoberfläche sowie dem Lockern dieser durch Arthropoden zugeschrieben werden und nur bedingt Blattzersetzungsprozessen durch die Fauna, welche zu einer geringeren Bedeckung führen. Nichtsdestotrotz zeigt das Experiment den generell geringeren Sedimentab-

trag mit steigender Bodenbedeckung.

Zusammenfassend zeigt die vorliegende Arbeit weder großräumige Biodiversitätseffekte durch Baumartenvielfalt auf die TKE noch durch Blattstreudiversität auf die initiale Bodenerosion. Jedoch kann durch den nachgewiesenen Nachbarschaftsdiversitätseffekt auf die TKE angenommen werden, dass mit wachsenden Bäumen und dichteren Beständen auch großräumigere Biodiversitätseffekte auftreten. Abschließend kann davon ausgegangen werden, dass in jungen Waldbeständen die Baumstruktur, Blatteigenschaften sowie artenspezifische Unterschiede das erosive Potential des Niederschlags stärker beeinflussen als die Biodiversität.

3 List of publications in the thesis

3.1 Momentum or kinetic energy - how do substrate properties influence the calculation of rainfall erosivity? (published)

Manuscript 1, published as first author in Journal of Hydrology 2014, Volume 517, Pages 310-316. DOI: http://dx.doi.org/10.1016/j.jhydrol.2014.05.031.
Co-authors: Steffen Seitz, Christian Geißler, Tamas Lassu, Piet Peters, Manuel Seeger, Karin Nadrowski, Thomas Scholten.
The full publication may be found on Page 80.

3.2 Kinetic energy of throughfall in subtropical forest ecosystems as a function of tree species richness and spatial variability (under review)

Manuscript 2, under review as first author in Agricultural and Forest Meteorology 2015.
Co-authors: Steffen Seitz, Peter Kühn, Ying Li, Pascal Niklaus, Goddert von Oheimb, Thomas Scholten.
The full publication may be found on Page 105. Meanwhile, this manuscript was published as "' Throughfall kinetic energy in young subtropical forests: Investigation on tree species richness effects and spatial variability"' with DOI http://dx.doi.org/10.1016/j.agrformet.2015.06.019.

3.3 Species-specific effects on throughfall kinetic energy in subtropical forest plantations are related to leaf traits and tree architecture (under review)

Manuscript 3, under review as first author in PLoS ONE 2015.
Co-authors: Helge Bruelheide, Werner Härdtle, Wenzel Kröber, Peter Kühn, Ying Li, Steffen Seitz, Goddert von Oheimb, Thomas Scholten.

The full publication may be found on Page 137. Meanwhile, this manuscript was published as "' Species-specific effects on throughfall kinetic energy in subtropical forest plantations are related to leaf traits and tree architecture"' with DOI `http://dx.doi.org/10.1371/journal.pone.0128084`.

3.4 Rule-based analysis of throughfall kinetic energy to evaluate leaf and tree architectural trait thresholds to mitigate erosive power (ready for submission)

Manuscript 4, ready for submission as first author in Geophysical Research Letters 2015.
Co-authors: Karsten Schmidt, Steffen Seitz, Felix Stumpf, Thomas Scholten.
The full publication may be found on Page 160. Meanwhile, this manuscript is under review as "'Rule-based analysis of throughfall kinetic energy to evaluate biotic and abiotic factor thresholds to mitigate erosive power"' in Progress in Physical Geography.

3.5 The influence of leaf litter diversity and soil fauna on initial soil erosion in subtropical forests (accepted)

Manuscript 5, accepted for publication as Co-author in Earth Surface Processes and Landforms 2015.
Co-authors: Steffen Seitz, Pascale Zumstein, Thorsten Assmann, Peter Kühn, Pascal Niklaus, Andreas Schuldt, Thomas Scholten.
The full publication may be found on Page 186. Meanwhile, this manuscript was published as "'The influence of leaf litter diversity and soil fauna on initial soil erosion in subtropical forests"' in Earth Surface Processes and Landforms with DOI: `http://dx.doi.org/10.1002/esp.3726`.

4 Introduction

4.1 Soil erosion

Soil erosion is a major threat to ecosystems and agricultural land worldwide [Pimentel and Kounang, 1998; Lal, 2003; Morgan, 2005]. The degradation of soil leads to destabilized soil aggregates, reduction of plant and fauna diversity, changes in the water-holding capacity, relocation of organic carbon stocks and nutrient losses [Lal, 2003; Duran Zuazo et al., 2008]. Thus, soil erosion not only affects ecosystem functions, but also food production and food security [Shi, 1998; Lin et al., 2002; Yu et al., 2006; Pimentel, 2006]. High economic costs have to be expended to counteract reduced land productivity, off-site effects caused by deposits and pollutants from eroded sites [Lal, 1998; Pimentel and Kounang, 1998; Montgomery, 2007]. This makes soil erosion a major environmental problem and hence a central research topic in the last decades [Huang, 1987; Cai et al., 2005; Wang et al., 2005]. In addition, the United Nations have proclaimed 2015 as the "Year of the Soils" to raise awareness of soil erosion and of soils in general. Soil erosion is influenced by inclination, soil erodibility, vegetation and rainfall characteristics. Mainly due to the latter, soil erosion rates vary in different regions of the world [Levia and Frost, 2006]. In subtropical parts of China, for example, high rainfall intensities cause severe and continuous losses of soil and thus important disservices in ecosystems [Wang et al., 2005; Shi, X., Liang, Y., Gong, Z., 2008]. The degradation of soil will remain one of the principle environmental problems, as the occurrence of extreme weather events will increase associated with changes in mean precipitation in the future [IPCC, 2007; Xu et al., 2007].

Rainfall erosivity as part of the soil erosion process

Rainfall erosivity is one factor to express the potential of rain to detach soil particles by raindrop impact that may be subsequently transported by overland flow (e.g. [Ellison, 1947]). Rainfall erosivity symbolizes the first factor in the erosion process by which erosion rates can be estimated even before soil particles are moved. Mathematically, it

can be expressed by:

$$R = I_{30} \cdot KE$$

where R=rainfall erosivity, I_{30}=30 minute rainfall intensity, KE=rainfall kinetic energy. Thus, it combines two major rainfall characteristics. Rainfall erosivity can have an important influence on ecosystems through the initiation of soil erosion and is related to changes in climate [Diodato and Bellocchi, 2009; Elagib, N. A., 2011]. In soil erosion modeling, rainfall erosivity is incorporated in empirical (R-factor in the Revised Universal Soil Loss Equation RUSLE, Renard et al. [1997]) and physically based models (Water Erosion Prediction Project WEPP, Demény et al. [2010]). Certainly, rainfall KE solely is the most prominent erosivity index in soil erosion research to estimate the erosive power of rainfall [Morgan, 2005]. However, besides KE, momentum or momentum multiplied by rain drop diameter are used to describe the erosivity of rain drops [Rose, 1960; Salles et al., 2001]. There is an ongoing discussion which predictor is the best to describe initial soil detachment [Rose, 1960; Ghadiri and Payne, 1988; Salles and Poesen, 2000; Sanchez-Moreno et al., 2012]. Based on

$$KE = \frac{1}{2}m \cdot v^2 \qquad and \qquad M = m \cdot v$$

where m=rain drop mass (equivalent to rain drop diameter d^3), v=rain drop velocity and M=momentum, KE and M are both related to drop mass and drop velocity, whereas kinetic energy is a power function with 2 as exponent and momentum is a linear relation, equivalent to an exponent of 1. Hence, modeling the exponents of drop mass and velocity can show which erosivity index performs best to predict splash detachment.

Rain drop size and velocity contribute to soil loss such that smaller and slower drops are less efficient for soil detachment [Sharma and Gupta, 1989]. Hence a drop size and velocity change can lead to different detachment rates. These changes are depended on rainfall intensity [Carter et al., 1974; van Dijk et al., 2002; Assouline, 2009] at open sites and on a modification of the drop size distribution of throughfall below vegetation [Brandt, 1988, 1989; Nanko et al., 2011; Geißler et al., 2012a]. Considering

the relation of KE or M to soil properties for describing splash detachment, it was shown that detachment rates are soil-type dependent [Wainwright and Parsons, 2002; Assouline et al., 2007]. Additionally, inherent soil properties like texture and structure stability influence splash detachment [Ellison, 1947; Poesen and Savat, 1981; Quansah, 1981; Bradford et al., 1987] and thus the erosivity index by which this detachment is modeled. For example, grain-size distribution has to be taken into account to improve the definition of soil detachability by raindrop impact [Torri et al., 1987]. From this point of view, it is not clear how different substrates transform this energy and whether one erosivity index (KE or M) is sufficient to describe splash detachment of different substrates. Thus, quantifying the exponents of drop mass and velocity in relation to splash detachment of different substrates may help to close this knowledge gap.

Splash and interrill erosion as part of the soil erosion process

The detachment of soil particles by rain splash symbolizes the initial process of erosion [Morgan, 2005]. This so-called interrill erosion is closely linked to rain properties [Salles and Poesen, 2000], e.g. rainfall erosivity. Raindrop impact is the most important cause of soil detachment before the stage of rill and gully erosion by overland water flow [Rose, 1960]. It must be regarded as an important denudational process especially in regions where rains can not generate overland flow, but splash detachment sets in at the first drop impact [Bauer, 1985]. In addition, Morgan [2005] considered rain splash as the most important detaching agent.

4.2 Soil erosion in forests

Vegetation is regarded as a main attribute to mitigate the intensity of erosion caused by water [Thornes, 1990; Morgan, 2005]. Thus, huge efforts are currently made in many regions of the world to increase the forested area by means of afforestation to overcome severe soil loss due to increased surface cover and stabilized soil aggregates. Besides the improvement of erosion control, increase of timber, fuel and pulp wood production, the reduction of atmospheric CO_2 by carbon sequestration in forest soils, or the stabilization

of regional climate conditions [Dixon and Wisniewski, 1995; Houghton, R. A. et al., 2012] are motive forces for afforestation. In China, total forest cover increased in the last 60 years due to afforestation, although natural forests are continuously declining [Song and Zhang, 2010].

In forests, erosion processes are much more complex than in open field. The alternation of rain drop size and velocity by forest canopies [Nanko et al., 2008b; Geißler et al., 2013; Goebes et al., 2015a,b], the changes in rain splash and sediment discharge due to soil surface cover by leaf litter [Morgan, 2005; Seitz et al., 2015] as well as different soil structures by tree roots lead to mechanisms that have been rarely studied since now.

4.2.1 Throughfall kinetic energy

Throughfall kinetic energy (TKE) is the power of rain drops to detach soil below vegetation. While freefall characterizes the drop size distribution of rainfall in open field, throughfall is the part of rainfall whose drop size distribution is modified by vegetation (Figure 1).
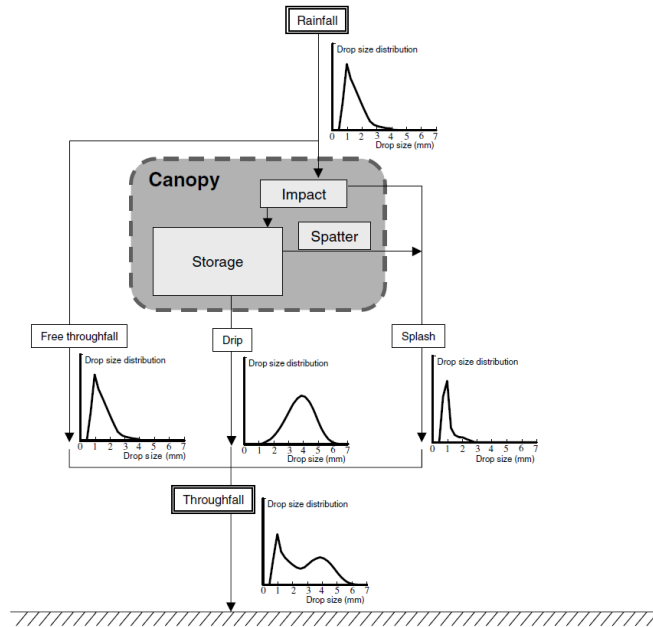
Figure 1: Partitioning of rainfall into the components of throughfall with characteristic drop size distributions (Nanko et al., 2006). Raindrop velocity is not considered.

The modification occurs when rain drops hit the plant canopy and either confluence to drip as larger drops or shatter and break to drip as smaller drops. Moreover, rain drop velocity is changed due to different falling heights. These transformation processes can lead to twice higher TKE in forests than in open field, increasing the erosion potential [Morgan et al., 1998; Nanko et al., 2004; Geißler et al., 2010, 2012a] although soil erosion is generally reduced in forests [Hill and Peart, 1998]. Nevertheless, with a sparse understory vegetation and leaf litter cover, TKE can strongly increase soil erosion under forest. Increasing TKE can be attributed to a drop size increase by confluence of drops on leafs and branches. Drop velocity, however, mostly decreases in forests due to shorter falling heights compared to open field. This is especially true in young succession stands [Goebes et al., 2015b].

Measurement of throughfall kinetic energy

TKE can either be measured directly or indirectly. In most cases, TKE is measured indirectly by deriving values from rainfall intensity [Salles and Poesen, 2000; van Dijk et al., 2002]. However, this conversion often is defective due to conversion inaccuracy, although easy to obtain. Direct TKE measurements can be carried out using splash cups [Scholten et al., 2011], the paper stain method [Brandt, 1988; Shrestha et al., 2010], the flour pellet technique [Brandt, 1989], laser disdrometers [Hall and Calder, 1993; Nanko et al., 2008b] and piezo-electric sensors [Licznar et al., 2008]. Laser disdrometers and piezo-electric sensors can directly measure the drop size distribution, but are limited by the number of replications due to high financial and technical demands. In recent years, increased focus has been given to experimental studies measuring TKE directly [Scholten et al., 2011; Geißler et al., 2012a,b, 2013]. These studies worked with splash cups that were first introduced in 1947 by Ellison [1947], further modified by Mosley, M. P. [1982] and calibrated for the use of large-scale TKE measurements by Scholten et al. [2011]. Their major advantages are an easy handling in the field and a high number of replications that can be obtained at low costs [Scholten et al., 2011].

Biotic factors influencing throughfall kinetic energy

Forests highly influence the kinetic energy of rainfall as first step towards erosion occurrence due to their structure and species composition [Geißler et al., 2010, 2012b, 2013]. Many studies on throughfall have been conducted [Staelens et al., 2008; André et al., 2011], but mechanisms can be different, if TKE is examined. Literature distinguishes between tree architectural and leaf traits.

Tree height is the most prominent tree architectural trait that influences TKE [Mosley, M. P., 1982; Brandt, 1990; Foot and Morgan, 2005; Nanko et al., 2008b; Geißler et al., 2010, 2013]. Increasing tree height can contribute to higher TKE by two main processes: (i) higher drop velocity due to higher falling heights [Gunn and Kinzer, 1949] and (ii) larger crown width [Li et al., 2014] that increases drop size by increased confluence. The positive height effect was recently shown by Geißler et al. [2010]. In their study, tree height increased with increasing successional stage of a forest stand, resulting in higher TKE. However, a higher canopy may increase the space for vegetation layering which can mask the height effect [Wiersum, 1985]. It can be assumed that stand height is a very important factor only in young forest plantations [Geißler et al., 2013]. If the sufficient stand height for rain drops reaching terminal velocity has been achieved, further height gain will not affect rain drop velocities [Stuart and Edwards, 2006].

Crown base height (CBH) positively influences TKE [Moss and Green, 1987; Brandt, 1990]. After passing the canopy layers, the crown base height determines the terminal falling height of rain drops. According to tree height, this trait may be more important in young forests. However, Goebes et al. [2015a] showed that CBH affected TKE much less than tree height, which can be caused by similar CBH at trees along a large range of tree heights.

Up to now, the effect of crown area on TKE has been investigated only in two studies. Goebes et al. [2015b] found a positive effect on TKE which can be ascribed to a gathering of rain drops on larger crown areas and a higher area at which throughfall occurs. In contrast, Nanko et al. [2008b] showed a negative trend of crown area on TKE,

but used much larger crown areas. In this case, increased canopy water storage with increasing crown area can result in less throughfall for low rainfall amounts.

The number of branches of a tree combined with the leaf area index (LAI) account for the effect of canopy architecture. Herwitz [1987] showed the importance of branches, their angles and position in the canopy in his study. By hitting branches, rain drops break resulting in smaller drops. Moreover, branches gather throughfall and release it at any random position at the branch or transfer it directly to the stem in dependence of the branch angle. This effect can increase stemflow and hence decrease throughfall [André et al., 2011]. However, Goebes et al. [2015a] found that this might be a weak effect and water might both be distributed along the branches and transferred to the stem in equal proportions. LAI negatively affects TKE [Park and Cameron, 2008; Geißler et al., 2013]. LAI summarizes effects of canopy thickness, leaf and branches and forms a dimensionless number. High canopy thickness as substitute of LAI increases drop splitting by dripping on branches and leaves [Nanko et al., 2006, 2008a,b], which in turn may decrease raindrop sizes. Moreover, higher canopy thickness in young forest stands might decrease space between vegetation and surface, resulting in slower rain drop velocities by a less likely re-interception [Geißler et al., 2012b]. In general, throughfall decreases with increasing LAI [Gómez et al., 2001; Levia and Frost, 2006].

Furthermore, TKE is highly spatially variable. The height of the first branch affects TKE [Stout and McMahon, 1961; Clements, 1971; Staelens et al., 2008; Nanko et al., 2008b]. It is the last barrier for drops before reaching the soil surface. Hence, low rain drop velocities occur more often at this position leading to low TKE. In addition, Nanko et al. [2008b] reported a positive "distance to stem effect" of TKE below a Japanese cypress *Chamaecyparis obtusa*, while Goebes et al. [2015b] investigating 24 subtropical tree species showed that TKE was lowest below the first branch and highest in the middle of four tree individuals .

In addition to tree architectural effects on TKE, leaf traits affect TKE. Leaf habit (deciduous, evergreen or coniferous trees) affects the rain drop size distribution. In literature, different rain drips can be distinguished resulting in a "launch drip" or a

"reservoir drop" [Armstrong and Mitchell, 1988]. Geißler et al. [2012b] showed that
Castanea henryi and *Quercus serrata* as examples of deciduous species yielded higher
TKE than the evergreen species *Schima superba*. Hall and Calder [1993] and Nanko
et al. [2006] showed that coniferous trees produce smaller drops than leaved trees due
to a low water storage capacity of needles. Another leaf trait affecting TKE is the leaf
area [Levia and Frost, 2006; Park and Cameron, 2008]. A larger leaf can increase the
gathering of rain water and thus may cause larger rain drops resulting in higher TKE.
Further, species with broad leaves and a rough cuticle produce larger drops than species
with smaller and wax-coated leaves and thus, might increase TKE [Nanko et al., 2006].
However, studies are lacking that investigate the effect of other leaf traits on TKE, such
as surface hydrophoby, leaf pinnation or leaf margin, and that combine the investigation
of both tree architectural and leaf traits and their effect on TKE.

These different tree architectural and leaf trait effects lead to highly species-specific
TKE. For instance, TKE below *Castanea henryi* and *Quercus serrata* was higher than
that of *Schima superba*, *Elaeocarpus decipiens* and their mixture [Geißler et al., 2012b].
These differences can be attributed to species-specific differences regarding the number
of branches and the angle of the first branch. Consistent with different TKE, different
drop size distributions were found between *Chamaecyparis obtusa*, *Quercus acutissima*
and *Cryptomeria japonica* [Nanko et al., 2006]. Most preceding studies have only dealt
with a maximum of four different species [André et al., 2011; Geißler et al., 2012a,b],
precluding cross-species comparisons of TKE-trait relationships. However, there are
studies that found no difference in TKE, interception or soil erosion amounts among
certain species [Aston, 1979; Cao et al., 2008; Geißler et al., 2012a].

Abiotic factors influencing throughfall kinetic energy

Besides biotic effects, TKE is influenced by the abiotic effects, such as rainfall amount,
rainfall intensity, wind speed, rainfall drop size distribution and rain drop velocity [Levia
and Frost, 2006; Scholten et al., 2011]. Characteristics of a rainfall event (intensity,
duration, amount) are of major importance to predict TKE. Rainfall intensity can induce

biotic effects [Loescher et al., 2002]. Goebes et al. [2015a] showed that species-specific effects on TKE only occur at low peak intensities. Neighborhood tree species richness effects on TKE are induced by low peak intensities as well as spatial variability of TKE and throughfall [Staelens et al., 2006; Goebes et al., 2015b]. During high intensity rainfall normally accompanied by high wind speeds, considerable canopy vibration occurs which reduces drop sizes, resulting in less variable TKE [Hall and Calder, 1993; Nanko et al., 2006]. Moreover, canopy saturation plays an important role in retaining water during rainfall events with low rainfall amounts [Nanko et al., 2006; Park and Cameron, 2008]. However, this effect rapidly declines after saturation of the canopy. Furthermore, TKE is positively influenced by throughfall amount [Scholten et al., 2011]. In summary, rainfall characteristics may superimpose the influence of biotic factors [Park and Cameron, 2008].

4.2.2 Litter cover and fauna effects

After passing the canopy, throughfall drops hit the soil surface. If this impact induces soil erosion, the latter will be highly dependent on the soil surface cover [Thornes, 1990; Morgan, 2005]. Forest in general reduces the risk of considerable soil loss, and especially the litter cover is known to reduce the erosivity of rainfall by absorbing the impact of raindrops, leading to a lower sediment discharge compared to bare ground [Morgan, 2005]. In general, erosion rates increase with decreasing litter cover [Duran Zuazo et al., 2008]. However, the relationship between litter cover and sediment discharge is often not linear. Some studies indicated that erosion rates doubled from 100 % cover to 40 %, but were tenfold higher from 40 % cover to bare ground [Francis and Thornes, 1990; Lang, 1990]. Since leaves of different species vary in their sizes, shapes and decomposition rates [Cornelissen, 1996], they may have an important influence on ground coverage and thus on the erosion rates. It is suggested that a highly structured and diverse litter cover is an important factor for soil erosion control on mountain slopes [Körner, C., Spehn, EM., 2002]. However, studies are limited that investigate the structure of leaf litter and its effect on soil erosion.

In general, quality and quantity of litter determines decomposer communities ranging

from microbes and fungi to animals of different size classes [Hättenschwiler and Gasser, 2005]. Leaf litter provides habitats, maintains a favourable microclimate for soil fauna and is also an important food source [Sayer, 2006]. Although the main part of litter decomposition is performed by microbes [Bardgett, 2005], the meso- and macrofauna constitutes the dominant physical litter transformers. It is consequently essential for promoting both litter decomposition [Hättenschwiler et al., 2005] and physical-chemical soil parameters [Gabet et al., 2003]. Many species of the macro fauna groups influence soil processes in terrestrial ecosystems [Lavelle et al., 1997] and can show burrowing behavior when searching for food or when trying to evade short- or long-term unsuitable microclimate conditions on the soil surface [Swift et al., 1979; Gabet et al., 2003; Dostál et al., 2005]. On these grounds, these organisms have the potential to influence soil erosion. However, knowledge about how these fauna-induced processes affect soil erosion is still rudimentary. Most of the relevant studies deal with bioturbation and illustrate only the role of one or few functional groups of soil meso- and macrofauna as geomorphic agents [Viles, 1988], e.g. ants [Cerdà and Jurgensen, 2011].

4.3 Biodiversity, ecosystem functioning and soil erosion

Biodiversity has been investigated since the end of the 1970s [Soule and Wilcox, 1989]. Growing concern about species, habitats and even ecosystem loss accompanied by high financial demands let the topic biodiversity arise. According to Díaz et al. [2006], biodiversity is defined as "number, abundance and composition of genotypes, populations, species, functional types and landscape units in a given system." Since the 1970s, numerous studies have been performed to identify how biodiversity is affected by human alternations of ecosystems with the aim of conservation [Baillie et al., 2004]. However, recent studies showed that the relationship is also vice versa and biodiversity affects ecosystem functions and thus, benefits that humans obtain from them [Díaz et al., 2006]. These benefits provided by ecosystems are referred to as ecosystem services [Scherer-Lorenzen, 2005]. The "Convention of Biological Diversity" defined four groups of ecosystems services: (i) provisioning services, e.g. supply of goods, (ii) regulating

services, e.g. prevention of soil erosion, (iii) cultural services, e.g. spiritual value and (iv) supporting services, e.g. formation of soils. In contrast, ecosystem functions are "intrinsic processes and fluxes whereby an ecosystem maintains its integrity" [Díaz et al., 2006]. The relationship between biodiversity and ecosystem functions to offer ecosystem services represents a major research topic in biodiversity research [Scherer-Lorenzen, 2005].

As a consequence, the United Nations have proclaimed the decade 2011–2020 as the "United Nations decade on biodiversity" to encourage investigating underlying causes of biodiversity loss, reducing direct pressure on biodiversity, improving the safeguarding of ecosystems and enhancing the benefits for all resulting from biodiversity and the ecosystem services it provides. In the course of these arrangements, it was found out that biodiversity can enhance ecosystem functions, such as primary production, nutrient cycling, decomposition, soil respiration, rainfall partitioning or litter production [Nadrowski et al., 2010]. However, in forests effects of diversity on ecosystem functions (e.g. production, decomposition, resistance to herbivory, element cycling) are often outperformed by the effects of species identity on these functions [Nadrowski et al., 2010]. Although soils provide habitats for fauna and regulate water balance, the impacts of soil erosion might be responsible for the loss of keystone species which can cause cascading effects on a wide array of species and negatively influence ecosystem functioning [Duran Zuazo et al., 2008]. Thus, soils represent a major factor in ecosystem functioning. For instance, one square meter of soil contains about 200,000 arthropods and enchytraeids and billions of microbes [Lee and Foster, 1991]. However, the influence of biodiversity on soil erosion has been investigated only rarely.

In this thesis, biodiversity effects were studied using tree species richness and leaf litter diversity as biodiversity indicators.

4.3.1 Tree species richness effects

As stated above, afforestation is a common measure to mitigate soil erosion. Most often afforestation takes place by the establishment of easily manageable monocultures. In

recent years, monocultures have increasingly come under criticism due to their greater susceptibility to adverse environmental conditions, pathogens [Hantsch et al., 2013] or herbivores [Jactel and Brockerhoff, 2007], and their negative long-term impacts on soil fertility [Puettmann et al., 2008]. There is growing evidence that mixed-species forest stands have beneficial effects on ecosystem functions and services (e.g., growth rates, biomass production, nutrient cycling, light harvesting, plant nutrition and crown cover [Kelty, 1992; Loreau et al., 2001; Richards et al., 2010; Forrester et al., 2006; Potvin and Dutilleul, 2009; Gamfeldt et al., 2013; Forrester, 2014]). Species-specific differences in growth and biomass allocation patterns as well as plant architecture are due to niche separation and resource partitioning [Scherer-Lorenzen, 2005]. As a result, stratified canopies with a high degree of crown overlap and thus an increased mean vegetation cover and greater biomass density can be found in mixtures more frequently than in monocultures [Menalled et al., 1998; Lang et al., 2010, 2012; Pretzsch, 2014].

Concerning soil erosion, it is known that in particular TKE reacts strongly to these parameters (Chapter 4.2.1; [Nanko et al., 2006, 2008a,b; Geißler et al., 2013]). As a consequence, tree species richness might affect soil erosion processes. However, only very few studies yet reported tree species richness effects on soil erosion and TKE. In tropical conditions, a negative correlation between plant diversity and soil erosion was found [Shrestha et al., 2010]. In contrast, a positive tree diversity effect on TKE was observed in a subtropical secondary forest along a range of successional stages [Geißler et al., 2013]. This effect was attributed to an increase of both tree species richness and canopy height with increasing stand age.

4.3.2 Leaf litter diversity effects

According to Chapter 4.2.2, leaf litter is a major inhibitor of soil erosion, especially of initial erosion processes caused by rain splash [Duran Zuazo et al., 2008; Morgan, 2005]. Hence, leaf litter is one major reason why soil erosion rates below forests are more than ten times smaller than on agricultural land [Hill and Peart, 1998]. Relating to biodiversity, full leaf covered soil surfaces might be better protected against soil erosion

by greater overlap and gap-filling in highly diverse leaf litter mixtures due to different leaf shapes and sizes. At the same time, highly diverse leaf litter mixtures may lead to faster leaf decomposition due to more active decomposer communities and thus soil surfaces will get bared faster. As a consequence, this effect could lead to an inferior conservation of soil surfaces and therefore to higher erosion rates at later times. As seen in Chapters 4.3 and 4.3.1, studies are lacking investigating the importance of plant, tree or leaf litter diversity on soil erosion processes. Körner, C., Spehn, EM. [2002] suggested that slopes are better stabilized by a vegetation with diverse growth forms than uniform vegetation. In addition, higher plant species numbers lead to more stabilized soil aggregates for soil covered by grasses, forbs and shrubs, while this is not true for moss, lichen or crusts [Pohl et al., 2009].

5 Objectives

This thesis seeks to investigate mechanisms of soil erosion in subtropical forests. Since soil erosion in forests reveals many different and complex processes (Chapter 4.2), a separation of these processes is necessary. Thus, in a first step this thesis focuses on the rain splash potential to detach different substrates by investigating the optimal erosivity index to model this detachment (hereinafter referred to as Wageningen Experiment, Manuscript 1). The main part of this thesis investigates rainfall energy below forest vegetation (TKE) and the related processes. Links are created to the influence of biodiversity, spatial variability, species identity as well as tree architectural and leaf traits on TKE (Manuscripts 2, 3 and 4). At last, the process of sediment discharge below forest leaf litter cover is investigated with respect to the influence of leaf litter diversity and soil meso- and macrofauna (hereinafter referred to as NILEx, Manuscript 5).

In detail, this thesis has the following objectives:

(i) to prove that the momentum is best suited to predict substrate-independent detachment, while fine substrates respond to the kinetic energy and coarse substrates respond more to the momentum (Wageningen Experiment);

(ii) to quantify the role of tree species richness as a measure of biodiversity on TKE on a plot- and local neighborhood scale (Manuscript 2);

(iii) to test for spatially different positions below the forest canopy (Manuscript 2);

(iv) to identify tree architectural and leaf trait effects on TKE (Manuscripts 2, 3);

(v) to test for species-specific effects on TKE and identify tree architectural and leaf traits that mediate these effects (Manuscript 3);

(vi) to rank leaf and tree architectural traits by their importance in influencing TKE (Manuscripts 3, 4);

(vii) to identify thresholds of tree architectural and leaf traits below or above which TKE can be minimized (Manuscript 4);

(viii) to quantify the role of leaf litter diversity and soil meso- and macrofauna on initial soil erosion (NILEx) using full and decomposed litter cover.

According to the objectives, specific experimental designs are needed. The framework is provided by the "Biodiversity and Ecosystem Functioning China" (BEF-China) project, an interdisciplinary research group investigating the effect of biodiversity on several ecosystem functions (soil erosion, tree growth, nutrient fluxes, litter decomposition etc.).

This thesis is part of the BEF-China research group and thus its results will contribute to link ecosystem functions to biodiversity.

6 Methods

6.1 Study area

The study area for the main part of this thesis (Manuscript 2, 3 and 4) is located at Xingangshan, Jiangxi Province, PR China (N29°08–11, E117°90–93). The mean annual temperature is 17.4 ℃ and mean annual rainfall is 1635 mm. The climate of the study area is characterized by subtropical summer monsoon with a wet season from May to July and a dry winter. The study area is part of the "Biodiversity and Ecosystem Functioning China" (BEF-China) project. Elevation of the study site ranges from 108 m to 250 m with a mean of 190 m a.s.l. Slopes range from 0 to 45 degrees. The experimental area holds 261 plots on two sites (A and B) with seven tree richness levels of 0, 1, 2, 4, 8, 16 and 24 tree species [Bruelheide et al., 2014]. Trees were planted after harvest of the previous stand in 2008 and were six years old during the measurements. The plot size is 25.8 m x 25.8 m and 400 tree individuals were planted with a horizontal distance of 1.20 m per plot. Species were randomly assigned to individual planting positions within the plots, and treatments (i.e. species richness) were randomly assigned to the plots. Soils are mostly Cambisols. Further details on the general design and establishment of the BEF-China experiment are provided by Yang et al. [2013] and Bruelheide et al. [2014].

Considering NILEx, a study site near BEF-China Site B in a *Castanea mollissima* plantantion was chosen. This site covers an area of 1200 m^2 with an elevation difference of 11 m and is characterized by moderately steep to steep slopes (13°to 38°).

The study of the Wageningen Experiment was conducted at the Soil Physics Laboratory, Wageningen University, Netherlands.

6.2 Experimental design

In this thesis, 40 plots on site A were measured covering 24 tree species and tree species richness levels 1, 2, 4, 8, 16 and 24. 17 monocultures, 10 2-species mixture, six 4-species mixture, four 8-species mixture, one 16-species mixture and two 24-species mixture plots

were sampled. Concerning species-specific effects on TKE, 11 monoculture species on 17 plots were used. Each plot has a core area, which consists of the central 6 x 6 tree individuals. The core area with these 36 individuals was divided into 9 sections (Figure 2). In each section, a specific TKE measurement was located. The positions were (1) 15 cm away from tree stem, (2) in the middle of two tree individuals, (3) in the middle of four individuals, (4) 45 cm away from tree stem, (5) at the 45 cm x 120 cm intersection between two individuals, (6) below the first branch of a tree individual, (7) at the 75 cm x 75 cm intersection between two individuals, and (8) 30 cm away from tree stem and (9) outside the plot as no-vegetation reference (Figure 2).
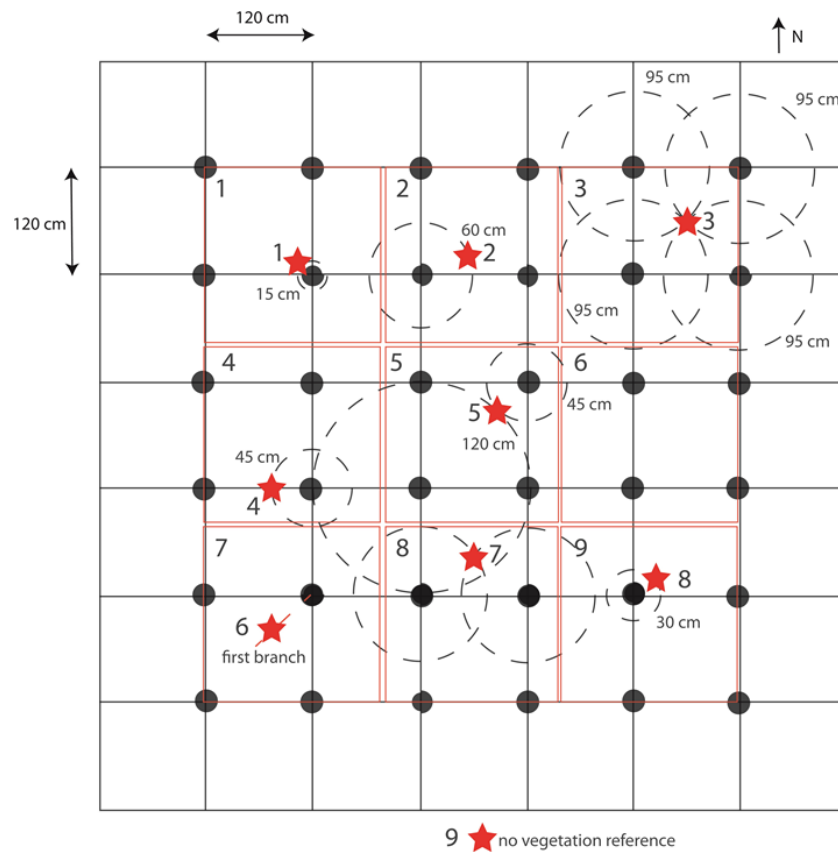
Figure 2: Sampling design with nine measurement positions. Black dots symbolize tree individuals and red stars throughfall kinetic energy measurement position with rainfall gauge.

Considering NILEx, a full-factorial random design on 96 plots in 4 blocks was es-

tablished next to Site B of BEF-China. The plots were equipped with 7 domestic leaf species covering leaf litter diversity levels 0 (bare), 1, 2, and 4 in two species pools. Additionally, a fauna exclusion treatment was installed in half of the plots. Erosion on the plots was triggered by a rainfall simulator [Seitz et al., 2015].

6.3 Measurement of throughfall kinetic energy

TKE and rainfall KE were measured by using Tübingen Splash Cups (T-Cup, Scholten et al. [2011], Figure 3). The T-Cup consists of three different parts: (1) water-filled polyethylene (PE) flask with a (2) carrier system connected by cotton wick to maintain stable moisture over long time and (3) a removable cup connected to the carrier system by a silk mesh that is in hydraulic contact to the carrier system and provides constant moisture. The cups themselves have a diameter of 4.6 cm and a height of 4 cm to exclude rim and wash-off effects during rainfall, which was approved in field studies in China [Geißler et al., 2010, 2013]. Splash cups were filled with fine-sized sand (0.125 μm), and detached sand by rain splash was calculated by subtracting weight of dry sand after the rainfall event from initial sand weight of the full-filled splash cup.

Since rainfall KE and sand loss from the splash cups follow a linear relationship, representative values of TKE [$J \; m^{-2}$] can be obtained with the following function (modified from Scholten et al. [2011]):

$$KE_{splash \; cups} = sand \; loss_{splashcups} \cdot \frac{10,000 cm^2}{\pi r_{splashcup}^2} \cdot 0.1455$$

For measurements investigating the role of different erosivity indices (Manuscript 1), splash cups were filled with five different substrates covering a wide range of particle size and densities: (1) coarse sized quartz sand (1000–1200 μm), (2) medium sized quartz sand (400–600 μm), (3) fine sized quartz sand (125–200 μm), (4) PE balls (100–200 μm), and (5) silt (2–100 μm).
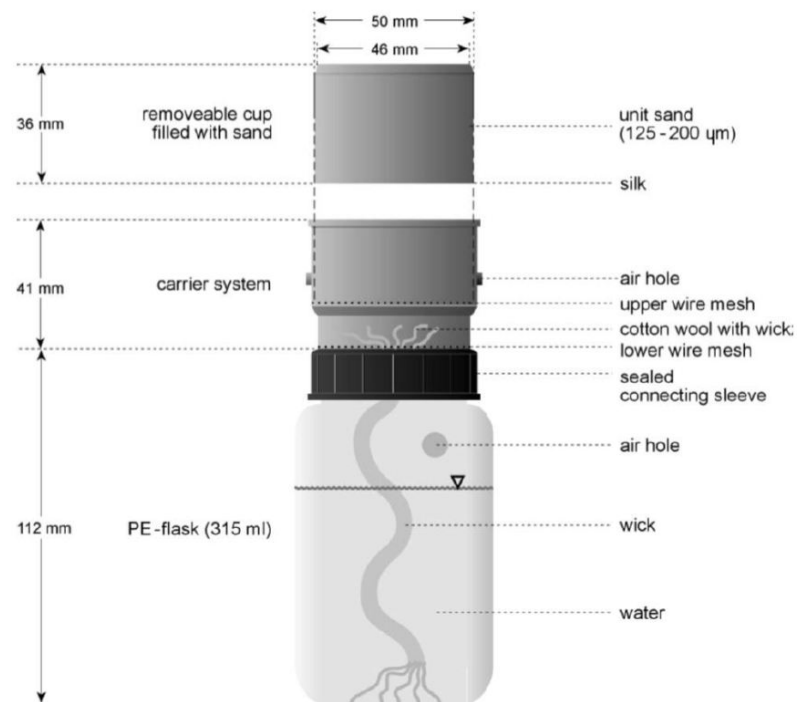
Figure 3: The Tübingen splash cup (T-Cup) to measure throughfall and rainfall kinetic energy (Scholten et al. 2011).

6.4 Measurement of sediment discharge

In NILEx, sediment discharge was measured with micro-scale runoff plots (ROPs; 40 $cm \cdot 40\ cm$) to determine initial soil erosion. In this particular experiment four holes in the side panels were provided. Those holes were equipped with mesh to exclude bigger animals (e.g. mice and toads), but to allow access to litter decomposing meso- and macrofauna. Half of the plots were additionally equipped with pitfall traps and a finer mesh to exclude or at least strongly reduce soil meso- and macrofauna abundance from ROPs (fauna treatment). Micro-scale ROPs were chosen to establish a maximum number of replicates within a factorial random design and to assure a high level of maintenance and control [Hudson, 1993]. Moreover, micro-scale ROPs allow focusing on initial soil erosion processes.

6.5 Measurement of leaf and tree architectural traits

A total of nine leaf traits were analyzed. Leaf traits included leaf area (LA), specific leaf area (SLA), leaf pinnation (simple or pinnate), leaf margin (entire or dentate), trichome cover of upper leaf surface, leaf thickness, leaf toughness, leaf habit (deciduous or evergreen) and leaf area index (LAI). These traits with the exception of LAI were measured on individuals planted in the experiment [Kröber et al., 2014; Kröber and Bruelheide, 2014]. LAI was registered at each TKE measuring point (Figure 2) below diffuse radiation conditions, using a Nikon D100 with a Nikon AF G DX 180°and HemiView V8 (Delta-T) [Kundela, 2009].

To specify the influence of tree architectural traits on TKE, the total tree height, stem diameter at 5 *cm* above ground (GD), crown diameters, crown base height and the number of branches of neighboring trees of measuring points were measured [Li et al., 2014]. Total height was measured with a measuring pole as the length from stem base to the apical meristem. GD was measured with a caliper to the nearest millimeter. Crown diameters were determined with a linear tape along two directions (north-south and east-west). Based on the measured crown diameters, crown area was calculated as an area of ellipse. Crown base height was measured as the distance up to bifurcation point of the lowest living crown branch. Table 2 on page 29 shows 11 species investigated in Manuscript 3 and their corresponding tree architectural and leaf traits.

In cases where more than one tree individual had an impact on the splash cup measurement (e.g. Position 3 in Figure 2), mean values of the tree individuals involved were calculated.

6.6 Rainfall characteristics

In total, five different rainfall events were measured every 5 minutes by the climate station of BEF-China situated at Site A for data generation of Manuscript 2, 3 and 4 (Table 1).

In NILEx (Manuscript 5), rainfall was simulated for 20 minutes at two timesteps

in May and September 2012 to investigate the influence of litter decomposition on sediment discharge from timestep 1 to timestep 2. Rainfall was simulated using a Lechler 460.788.30 nozzle with a falling height of 3.5 m. The sprinkle area was 1 m^2 and protected against outer influences by a tent. Rainfall intensity was set to 60 $mm\ h^{-1}$.

In the Wageningen Experiment (Manuscript 1), a rainfall simulator with a sprinkling height of 4.0 m and a Lechler nozzle type 461.008.017 was used. Water flow rate was set to 14 liters per minute. Within the nozzle's heterogeneous sprinkling behavior, the rainfall simulator produced seven different rainfall intensities ranging from 52 $mm\ h^{-1}$ to 116 $mm\ h^{-1}$. Rain drop size and velocity of each intensity were measured using laser disdrometers.

Table 1: Rainfall characteristics of five rainfall events measured for this thesis.

Rainfall events	Rainfall amount [mm]	Rainfall duration [h]	Mean throughfall amount [mm]	Rainfall intensity I_{5min} [mm h^{-1}]	Rainfall intensity [mm h^{-1}]
Event 1	23.3	10.16	35.88	12.1	2.29
Event 2	39.3	11.50	41.91	22.8	3.42
Event 3	61.2	14.50	93.77	44.4	4.25
Event 4	6.6	2.33	5.84	25.2	2.83
Event 5	185.7	30.58	246.57	127.2	6.07

6.7 Data processing

Considering Manuscripts 2, 3 and 4 (objectives (ii)-(vi)), 1800 splash cups were measured during 5 rainfall events in summer 2013 (9 positions · 40 plots · 5 rainfall events). The no-vegetation reference was omitted in analyzing tree species richness effects, spatial variability and species-specific effects. In addition, tree species richness effects on TKE were analyzed using all 8 positions on 40 plots during 5 rainfall events (n=1600). Spatial variability of TKE was analyzed using only vegetation-covered positions (n=1411).

Table 2: Leaf and architectural traits of the tree species included in the present study according to a significant influence on throughfall kinetic energy. Values represent means of the variables measured. Abbreviations: D = deciduous, E = evergreen, S = simple, P = pinnate, D = dentate, E = entire.

Species name	Abbr.	Leaf area index	Leaf area	Leaf habit	leaf pinnation	Leaf margin	Tree height	Number of branches	Crown base height	Throughfall amount
Castanea henryi Rhed. & Wils.	cah	2.77	3,128	D	S	D	488	19	81.9	70.0
Choerospondias axillaris (Roxb.) Burtt & Hill	cha	2.31	35,484	D	P	D	576	12	268.5	93.7
Cyclobalanopsis glauca (Thunb.) Oerst.	cyg	0.29	2,474	E	S	D	143	16	29.3	83.7
Koelreuteria bipinnata Franch.	kob	0.27	30,727	D	P	D	119	1	58.7	98.3
Liquidambar formosana Hance	lif	1.06	5,051	D	S	D	225	32	23.9	87.7
Lithocarpus glaber (Thunb.) Nakai	lig	0.77	1,956	E	S	E	192	27	30.0	63.4
Quercus fabri Hance	quf	0.55	1,912	D	S	D	166	24	35.9	82.5
Quercus serrata Murray	qus	0.41	1,972	D	S	D	110	23	16.4	98.2
Sapindus saponaria Linn.	sas	1.13	42,231	D	S	E	233	5	68.4	94.4
Triadica sebifera Small	trs	1.20	2,108	D	S	E	265	19	32.9	88.6
Schima superba Garder & Champion	scs	3.06	3,230	E	S	D	338	47	42.3	49.9

Species-specific effects were analyzed using 8 positions on 17 monoculture plots during 5 rainfall events (n=625).

Tree species richness, spatial variability, species-specific as well as leaf and tree architectural trait effects on TKE were analyzed using linear mixed effect models [Pinheiro and Bates D., 2000; Zuur et al., 2009]. These models account for pseudo-replication and remove unnecessary variance in the hierarchical data by using random effects like plot, block or species composition. To obtain effect sizes of leaf and tree architectural traits on TKE, model predictions of TKE were used. Mediation analysis was performed to identify leaf and tree architectural traits that account for the species-specific differences. Binary contrasts were used to detect spatial positions or species that show significantly higher or lower TKE than mean of all other spatial positions or species. For further information on the statistics used, see Manuscripts 2 and 3 in the Appendix.

Considering objectives (vi)-(vii), the complete data without the no-vegetation positions were used (n=1600). To model thresholds of leaf and tree architectural traits below which or above which a certain TKE occurs, Random Forests were used to identify variable importance [Breiman et al., 1984; Breiman, 2001; Cutler et al., 2007]. The most important input variables were used for classification and regression trees (CART) of all single rainfall events as well as of data combining all rainfall events. Within CART, regression was used since the predictor is continuous. Suitability to minimize TKE was evaluated by comparing TKE (standardized by rainfall amount of each event) at each terminal node with TKE classes (very low (mean=7.5), low (mean=14.1), average (mean=20.7) and high (mean=27.3)) calculated from a literature review (Table 4 on Page 53).

Considering NILEx (objective (viii)), data of all 96 ROPs at two timesteps were used. Effects of leaf litter diversity and soil meso- and macrofauna were analyzed using linear mixed effects models. To distinguish bare ground plots (leaf litter diversity 0) from leaf covered plots (leaf litter diversity < 0), a binary contrast was fitted in the models.

Considering the Wageningen Experiment (objective (i)), seven measurement positions of splash detachment were selected in the sprinkle area of the rainfall simulator and were measured three times for each of the five substrates (n=105). Effects of rain drop mass (or rain drop diameter d) and velocity on substrate detachment were analyzed, using linear mixed effects models with the general formula:

$$D_{substrate} = m^x \cdot v^y$$

(with $D=$ detachment, $m=$rain drop mass, $v=$rain drop velocity). Taking the logarithm of this formula turned it into a linear model, where the slope symbolized the exponent. A slope of 2 for y would indicate that kinetic energy explains detachment best, while a slope of 1 for y indicated the use of momentum. By knowing rain drop mass and velocity as well as the splash detachment amount, the model returned the exponents of rain drop mass and velocity. Furthermore, substrate diameter and density were added separately to models to compare the influence of different substrate properties. Models were compared based on Akaike Information Criterion (AIC).

All analyses were carried out using R 2.15.3. [R Core Team, 2013] with the packages "asreml" [Butler, 2009] and "lme4" [Bates et al., 2013] for mixed effect model analyses as well as "randomForest" [Liaw, A., Wiener, M., 2002], "rpart" [Therneau, T., Atkinson, B., Ripley, B., 2013] and "caret" [Kuhn, 2014] for rule-based approaches. Figures were created using "ggplot2" [Wickham, 2009].

7 Results

7.1 Erosivity indeces

Results showed that the model including substrate diameter, drop mass and velocity had the smallest AIC (268.89) and was therefore the preferred model. This model explained 45 % of the total variance (conditional R^2=0.45). Based on these results, the relationship between detached substrate (D_S), drop mass (m) or drop diameter (d) and velocity (v) was expressed by

$$D_S \sim m^{0.7} \cdot v^{1.0}$$

which is equivalent to

$$D_S \sim d^{2.1} \cdot v^{1.0}$$

(intercept has been omitted in these equations for simplification).

Analyzing each substrate resulted in different parameter estimates of drop mass and drop velocity. Therefore, five different relationships between detached amount of substrate and drop mass and drop velocity led to five different equations. Detachment of silt was best described by low drop mass and low drop velocity while medium sized sand was best described by high drop mass and and high drop velocity (Table 3).

Table 3: Final model equations (drop mass m and drop diameter d) that were used to calculate the best fit of splash detachment rates for substrates with different diameters and densities (n=21 for each substrate) and conditional R^2-values (intercepts of model equations have been omitted due to simplification purposes).

Substrate	Optimum equation (m)	Optimum equation (d)	Cond.R^2
Coarse sand	$D_S \sim m^{1.3} \cdot v^{0.2}$	$D_S \sim d^{3.9} \cdot v^{0.2}$	0.55
Medium sand	$D_S \sim m^{2.9} \cdot v^{3.5}$	$D_S \sim d^{8.7} \cdot v^{3.5}$	0.56
Fine sand	$D_S \sim m^{1.3} \cdot v^{2.6}$	$D_S \sim d^{3.9} \cdot v^{2.6}$	0.75
PE balls	$D_S \sim m^{0.4} \cdot v^{1.3}$	$D_S \sim d^{1.2} \cdot v^{1.3}$	0.22
Silt	$D_S \sim m^{0.5} \cdot v^{0.5}$	$D_S \sim d^{1.5} \cdot v^{0.5}$	0.50

7.2 Tree species richness effects on throughfall kinetic energy

Results showed no significant effect of plot-level tree species richness on TKE ($F_{1,21} = 0.2, P = 0.94$) (Figure 4).
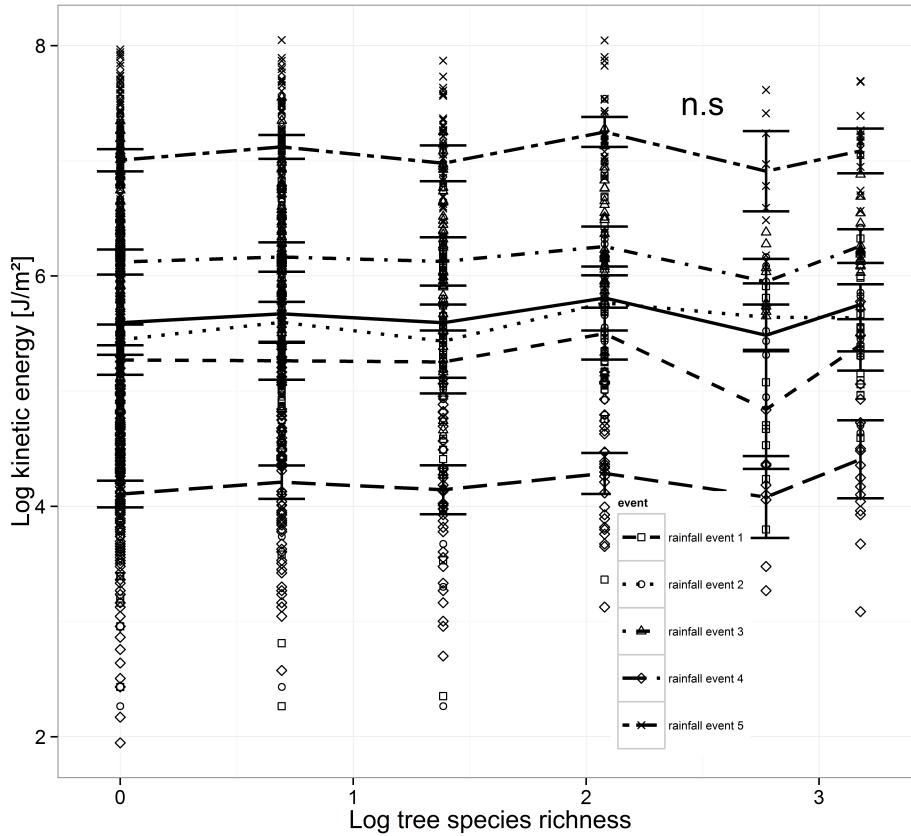
Figure 4: Log throughfall kinetic energy versus diversity treatment during five rainfall events. Black solid line symbolizes mean of all events. Different symbols show different rainfall events and dashed lines connect mean values of each tree species richness level for each rainfall event.

The highest TKE occurred in the 8-species mixture, being 41 % higher than the lowest TKE (occurring in the 16-species mixture). However, no statistical evidence could be found by comparing these two levels ($F_{1,1} = 0.68, P = 0.56$). During rainfall event 1 TKE exhibited the widest range of values between species richness levels (increase of 83 % from the 16- to the 8-species mixture). Tree species richness had no significant effect on TKE neither at each rainfall event ($F_{1,75} = 0.30, P = 0.99$), nor by focusing on one measurement position ($F_{1,114} = 1.00, P = 0.51$). However, on the neighborhood level,

tree species richness positively influenced TKE ($F_{1,45} = 4.30, P < 0.05$).

7.3 Spatial variability of throughfall kinetic energy

TKE showed a significant spatial variability (Figure 5; $F_{1,119} = 1.90, P < 0.1$). Investigating each rainfall event separately, this pattern was strong at rainfall event 1 ($F_{1,237} = 2.44, P < 0.05$) and 5 ($F_{1,237} = 2.00, P < 0.05$), whereas no significant spatial variability was found at rainfall events 2, 3 and 4. At each event, splash cups placed below the first branch showed on average 20 % less TKE than at the other positions ($F_{1,237} = 7.90, P < 0.01$; P6 in Figure 5). TKE was significantly 13 % higher in the middle of four individuals (P3 in Figure 5) compared to the mean of all other positions ($F_{1,237} = 4.30, P < 0.05$).
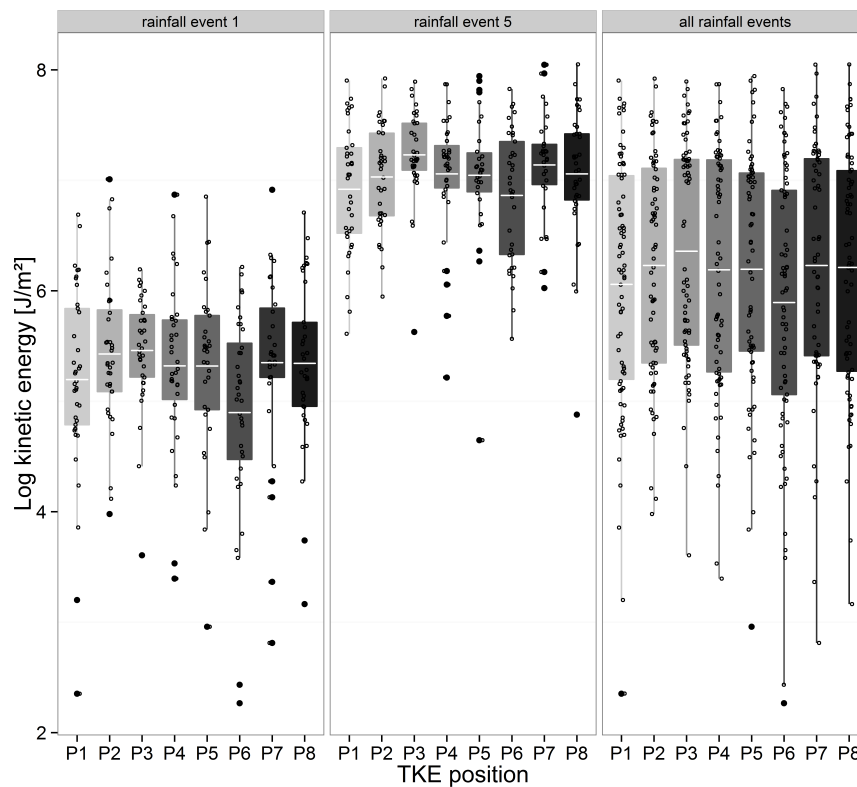
Figure 5: Log throughfall kinetic energy (TKE) and spatial position of TKE measurement at rainfall event 1 (left), rainfall event 5 (middle) and all five rainfall events (right). Different colors indicate different positions (see Figure 1) and white lines represent means.

This effect was strongest at rainfall event 5 ($F_{1,237} = 8.00, P < 0.01$). TKE was positively affected by the number of influencing tree individuals ($F_{1,119} = 6.20, P < 0.05$). TKE increased on average by 13 % from one to four influencing individuals. Regarding the single rainfall event, this pattern is only significant at rainfall event 1 ($F_{1,237} = 3.04, P < 0.05$) and rainfall event 5 ($F_{1,243} = 4.80, P < 0.01$).

7.4 Tree species identity effects on throughfall kinetic energy

TKE was species-specific and strongly depended on the rainfall event (Figure 6). Species identity significantly affected TKE at rainfall events 1 and 2 ($F_{1,6} = 6.3, P < 0.05$ and $F_{1,6} = 4.6, P < 0.05$, respectively), whereas it was not significantly related to TKE at rainfall events 3, 4, and 5, all of which had higher rainfall intensities.
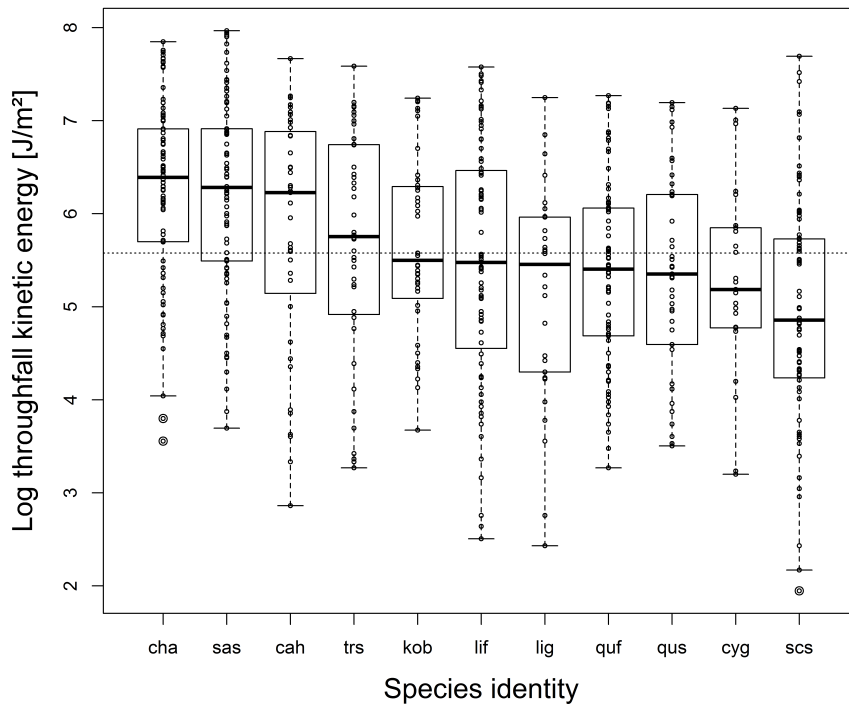
Figure 6: Throughfall kinetic energy (TKE, log-transformed) of the 11 species analyzed. Dotted line represents the total mean TKE. For abbreviations of species names see Table 2.

TKE below the canopy of *Choerospondias axillaris* and *Sapindus saponaria* were significantly higher (58 %, $F_{1,6} = 11.89, P = 0.013$, and 62 %, $F_{1,6} = 10.11, P = 0.019$, respectively) and TKE below the canopy of *Schima superba* was significantly lower (42 %, $F_{1,6} = 8.63, P = 0.026$) than the mean TKE of all other species. The effect of species identity on TKE was mediated by LAI, LA, leaf habit, leaf pinnation, tree height, number of branches, CBH, rainfall amount, crown area and SLA. Regarding categorical traits, the highest difference between factor levels occurred between different leaf habits (with a 92 % increase of mean TKE from evergreen to deciduous trees). Increase of mean TKE for pinnated leaves was 60 %. Considering vegetation continuous traits, high effect sizes were found for LA (+ 92 %), tree height (+ 33 %), LAI (− 25 %), SLA (+ 17 %), rainfall amount and CBH (each + 16 %). Effect sizes were small for the number of branches (all < 7 %).

7.5 Tree architectural and leaf trait effects on throughfall kinetic energy

Tree architectural and leaf trait effects on TKE in mixed-species stands

TKE was significantly positively affected by LAI ($F_{1,211} = 12.3, P < 0.001$), tree height ($F_{1,193} = 2.8, P < 0.1$), crown base height ($F_{1,85} = 9.4, P < 0.01$), crown area ($F_{1,215} = 4.7, P < 0.05$), and throughfall amount ($F_{1,164} = 2126, P < 0.001$), and significantly negatively affected by the number of branches ($F_{1,211} = 9.6, P < 0.01$) in all rainfall events. In contrast, GD had no significant effect on TKE ($F_{1,211} = 1.2, P > 0.1$).

Tree architectural and leaf trait effects on TKE in monocultures

In general, TKE was significantly positively related to LAI, LA, tree height, CBH and throughfall amount, but negatively influenced by the number of branches. Moreover, deciduous species (+ 13 J/m^2), species with pinnate (+ 32 J/m^2) and entire margined (+ 20 J/m^2) leaves showed higher TKE than evergreen species, species with simple leaves and species with dentate leave margins, respectively (Figure 7). TKE was not

affected by leaf thickness, leaf toughness and the trichome cover of the upper leaf surface.
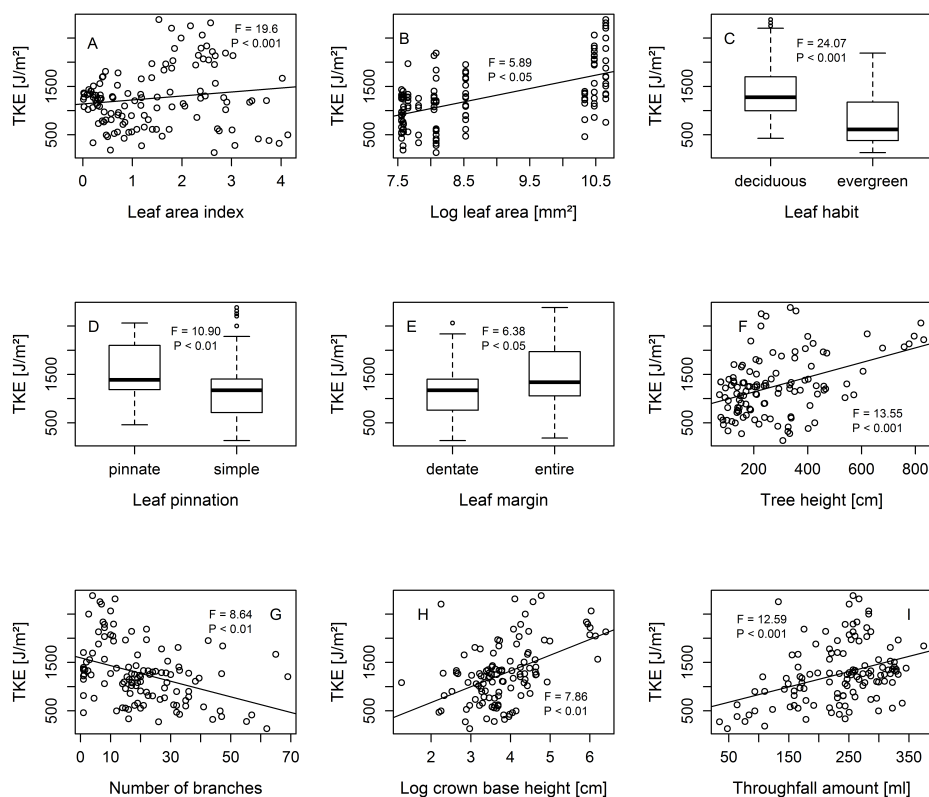
Figure 7: Throughfall kinetic energy (TKE) versus leaf traits (A-E), tree architectural traits (F-H) and abiotic covariates (I) of rainfall event 5. Black solid lines indicate linear trend.

7.6 Vegetation thresholds to mitigate erosion based on throughfall kinetic energy

The final CART model considering all rainfall events is displayed in Figure 8. Figure 13 shows modeling results of rainfall event 2 (Page 55).

Leaf area and throughfall amount were most important in predicting TKE and occurred in all six CARTs. Tree height and LAI were second prominent with five times occurrence. Position, coverage, specific leaf area, ground diameter and neighborhood diversity occurred only once. Leaf area was the most prominent variable in first splits.
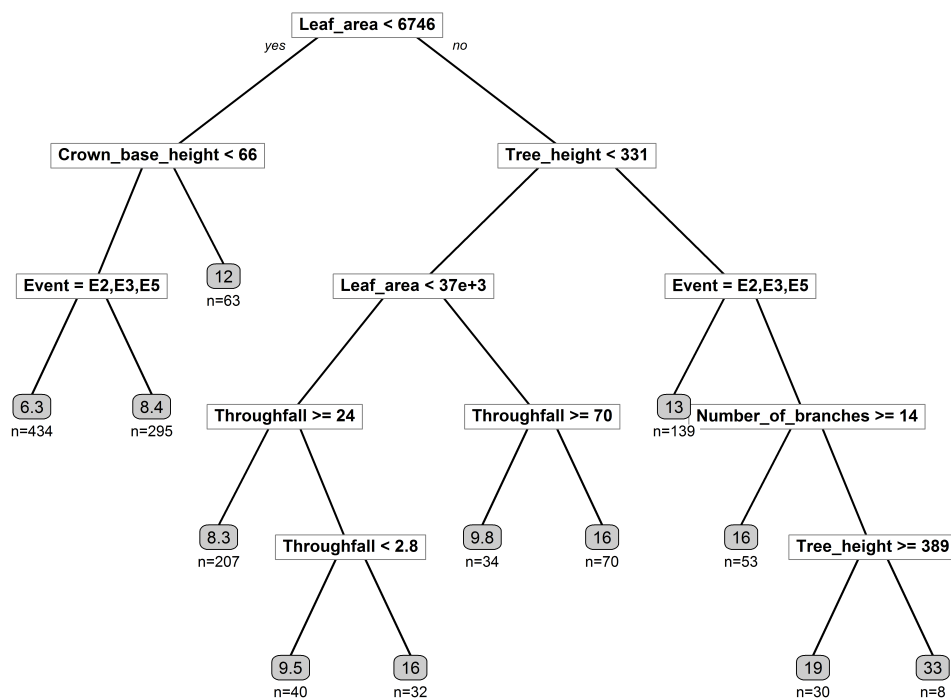
Figure 8: Classification and regression tree of all events combined and of each event. Target variable was throughfall kinetic energy (TKE) and input variables were tree species richness, spatial and number of individuals treatment, three leaf traits, seven tree architectural traits and throughfall amount. TKE was standardized to $J\ m^{-2}\ mm^{-1}$.

Throughfall amount, tree height and LAI were most prominent in second splits while leaf area, throughfall amount, LAI, number of branches and crown base height appeared most important in third splits. The thresholds of each variable depended on the rainfall event. To monitor very low TKE, thresholds were set by leaf area, throughfall and tree height as the most prominent variables. Leaf area, throughfall, LAI and crown area were most prominent in building splits to yield low TKE, while specific thresholds of leaf area, throughfall, crown area, number of branches and crown base height led to average TKE. High TKE was monitored with splits occurring by leaf area, throughfall amount and LAI. CART model performance was $R^2 = 0.68$, 0.45, 0.37, 0.46, 0.41 and 0.43 and RMSE = 32.0, 16.0, 25.7, 26.5, 4.9 and 52.7 for the model combining all rainfall events and single rainfall events 1, 2, 3, 4 and 5, respectively.

7.7 Litter cover and faunal effects on soil erosion in forests

Sediment discharge was on average lower at high than at low diversity levels, but at both timesteps no significant effect of leaf litter diversity on sediment discharge was found (Figure 9). Likewise, functional diversity had no significant effect on sediment discharge. Furthermore, no difference between mono-species plots and mixed species plots concerning sediment discharge was found nor did a single leaf species account for a leaf litter diversity effect on sediment discharge.
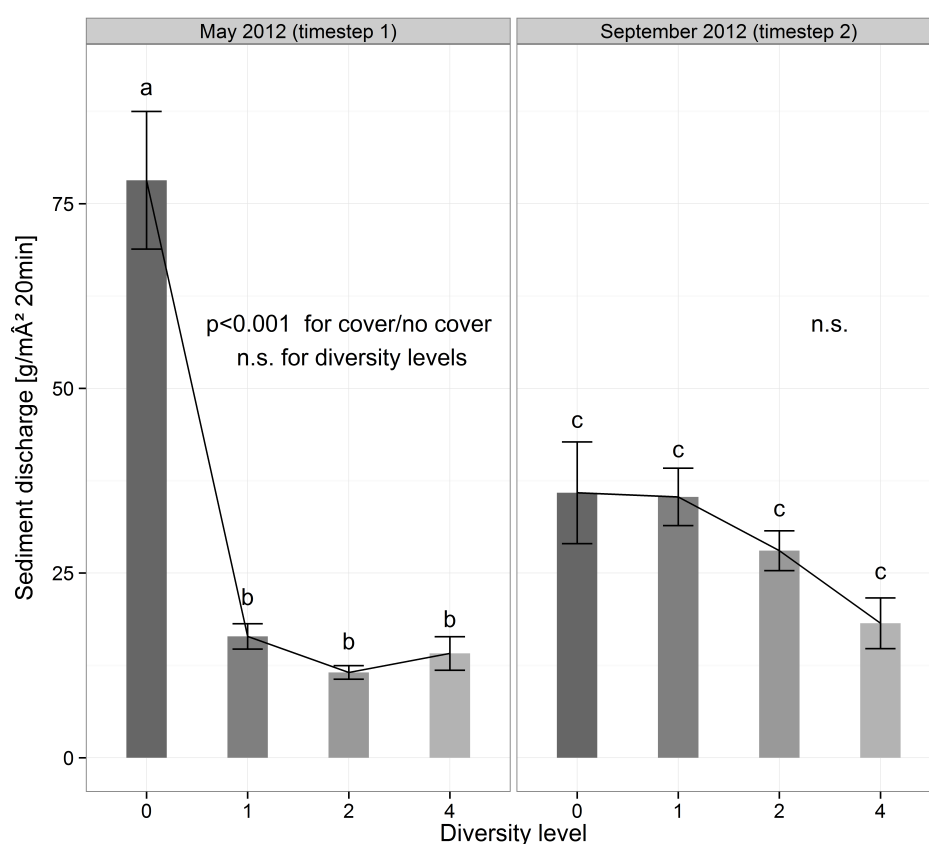
Figure 9: The effect of leaf litter diversity and bare ground (diversity = 0) on sediment discharge at timestep 1 (May 2012) and timestep 2 (September 2012). Small letters indicate significant mean differences.

A clear difference between fauna and no-fauna treatment was evident at both time-steps (Figure 10) and sediment discharge was significantly influenced by the fauna treat-

ment in May ($p < 0.001$) and September ($p < 0.05$). Discharge was 58 % higher with fauna than without. This effect is decreasing from timestep 1 (60 %) to timestep 2 (56 %).
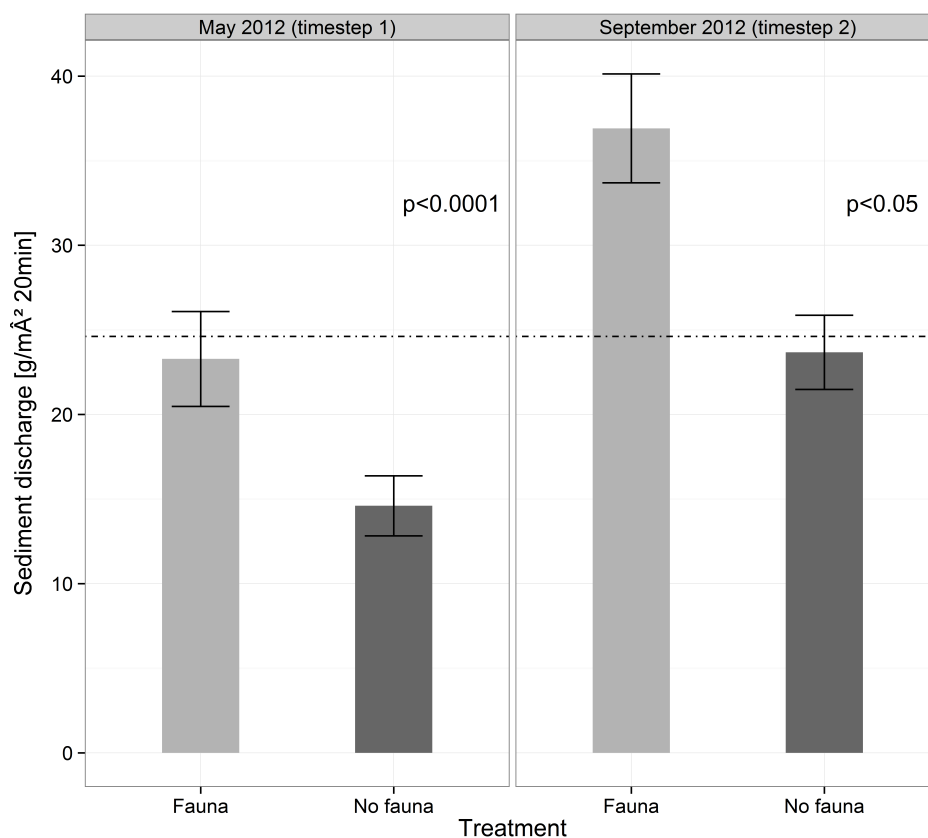
Figure 10: The effect of the fauna treatment on sediment discharge at timestep 1 (May 2012) and timestep 2 (September 2012).

Litter cover negatively affected sediment discharge ($p < 0.001$). Mean sediment discharge was 60 % higher in September than in May (Figure 9). In May mean sediment discharge decreased from bare plots (diversity level 0) to leaf covered plots by 82 % ($p < 0.001$). A slight decrease was still visible with reduced litter cover in September, but no longer significant (Figure 9).

8 Discussion

This thesis investigated rainfall kinetic energy, TKE and sediment discharge. It was shown that momentum divided by drop diameter is the best erosivity index to predict substrate detachment of various substrates. This thesis showed that TKE is affected by neighborhood species richness rather than plot-scale tree species richness. In addition, TKE was spatially variable and influenced by tree height, LAI, crown area, number of branches, CBH as tree architectural traits as well as leaf habit, leaf area, leaf margin and leaf pinnation as leaf traits. This was confirmed by using linear mixed effect models and a rule-based CART approach. Moreover, TKE was found to be highly species-specific. Furthermore, the detachment of sediment on forest floors was affected by soil meso- and macro fauna and leaf litter cover, but not by the diversity of these leaves.

8.1 Erosivity indices (Manuscript 1)

Results showed that neither M nor KE described the splash effect optimally. The overall substrate independent model showed M divided by drop diameter was the best predictor for splash detachment. This suggests that the drop diameter is less important than represented by momentum (–0.9), and that drop velocity is as important as in describing momentum. As reported in former studies (e.g. Torri et al. [1987]), grain size distribution or in this experiment substrate diameter was the ideal parameter to explain splash detachment of different substrates. For rain drops comparable findings have been reported by Abd Elbasit et al. [2010], Licznar et al. [2008], Salles et al. [2001], Salles and Poesen [2000], and Sanchez-Moreno et al. [2012] who suggested drop diameter exponents of 3 or 4 and velocity exponents of 1 or 2.

Exponents in a splash-detachment-rate-describing equation of drop mass and of drop velocity differed between substrates, and within the same substrate between different particle sizes. The use of momentum divided by drop diameter to the power of 1.5 was suggested to describe splash detachment of light substrates. These findings show less influence of drop mass as reported by Sanchez-Moreno et al. [2012] and Abd Elbasit

et al. [2010]. Regarding bigger particles and denser substrates, the use of kinetic energy multiplied by drop diameter was confirmed. Compared to Salles and Poesen [2000] and Salles et al. [2001] the influence of drop mass and drop diameter for medium sized sand was still more pronounced with exponents of 8.7 for drop diameter and 3.5 for drop velocity compared to 2 or 1 and 4, respectively. Accordingly, two groups of substrates showed different behavior under simulated rainfall: (A) small particles with medium density (diameter $< 100 \ \mu m$, density $< 1.20 \ g \ cm^{-3}$) like silt or medium sized particles (diameter $< 300 \ \mu m$, density $< 0.80 \ g \ cm^{-3}$) like PE balls with low density, and (B) large particles with high density (diameter $> 170 \ \mu m$, density $> 1.40 \ g \ cm^{-3}$) like fine, medium or coarse sized sand. Particles of group A showed very low impact of raindrop mass, but relatively high influence of raindrop velocity. In contrast, particles of group B generally showed stronger influence of drop mass and of drop velocity, with the exception that detachment of coarse sand was better described by lower velocities. Dissimilar to previous studies (e.g. Salles et al. [2001]) it can be assumed that different soil substrates (group A and B) respond to rainfall properties, like drop mass and drop velocity, in a different way depending on how energy is transformed. Due to their higher proportion of negatively charged clay minerals, smaller sized substrates (Group A) like silt are likely to have much higher cohesive forces than sand. Therefore, more energy is needed to overcome those forces; hence less energy can be transformed into kinetic energy or momentum to detach substrate particles. This results in lower drop mass and drop velocity exponents. As a consequence, medium sized sand particles were detached much more efficiently by larger drops, indicated by an exponent of 8.7, as compared to the average over all substrate types of the full model that specified an exponent of 2.1.

Considering further measurements, different rainfall erosivity indices have to be used according to the measured substrate. Thus, drop size distribution and drop velocities have to be modeled with the appropriate exponents depending on which substrate (or combination of substrates) is investigated to obtain best soil erosion modeling performance in terms of a precise rainfall erosivity prediction. Furthermore, this experiment confirmed the use of kinetic energy as appropriate erosivity index for analysis of rainfall

power using Tübingen Splash Cups with fine-sized sand [Scholten et al., 2011]. This method was then adopted for the following three studies investigating biodiversity, spatial and species-specific effects of TKE (Manuscripts 2, 3 and 4).

8.2 Throughfall kinetic energy in subtropical forests (Manuscripts 2, 3 and 4)

As the same data of the same experimental forest plantation were analyzed in Manuscripts 2, 3 and 4 with different emphasis due to the objectives (ii)-(vii), this thesis is able to consolidate results and discuss them in a greater context.

8.2.1 Biodiversity and species identity effects

No significant relationship between TKE and plot-level tree species richness was found. However, this contradicts other studies [Martin et al., 2010; Geißler et al., 2013], which showed significant effects of biodiversity on TKE and sediment discharge. The main reason for the absence of a tree species richness effect may be the young age of the plantation. In such an early successional stage, crown cover, canopy or vegetation layering have not yet fully developed [Li et al., 2014] and therefore, plot-level TKE effects based on these forest structures might not (yet) be detectable. In addition, structural effects inside the stand at the individual tree level (e.g. LAI, number of branches, crown base height, tree height, and rainfall amount) may overlay plot-level biodiversity effects [Wiersum, 1985; Brandt, 1988]. This might indicate that vegetation parameters of one single tree individual affect TKE much more at this early stage than a fully developed and interacting crown layer or tree height at plot-level.

In accordance with the second aspect of objective (ii), TKE was positively affected by tree species richness at the local neighborhood level. In the experimental young succession forest, direct neighbors and their diverse composition as measures of subplot scale may much more influence TKE than plot-scale effects. However, this effect was rather weak. A main reason for the occurrence of this effect might be the positive relation

between neighborhood species richness level and certain vegetation characteristics, i.e. tree height, crown area, and number of branches (Figure 11).
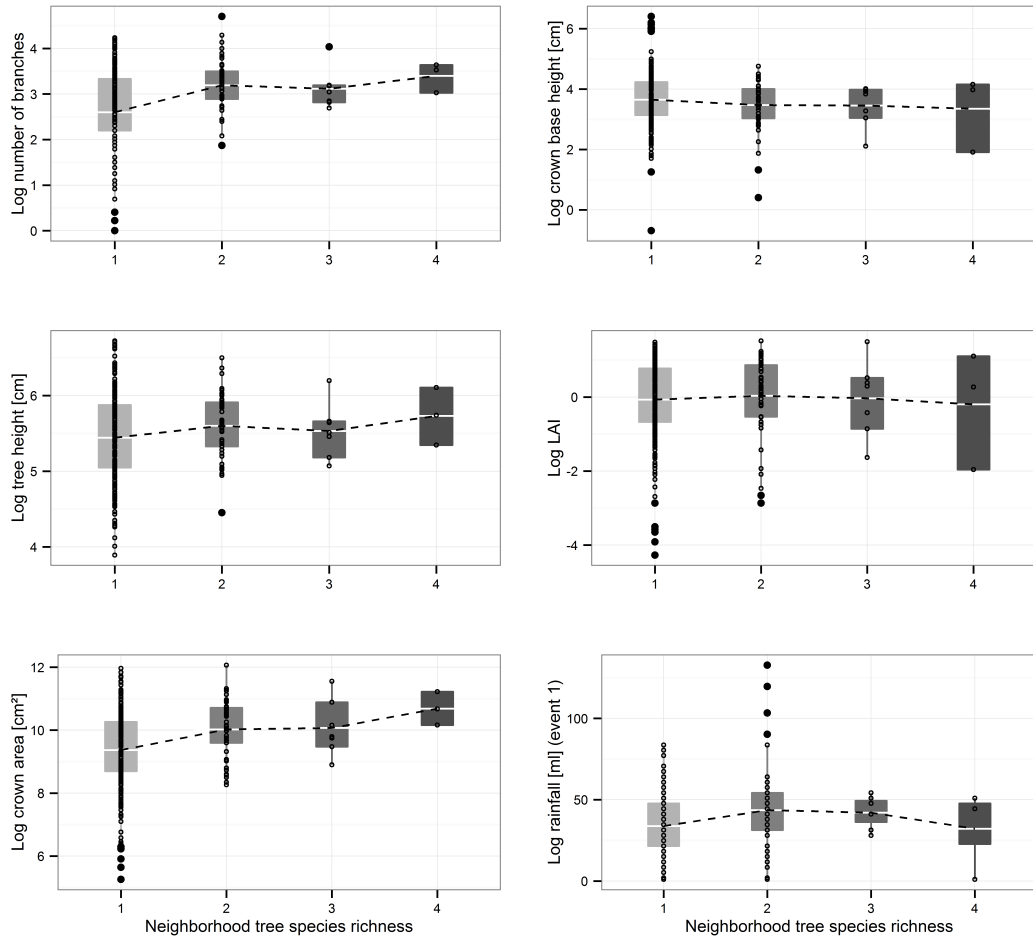
Figure 11: Vegetation covariates and neighborhood tree species richness. White lines indicate mean values and dashed black lines connect mean values of each tree species richness level.

It has been often found that the local neighborhood interactions strongly influence tree growth (tree height [Biging and Dobbertin, 1992; Getzin et al., 2008; Lang et al., 2012; Schröter et al., 2012]) and tree architecture (crown area and number of branches [Biging and Dobbertin, 1992; Getzin et al., 2008; Lang et al., 2012; Schröter et al., 2012]). These differences in vegetation structure as a response to the local neighborhood species richness might influence TKE. For instance, higher tree height in more diverse neighborhoods might lead to faster drop velocities as well as higher crown base heights

[Nanko et al., 2004; Geißler et al., 2013]. A higher crown area might lead to a higher TKE by creating bigger rain drops through confluence. However, in this study the effects of the local neighborhood species richness cannot be completely separated from the plot-level species richness effects. Higher local species richness is more likely to occur in plots with higher tree species richness. In addition, plot-level tree species richness interacts with local neighborhood species richness, if both are fitted in one model. Nevertheless, TKE of specific neighborhood richness (e.g. 2) did not vary among different plot tree species richness levels.

Weak diversity effects on several ecosystem functions have been reported frequently [Nadrowski et al., 2010]. There are generally stronger effects of species identity than of diversity on decomposition, resistance to herbivory, production or survival and thus species identity effects can overlay diversity effects [Nadrowski et al., 2010]. The present thesis widens this list with rainfall erosivity as soil erosion predictor. The overlay could be especially true for young succession plantations, where species interactions have not been developed due to low tree heights and crown widths as well as a far planting distance between tree individuals.

To confirm the above findings, besides showing the neighborhood tree species richness effect, TKE was highly species-specific.Three out of 11 species showed distinct differences in TKE compared to overall means. Among these, two species positively (*Choerospondias axillaris* and *Sapindus saponaria*) and one species negatively (*Schima superba*) affected TKE (Figure 6). Species-specific differences of throughfall amount or interception have been frequently reported [Aston, 1979; Levia and Frost, 2006]. Moreover, drop size distribution as an important driver of TKE was found to be species-specific [Nanko et al., 2013]. Nevertheless, preceding studies found no significant difference in TKE among certain species [Aston, 1979; Cao et al., 2008; Park and Cameron, 2008; Geißler et al., 2012a,b], which is in line with our findings. Furthermore, the highly significant interaction of species identity with rainfall event emphasizes the importance of abiotic characteristics in TKE distribution [Levia and Frost, 2006]. A profound influence of species identity on TKE was found at low peak intensity rainfall, whereas TKE at high

intensity rainfall was not species-specific. Higher intensity rainfall usually results in considerable canopy vibration, through which the drop sizes are reduced [Nanko et al., 2006]. Therefore, the variation of TKE at high intensity rainfall can be much less than that at low intensity rainfall, leading to absent species-specific differences. However, this effect often is superimposed by an increase of total throughfall amount with higher rainfall intensities.

The species-specific effects of canopies of *Choerospondias axillaris*, *Sapindus saponaria* and *Schima superba* have strong implications on TKE. Planting *Schima superba* which negatively affected TKE has the potential to decrease soil erosion in early successional stages. *Schima superba* is also well-known for high values of canopy interception during rainfall [Guo et al., 2006]. This can be partially attributed to a high LAI and re-interception of rainfall by lower canopy layers [Brandt, 1988; Nanko et al., 2008b]. Low TKE below *Schima superba* was also reported by [Geißler et al., 2012b]. These findings are all the more relevant, as *Schima superba* represents one of the dominant tree species in the regional species pool [Bruelheide et al., 2011; Kröber et al., 2012]. Hence, *Schima superba* provides benefits to ecosystems (ecosystem service, Chapter 4.3) in terms of mitigating the soil erosion potential. *Choerospondias axillaris* increased TKE which is consistent with high runoff volumes found for this species in comparison to peanut crops [Wei et al., 2007]. However, despite a TKE increase, higher soil loss with *Choerospondias axillaris* can be counteracted by an intact litter cover [Vis, 1986]. Nevertheless, *Choerospondias axillaris* and *Sapindus saponaria* might be responsible for the loss of keystone species due to increased soil erosion (Chapter 4.3) causing negative effects for plants and animals [Duran Zuazo et al., 2008].

To conclude, more investigations at the subplot-level have to be carried out to strictly isolate the local neighborhood diversity effects from the plot-level effects. In addition, it is expected that the impacts of tree species richness on TKE at plot-level will change with the further development of the experimental plantation [Geißler et al., 2010]. Thus, further investigation on TKE in this experimental plantation of BEF-China is needed in the future.

8.2.2 Spatial variability

TKE showed a strong spatial variability in forests. The results (Chapter 7.3) strengthen the assumption that different mechanisms cause a high spatial variability of TKE. In particular, the positions directly below the first branch of a tree and in the middle of four tree individuals showed distinct differences in TKE. Furthermore, the data showed a trend towards a positive distance to stem effect [Bochet et al., 2002; Nanko et al., 2008b] which appeared at all rainfall events with rainfall amounts $> 20\ mm$. This increase of TKE towards the crown perimeter might be caused by concentrated dripping like that from a peaked roof [Clements, 1971].

First branch effect

The first branch effect results in significantly lower rainfall erosivity (Figure 5). This can be explained by three crucial components of this effect: firstly, the breaking of drops in smaller ones when they hit these branches. Secondly, a shorter falling height leading to lower rain drop velocity and thirdly, interception of throughfall and transfer to tree stems without release [Herwitz, 1987]. The first branch effect is mediated by high LAI, the least number of branches, and low throughfall compared to all other measurement positions. High LAI values can be the reason for higher re-interception and thereafter, evaporation from leaves [Brandt, 1988]. This leads to decreasing throughfall amount and therefore, lower TKE [Aston, 1979]. Additionally, few branches prevent drops from confluence, resulting in lower TKE due to a lighter drop mass. Despite these vegetation parameters, the first branch is the last barrier for drops before reaching the soil surface [Nanko et al., 2008b]. Hence, low rain drop velocities occur more often leading to low TKE.

Position of splash cup in the middle of four tree individuals

The middle position between four tree individuals showed the highest TKE. In this thesis, this effect is attributed to a high number of branches, a low LAI, a large crown area, and, most importantly, high rainfall amounts at this position. Branches at this measurement position might also function differently than under the first branch. A high

number of branches increase the number of dripping points on the sheltered underside. It generates drop sizes of almost the same volume as coalescence drops from leaves and, thus is responsible for a higher TKE [Herwitz, 1987]. Low LAI can lead to high throughfall amounts by less interception and thus high TKE [Geißler et al., 2013]. Additionally, larger crown areas strengthen the important role of drop confluence on leaf tips by creating larger drops [Geißler et al., 2012a]. Interestingly, only horizontal parameters (number of branches, crown area, LAI) and not vertical parameters (such as tree height or crown base height) seem to differ between the positions. It might be that in such young forest stands horizontal vegetation parameters are of greater influence than vertical ones. This can also support the key role of raindrop mass for rainfall erosivity over drop velocity which is very low for small trees [Foot and Morgan, 2005; Goebes et al., 2014].

This thesis is the first to report a "number of surrounding tree individuals" (and their different composition) effect on TKE. The increase in TKE with increasing surrounding tree individuals can be ascribed to increasing throughfall, a greater number of branches, taller heights, lower LAI, and larger crown area with increasing surrounding tree individuals (Figure 12). These vegetation covariates function the same way in influencing TKE as described for the position that is influenced by four tree individuals.

To conclude, similar to the neighborhood tree species richness effect, further investigation is needed on the spatial variability of TKE. Although an effect of the number of surrounding tree individuals on TKE was shown, it could be investigated only at one position inside one plot, where TKE is influenced by four tree individuals. For future research, the relation of the species identity effect to the spatial variability seems promising, since it can be assumed that different species spatially distribute TKE differently.

8.2.3 Tree architectural and leaf trait effects

As it was discussed in the previous chapters (8.2.1 and 8.2.2), TKE was influenced by tree architectural and leaf traits (Figure 14). This thesis is the first to provide effect sizes and a ranking of those traits resulting from more than 1,400 field measurements and their analyses. A differentiation has to be made between investigating mixed-species
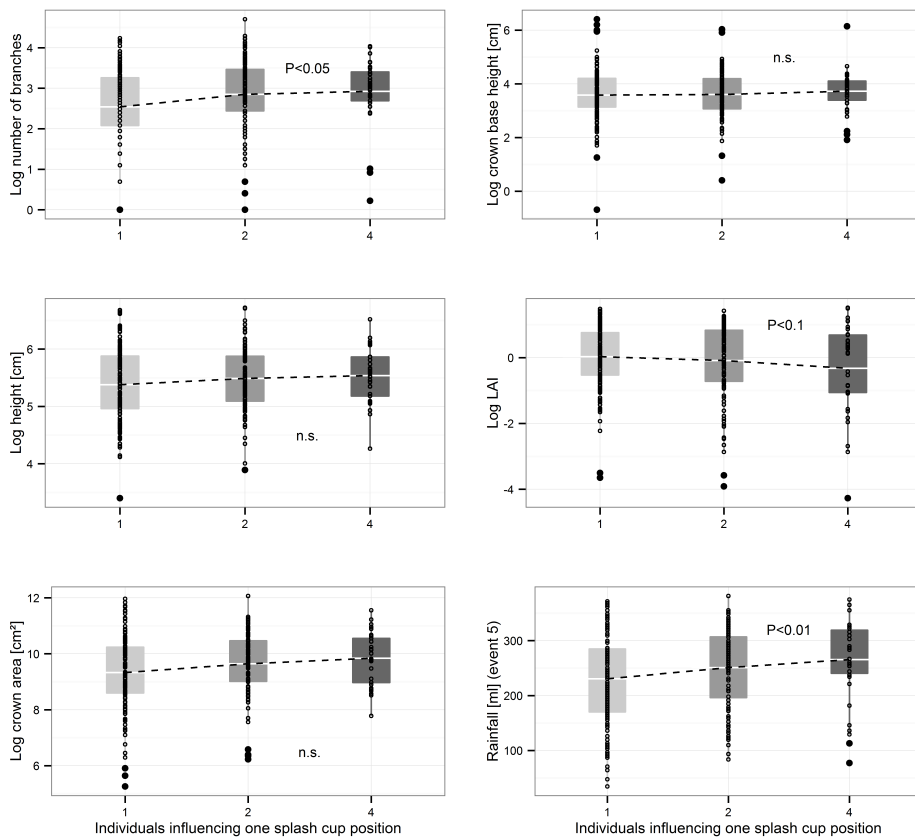
Figure 12: Vegetation covariates and "number of individuals" treatment. White lines indicate mean values and dashed black lines connect mean values of each tree species richness level.

stands and monocultures.

Regarding mixed-species stands, the linear mixed model approach in Manuscript 2 as well as the rule-based CART approach in Manuscript 4 identified similar traits that affected TKE. Whereas Manuscript 2 showed whether effects were significantly influencing TKE, results of Manuscript 4 ranked tree architectural and leaf traits by their importance in describing TKE. In general, leaf area, tree height, crown base height, crown area and LAI positively affected TKE. The branch number negatively affected TKE. Throughfall amount as abiotic factor positively affected TKE.

Leaf area was the most important trait to describe different TKE. A higher leaf area creates a larger surface for rain drop gathering as well as confluence and hence a release

of larger rain drops [Herwitz, 1987]. For instance, leaves of *Schima superba* (38,090 mm^2) increased sand loss in splash cups by 30 % compared to leaves of *Castanopsis eyrei* (12,920 mm^2) [Geißler et al., 2012a]. This shows that the erosion potential below vegetation can be dramatically reduced in comparison to that of natural rainfall with small leaf sizes.

Increasing stand heights lead to faster raindrops below the canopy and increase TKE [Geißler et al., 2010]. A larger crown width is associated with taller trees [Li et al., 2014]. This creates a larger surface on which drops gather and drip as high-erosive rain drops. However, a higher canopy may increase the space for vegetation layering which can mask the height effect [Wiersum, 1985]. It can be assumed that stand height seems to be a very important factor only in young forest plantations [Geißler et al., 2013]. When the sufficient stand height for rain drops reaching terminal velocity has been achieved, further height gain will not affect rain drop velocities.

LAI was the third important predictor of TKE. However, a positive LAI effect on TKE was observed which is contrary to the spatial treatments (Chapter 8.2.2) and previous studies [Nanko et al., 2008b; Park and Cameron, 2008; Geißler et al., 2013]. However, these studies dealt with LAI ranging from 1.5 to 11. Therefore, the positive effect of LAI might occur only for low LAI due to a close connection to canopy openness or crown area. Within these low values, a higher LAI represents a higher coverage and throughfall creation without creating more rainfall interception and drop-breaking points by different canopy layers. In addition, a higher LAI can promote confluence of rain drops and thus increase TKE if LAI is related to larger crown and total leaf area .

Crown base height as the fourth important predictor of TKE is related to tree height. CBH may constitute "the last barrier" in releasing throughfall drops and determines the falling height and thus drop velocity [Brandt, 1990].

A higher number of branches led to lower TKE due to a higher probability of drops being re-intercepted, dripping and breaking into smaller ones [Brandt, 1987; Herwitz, 1987; Geißler et al., 2012b]. Furthermore, branches gather throughfall and release it at

any random position or transfer it directly to the stem which decreases throughfall and increases stemflow [Herwitz, 1987]. The number of branches was considered as important as crown base height in predicting TKE in this thesis.

The crown area as low importance tree architectural trait affected TKE positively by increasing the surface for coalescence of rain drops and creating more dripping points.

Considering monocultures, results obtained from Manuscript 3 confirmed the positive influence of leaf area, tree height, LAI and crown base height and the negative influence of the number of branches on TKE. However, leaf traits were more important in monoculture plots, and besides leaf area, also leaf habit, leaf pinnation and leaf margin affected TKE. In addition, these eight tree architectural and leaf traits mediated the species-specific effect and thus can be considered as main drivers causing species-specific differences. Tree height and leaf area in monocultures were most important in predicting TKE, too, but CBH and number of branches affected TKE less than in mixed-species stands.

Complementary to mixed-species stands, TKE varied between deciduous and evergreen species where deciduous species showed higher TKE. Similarly, Geißler et al. [2012b] found that *Castanea henryi* and *Quercus serrata* as examples of deciduous species yielded higher TKE than the evergreen species *Schima superba*. Leaf habit represents a dominant segregation for many leaf traits and has been found to influence core functional and physiological processes specifically in the study species [Kröber et al., 2012] as well as globally [Aerts, 1995; Bugmann, 1996; Wright et al., 2005]. Deciduous species tend to have leaves with higher SLA [Reich et al., 1992], which was found to positively affect TKE. In addition, evergreen species tend to have a larger crown length ratio (ratio of crown length to the total tree height). Two mechanisms might elucidate the great variation between deciduous and evergreen species: (i) A lower tree height decreases falling height of raindrops and thus results in lower TKE; (ii) a larger crown area with lower tree height (higher crown length ration) may increase LAI which results in higher interception, leading to decreasing throughfall. Moreover, leaf pinnation (pinnate or

simple) can alter drop sizes. On the basis of higher margin circumference in relation to total leaf area [Givnish, 1978], pinnate leaves create more dripping points. Pinnate leaves showed the highest leaf area (Table 2) with the exception of *Sapindus saponaria*. However, different leaf margins contributed only marginally to species-specific changes in TKE.

Besides the significant effect of tree architectural and leaf traits on TKE, throughfall amount was highly correlated with TKE, but showed smaller effect sizes in monocultures than the findings from other studies [Tanaka et al., 2014]. In most studies, throughfall amount was found to be the major driver of spatial variability of TKE [Scholten et al., 2011; Geißler et al., 2012a]. However, species comparison revealed that shifts in drop formation and drop velocity within a specific rainfall event might have a higher impact on TKE than the total amounts of rainfall. Thus higher throughfall amounts do not necessarily lead to higher TKE at rainfall event level. Nevertheless, throughfall amount as abiotic factor was as important as tree height in describing TKE differences regarding mixed-species stands. This suggests that species-specific differences of TKE are more affected by biotic than by abiotic factors (Figure 14).

The strong impact of rainfall event on TKE suggests that the TKE variation is pre-determined by the characteristics of rainfall events, such as duration, total rain amount and rainfall intensity. Spatial variability, number of influencing tree individuals or species-specific effects occurred with different parameter values per rainfall event. In addition, within a specific rainfall event, the redistribution patterns of TKE differ among tree species. Interestingly, the effect direction of LAI and number of branches changed if the relationship to TKE was examined independent of the spatial treatment. This change was due to the integration of all measurements showing that treatment-induced mechanisms of tree architecture on TKE might function differently than those of a more general approach. For instance, LAI increased TKE in general due to an increased confluence of drops on a higher number of leaves and vegetation layers or total coverage while a low LAI (low coverage) in the middle of four individuals increased TKE due to a lower canopy water storage which in turn increased throughfall. Since the

"number of individuals" effect was only visible at low and high peak rainfall intensities, characteristics of the rainfall event might have caused this effect direction change [Goebes et al., 2015b] and TKE only reacts negatively to LAI related to very high and very low rainfall intensities (Table 1), because especially in heavy rains, a high LAI can enhance water storage [Herwitz, 1987].

Table 4: Literature overview of studies measuring throughfall kinetic energy standardized by rainfall amount. This table shows mean, minimum and maximum TKE ($Jm^{-2}mm^{-1}$). Rainfall characteristics show the amount of annual precipitation or simulated rainfall intensity and type of rainfall. Abbreviations: TF=throughfall, FF=freefall, art=artificial, SD=standard deviation.

Study	Rainfall characteristics	Mean	Minimum	Maximum
Sanchez-Moreno et al. 2012	300 - 500 mm, FF	21	4	70
Nanko 2007	2300 mm, TF + (FF)	27 (11)	23.8	32.2
Finney 1984	61 mm h^{-1} (art.), TF	7	0.4	10.5
Brandt 1987	n/a mm, TF	21.8	3	40
Nanko et al. 2008	40 mm h^{-1} (art.), TF+(FF)	17.5 (12.7)	15.9	20.7
Nanko et al. 2011	40 and 85 mm h^{-1}, TF	16.2	11.8	21.2
van Dijk et al. 2002	0.4 - 372 mm h^{-1}, FF	21	3.4	36.8
Brandt 1988	2478 mm, TF + (FF)	27 (18)	13.6	40.2
Zhou et al. 2002	1454 mm, TF	28	21	33
All 9 studies combined		20.7 (SD 6.6)	0.4	70
This study	**1642 mm, TF**	**9.6**	**0.3**	**54.8**

8.2.4 Comparison with previous studies

In this thesis, TKE [$J\ m^{-2}\ mm^{-1}$] was twofold lower compared to the mean of other studies investigating rainfall kinetic energy in open fields and below vegetation (Table 4). The age of the subtropical tree plantation can be considered as main reason for this behavior. Many trees have not yet reached full tree height which leads to low fall

velocities and thus lower TKE [Gunn and Kinzer, 1949]. Furthermore, a dense and thick crown cover has not developed in some plots in the previous six years this plantation existed. LAI and number of branches as major variables in modeling high TKE emphasized the importance of a thick crown cover (Chapter 7.5). To our knowledge, only one study measured similar TKE [Finney, 1984]. Comparable to this thesis, relatively low vegetation heights were used that did not allow rain drops to reach terminal velocity. In contrast, Nanko et al. [2008b], Nanko et al. [2011] and Sanchez-Moreno et al. [2012] measured average to high TKE which might be caused by high-intensity rainfall above 40 $mm\ h^{-1}$. These intensities exceeded those of four events measured in this study. Since throughfall amounts are similar to or lower than our measurements, rainfall intensity might function as the major abiotic factor leading to high TKE throughout all studies [Levia and Frost, 2006].

8.2.5 Vegetation thresholds to mitigate erosion based on throughfall kinetic energy

In Manuscript 4, results obtained from rule-based CART modeling were used to identify thresholds of tree architectural and leaf traits that mitigate soil erosion based on low TKE. Up to now, this thesis has been the first to discuss a wide range of tree architectural and leaf trait thresholds. In general, findings obtained from data of all events can be found in more detail by examining each event (Figure 8 and 13). Since TKE is standardized by rainfall amount, rainfall intensity and duration might change the optimal set of leaf and tree architectural traits and their thresholds.

Leaf area was the most important trait to yield very low, low, average or high TKE. With a leaf area higher than 32,000 mm^2 average to high TKE occurred, while a leaf area below 7,000 mm^2 led to very low TKE (Figure 8). The latter size was most prominent in all species and showed that species with only a large leaf area cannot function as erosion inhibitors. For instance, leaves of *Schima superba* (38,090 mm^2) increased sand loss in splash cups by 30 % compared to leaves of *Castanopsis eyrei* (12,920 mm^2) which led to TKE within the range of one standard deviation of natural rainfall [Geißler et al.,
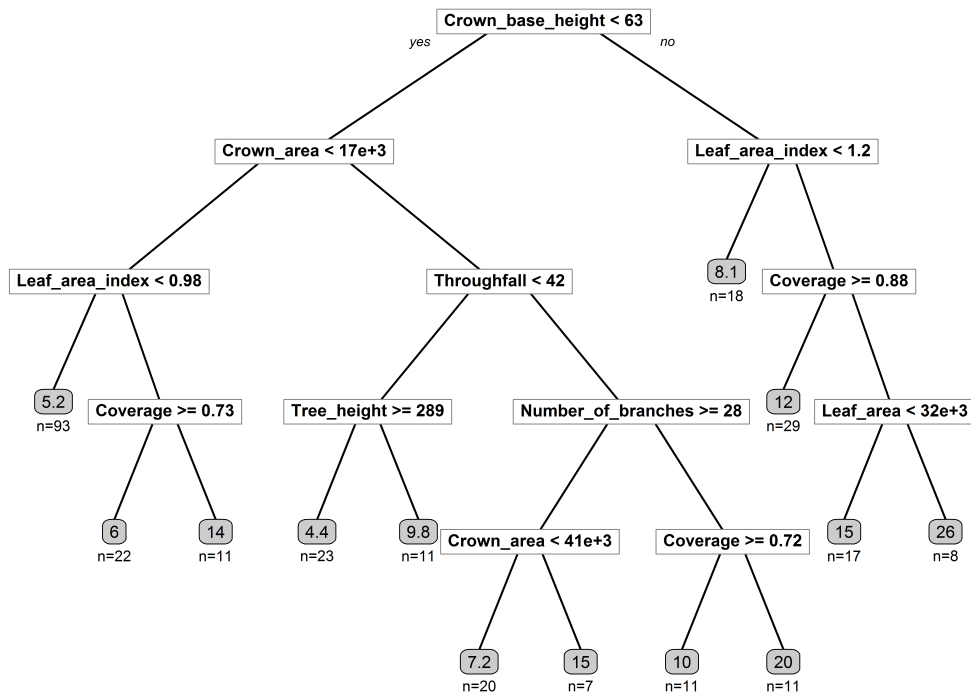
Figure 13: Classification and regression tree of rainfall event 2. Target variable was throughfall kinetic energy (TKE) and input variables were tree species richness, spatial and number of individuals treatment, three leaf traits, seven tree architectural traits and throughfall amount. TKE was standardized to $J\ m^{-2}\ mm^{-1}$.

2012b]. This shows that the erosion potential below vegetation can be dramatically reduced to that of natural rainfall with small leaf sizes.

A tree height shorter than 290 cm resulted in very low to low TKE (7.5 – 14.1 $J\ m^{-2}\ mm^{-1}$). This threshold leads to TKE only about 2 $J\ m^{-2}\ mm^{-1}$ below literature reported amounts [Brandt, 1990; Nanko et al., 2008b]. Brandt [1990] emphasized in her model that tree height changes affected TKE more with lower heights. Only tree heights above 389 cm led to high TKE, although 60 cm less height led to very low to low TKE. This suggests that there is a critical height approximately at 330 cm, above which TKE becomes highly erosive (Figure 8). However, this height is close to the mean of all species and shows that especially young trees produce non-erosive TKE.

A LAI higher than 1 led to average to high TKE (Figure 13), while a lower LAI led to very low to low TKE. A crown area higher than 40,000 cm^2 never led to very low or low TKE and thus symbolizes a maximum size below which the erosive potential of TKE can be contained. However, low rainfall intensities (rainfall event 1) counteract this effect when TKE is examined at 15 cm, 30 cm and 60 cm away from the tree stem. Nanko et al. [2008b] showed this negative effect of crown area on TKE examining areas larger than 85000 cm^2.

Rain drops falling from a crown base height lower than approximately 60 cm created very low and low TKE (Figure 13). Moss and Green [1987] showed in their study that the height-velocity relationship for rain drops increased rapidly over the first two meters and stated a threshold of 30 cm below which rain drops are non-erosive. This threshold represented the mean crown base height in this experiment and is another argument to consider low- and slow-growing tree species as erosion inhibitors.

The importance of the number of branches to classify TKE can be considered mediate. While less than 14 branches at low rainfall amounts (rainfall event 3 and 4, Table 1) led to average or high TKE (Figure 8), more than 47 branches led to very low and low TKE. If the surrounding trees consist of one species, very low TKE occurred. Species-mixtures, however, led to low TKE. Nevertheless, a classification by neighborhood tree diversity, ground diameter and specific leaf area was not prominent due to a low importance in CART.

The rule-based classification and regression tree approach showed an ambiguous effect of throughfall to predict TKE. Throughfall amounts lower than 229 mm led to low TKE while throughfall amounts higher or lower than 189 mm led to very low TKE in high rainfall amounts per event. However, very low throughfall amounts like 2.8 mm can also lead to high, average or low TKE. This neither positive nor negative effect can be ascribed to the standardization of TKE by the rainfall amount fallen at each event, which let biotic factors emerge. Thus, throughfall amount might play an important part in classifying TKE but to what extend remains unclear. This was especially visible when analyzing data of all events combined (Figure 8).

8.3 Sediment discharge and leaf litter diversity and soil fauna (Manuscript 5)

TKE can directly initiate soil erosion processes, for instance if a surface cover is absent. However, since TKE symbolizes only one part in the whole erosion process, it is clear that minimizing TKE might not lead directly to a prevention of soil erosion. As stated in Chapter 4.1 and 4.2, soil erodibility and surface coverage by stones, leaves or biological soil crusts play an important role in erosion occurrence. To further investigate the role of leaf litter cover and its diversity as well as the role of soil meso- and macrofauna on initial soil erosion, the NILEx project was conducted.

Findings emphasized the importance of a protecting litter cover in forest ecosystems against soil erosion. A surface litter cover of nearly 100 % decreased soil loss by 82 % compared to bare ground. Benkobi et al. [1993] indicated that a 60 % surface litter cover can reduce soil loss by 62 %. However, erosion rates did not differ significantly between plots with a litter cover of up to 38 % and bare ground plots in September suggesting that there is a threshold below which a coverage does not protect the soil sufficiently against erosion.

Leaf species diversity did not affect initial soil erosion. Even if rising leaf litter diversity seems to lead to a slightly smaller sediment discharge, these effects were not statistically significant. Moreover, no change in the influence of leaf litter diversity could be detected from May (full leaf coverage) to September (reduced leaf coverage). The large range of litter cover percentages indicated important differences in the development of soil cover between single leaf species but not between different leaf litter diversities. Different positive and negative feedbacks of leaf litter species are leveled within their mixtures, and the overlap and gap-filling within the leaf mixtures seems not to differ between the diversity levels [Hättenschwiler et al., 2005]. However, single leaf litter species differ in their influence on soil erosion as a result of their different sizes, shapes and decomposition rates. Sediment discharge from ROPs with leaves of *Liquidambar formosana, Machilus thunbergii* and *Cyclobalanopsis glauca* each in monocultures -

differed significantly from the mean sediment discharge. As mentioned in Chapter 8.2.1, species identity effects outperform the diversity effect. Nadrowski et al. [2010] showed in their review that decomposition was influenced by leaf litter species to the same extent as by leaf litter diversity. Thus, sediment discharge below leaf litter cover and TKE below forests are both mainly driven by species identity effects.

The presence of soil fauna positively affected sediment discharge. The activity of soil-dwelling and surface-active meso- and macrofaunal organisms might have led to the loosening and translocation of soil particles within the first centimeters of the soil surface. While springtails and mites were particularly abundant and might have contributed directly or indirectly to this process (by promoting the decomposition of the soil-protecting litter layer [Hättenschwiler and Gasser, 2005]), larger-sized and highly active ants and beetles can be assumed to have contributed significantly to the modification of the soil surface. Many species of these macrofauna groups influence soil processes in terrestrial ecosystems [Lavelle et al., 1997] and show burrowing behavior when searching for food or when trying to evade short- or long-term unsuitable microclimatic conditions on the soil surface [Swift et al., 1979; Gabet et al., 2003; Dostál et al., 2005]. When leaf cover decreases by decomposition, soil meso- and macrofauna attempt to protect themselves against transpirational water loss. This, in turn, can help to explain the fact that the impact of soil fauna slightly lost power in September. At this time, litter cover on the plots was reduced and microclimatic conditions were less optimal than earlier in the season leading to a decline of the soil faunal activity. Plots were not completely bare and thus still offered resources for decomposers and associated predators. Exclusion of the soil fauna apparently removed significant faunal impacts on soil surface slackening and decomposition processes that favor soil particles to be detached and washed away during rainfall events. Longer-term changes in microclimatic conditions, after litter is completely removed, might lead to the disappearance of many soil organisms [Gill, 1969]. Therefore, the erosion-supporting faunal effect might disappear when ROPs get completely bare and do not provide habitats for decomposing animals over a longer period. Results further showed that the soil meso- and macrofauna slightly affected litter de-

composition and thus reduced the protecting litter cover. Several of the more abundant taxa found in the plots, such as *Acari*, *Collembola* and *Oligochaeta*, play an important role in litter fragmentation and decomposition [Swift et al., 1979; Hättenschwiler and Gasser, 2005]. Nevertheless, a general pattern did not appear and results were contrary, when single leaf litter mixtures were considered. This effect is based on positive and negative feedbacks of soil fauna on different food availability and habitat conditions [Hättenschwiler and Gasser, 2005]. In this experiment positive feedbacks were slightly dominant and, as discussed above, might have strengthened the faunal effects on soil erosion. Hence, soil meso- and macrofauna affected sediment discharge rather by soil loosening and slacking than by increasing the leaf decomposition leading to a less covered soil surface.

9 Conclusion

This thesis investigated the role of biodiversity, species identity, tree architectural and leaf traits and spatial variability on rainfall erosivity (measured as throughfall kinetic energy). In addition, the influence of leaf litter diversity and soil meso- and macrofauna on initial soil erosion were investigated. The experiments were carried out in subtropical forests of southern China in the framework of the BEF-China project.

The present thesis showed that in early successional stages of a forest, only neighborhood diversity effects on soil erosion processes are present. Larger crown areas and taller tree heights in more diverse neighborhoods explained this effect by increasing TKE. In addition, TKE was highly spatially variable even at this early stage of a forest. TKE was lowest below the first branch of a tree individual and highest in the middle of four tree individuals, where a low LAI increased throughfall.

Furthermore, TKE was species-specific. Among all 11 species, two species positively (*Choerospondias axillaris* and *Sapindus saponaria*) and one species negatively (*Schima superba*) affected TKE. Thus, planting *Schima superba* has the potential to decrease soil erosion in early successional stages. The differences in TKE among varying species occur due to positive effects of tree architectural traits like tree height, leaf area index, crown area and crown base height as well as due to a negative effect of the number of branches. In addition, leaf traits like leaf area, leaf habit or leaf margin account for species-specific TKE differences. All TKE-influencing characteristics are summarized in Figure 14.

However, throughfall amount as abiotic factor as well as rainfall intensity predetermined biotic effects like the positive influence of tree architecture (tree height, crown base height, crown area) and leaf traits (leaf area index, leaf area) that induce a species-specific, tree species richness-affected and spatial variable TKE.

Considering tree architecture and leaf trait thresholds for soil erosion management, the erosive potential of TKE in this experimental forest can be mitigated by a smaller leaf area than 70 cm^2, a lower tree height than 290 cm combined with a lower CBH than 60 cm, a LAI smaller than 1, more than 47 branches and by using single tree species
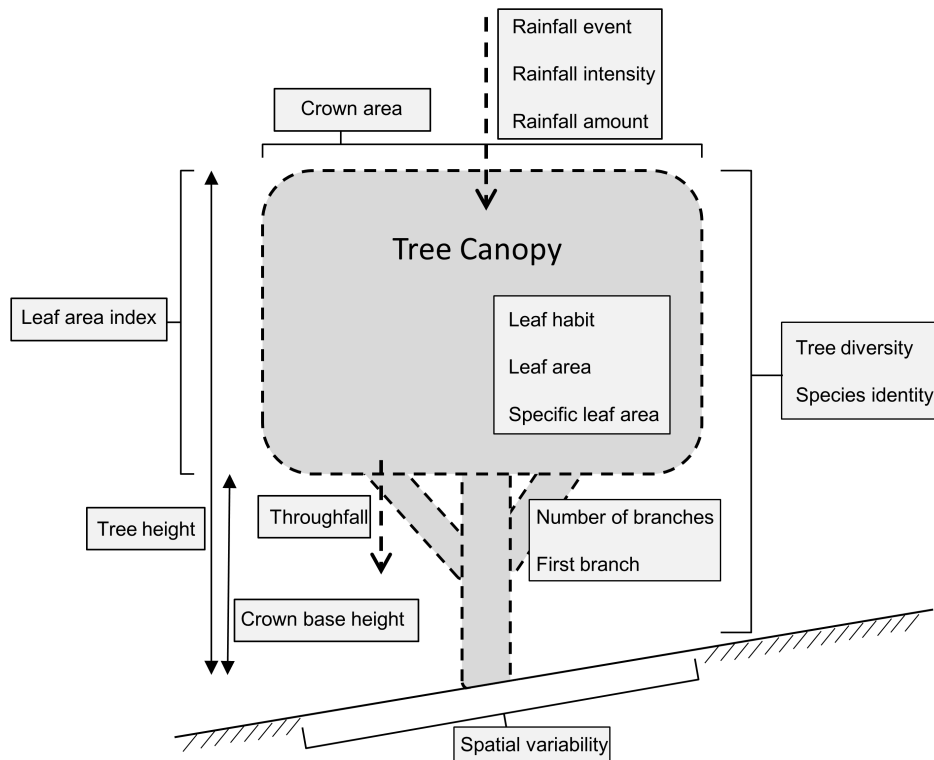
Figure 14: Graphical summary of leaf and tree architectural traits, abiotic factors as well as different treatments that affected TKE.

neighborhoods while the amount of throughfall can vary.

Furthermore, initial soil erosion (measured as sediment discharge) was not influenced by leaf litter diversity, but positively by the presence of soil meso- and macrofauna. This effect can be attributed to arthropods slackening and processing the soil surface. Indeed, only little contribution to the fauna effect on sediment discharge can be ascribed to litter decomposition by soil fauna leading to less coverage. However, leaf litter coverage highly negatively influenced the occurrence of initial erosion.

For future research, it will be essential to investigate these processes with further succession of the tree plantation of BEF-China. It can be assumed that with full-grown and dense tree canopies, tree species richness effects on TKE at plot-level appear. In addition, the combination of rainfall erosivity and initial soil erosion into one experiment might give further insights into the mechanisms of soil erosion in forests.

10 References

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Appendix

Manuscript 1 (published)

Momentum or kinetic energy - how do substrate properties influence the calculation of rainfall erosivity?

Philipp Goebes [a], Steffen Seitz [a], Christian Geißler [a], Tamás Lassu [b,c], Piet Peters [b], Manuel Seeger [d], Karin Nadrowski [e], Thomas Scholten [a]

[a] University of Tübingen, Department of Geosciences, Soil Science and Geomorphology, Rümelinstraße 19-23, 72070 Tübingen, Germany

[b] Wageningen UR, Environmental Sciences, Soil Physics and Land Management, PO Box 47, 6700AA Wageningen, Netherlands

[c] University of Pécs, Department of Physical Geography, Ifjúság útja 6, 7624 Pécs, Hungary

[d] University of Trier, Department of Spatial and Environmental Sciences, Physical Geography, 54286 Tier, Germany

[e] University of Leipzig, Faculty of Biosciences, Pharmacy and Psychology, Systematic Botany and Functional Biodiversity, Johannisallee 21, 04103 Leipzig, Germany

Abstract

Rainfall erosivity is a key component in soil erosion by water. While kinetic energy and momentum are used to describe the erosivity of rainfall, and both are derived from mass and velocity of raindrops, it is not clear how different substrates transform this energy. In our study we conducted rainfall simulation experiments to determine splash detachment amounts of five substrates (coarse sand, medium sand, fine sand, PE balls, silt) for seven different rainfall intensities (52—$116\ mm\ h^{-1}$). We used linear mixed-effect modeling (LME) to calculate erosivity predictors for each substrate. Additionally, we separated dropsize-velocity relationship into lower left and upper right quarter to investigate the effect of small and slow just as big and fast raindrops on splash detachment amounts.

We suggest using momentum divided by drop diameter as a substrate-independent erosivity predictor. To consider different substrates specific erosivity parameters are needed. Heavier substrates like sand are best described by kinetic energy multiplied by diameter whereas lighter substrates like silt point to momentum divided by diameter to the power of 1.5. Furthermore, our results show that substrates are differently affected by the size and velocity of drops. While splash detachment of light substances can be reliably predicted by drop size and velocity for small and slow drops, drop size and velocity loses its predictive power in heavier substrates like sand.

1. Introduction

The relationship between splash detachment of soil and rainfall characteristics has been in focus of research for over 60 years. Starting with Ellison (1947a), who regarded raindrop impact as dominant factor in water erosion and splash detachment of soil, several authors confirmed his findings and widened his results to a more precise link to rainfall parameters (Kinnell, 1973; Lal, 1976, 1998; Riezebos and Epema, 1985). Therefore, the erosivity of rainfall is mainly driven by intensity, drop size distribution (DSD) and terminal velocity of raindrops when hitting the soil surface. Additionally, inherent soil properties like texture and structure stability influence splash detachment

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(Bradford et al., 1987; Ellison, 1947b; Poesen and Savat, 1981; Quansah, 1981). For example, grain-size distribution has to be taken into account to improve the definition of soil detachability by raindrop impact (Torri et al., 1987).

The erosivity of rainfall can have an important influence on ecosystems through the initiation of soil erosion and is related to changes in climate (Elagib, 2011; Diodato and Bellocchi, 2009). Rainfall erosivity can increase in forest ecosystems compared to open field (Geißler et al., 2012; Nanko et al., 2004) and threaten their services and functions. In less dense ecosystems, rainfall erosivity can influence seed germination and sapling success e.g. during afforestation (Cerdà and Garcia-Fayos, 2002; Wang et al., 2012). Contrary, decreasing rainfall erosivity due to changes in climate can lower land degradation. On the other hand, increasing extreme seasonality of rainfall in semiarid lands can lead to high runoff and erosivity (Elagib, 2011).

In soil erosion modeling, soil loss by water erosion is related to rainfall by different precipitation properties. The Revised Universal Soil Loss Equation (RUSLE) includes R as the rainfall and runoff factor (Renard et al., 1997). The R factor gives information on how rain energy and intensity contribute to soil loss, using the rainfall erosivity index (EI). Other physically based models like the Water Erosion Prediction Project (WEPP) use rainfall amount, normalized peak intensity and time to peak intensity as input for rainfall erosivity (Demény et al., 2010).

Rainfall intensity and drop size contribute to soil loss in a way that smaller drops are less efficient for soil detachment with low rainfall intensities (Sharma and Gupta, 1989) and soil is more likely to be detached with higher rainfall intensities (Sloneker et al., 1976). Rainfall intensity only calculated by mean intensity and drop diameter rather than the complete DSD overestimates kinetic energy for low intensities and underestimates it for higher ones (Assouline, 2009). Underestimation of rainfall erosivity can also occur when comparing natural conditions to the prediction by the Universal Soil Loss Equation (van Dijk et al., 2002). However, decreasing rainfall intensities cannot always be linked to decreasing rain drop size and rain drop speed. Carter et al. (1974) measured decreasing drop diameter with increasing rainfall intensity above $50\ mm\ h^{-1}$. Whereas

Assouline (2009) found a threshold at 100 $mm\ h^{-1}$, Abd Elbasit et al. (2010) found this
threshold at 20 $mm\ h^{-1}$ and showed a decreasing kinetic energy with increasing rainfall
intensity. Further, these studies point out that the relation between rainfall intensity
and drop size and drop velocity is often non-linear. Therefore, more insight is needed
how the drop-size-velocity relationship (DSVR) affects splash detachment. Drop mass
and drop velocity describe the kinetic energy (KE) and momentum (M) of a rain drop.
Kinetic energy is calculated as $KE = \frac{1}{2} \cdot m \cdot v^2$ and momentum as $M = m \cdot v$ (where
m = rain drop mass and v = rain drop velocity). Some studies indicate that KE is not
describing raindrop erosivity reliably (Ghadiri and Payne, 1988) due to KE being not
a constant proportion of impact energy and suggest to better use M over KE (Rose,
1960). Other studies using rainfall simulation show that the intensity-kinetic energy
relationship follows natural conditions and KE and M can both be used to predict soil
splash (Abd Elbasit et al., 2010; Sanchez-Moreno et al., 2012). Another approach to
determine the influence of KE and M on sediment detachment was introduced by Salles
and Poesen (2000), using M multiplied by drop diameter to predict soil detachment. In
our study we take advantage of the similarity of the formulas deriving kinetic energy
and momentum: both are related to mass and velocity, but kinetic energy as a power
function with 2 as exponent and momentum as a linear relation, equivalent to an expo-
nent of 1. Thus, quantifying the exponents of the relation between splash detachment
and drop mass and velocity may help to identify whether KE, M or M multiplied by
drop diameter are best suited for describing erosivity.

For example, if kinetic energy is higher in forest ecosystems than in open field (Nanko
et al., 2004; Geißler et al., 2012) and if drops do not reach terminal velocity under
forests and are therefore slower (Nanko et al., 2008; Frasson and Krajewski, 2011),
kinetic energy can only be increased by heavier drops. Taking this together with the
observation that rain passage through forest canopies increases drop sizes, drop mass
may play a major role for rainfall erosivity especially under forest canopy. Thus, M
rather than KE may be the appropriate erosivity index under forest canopy. Since M
increases with drop diameter, the portion of large rain drops may contribute more to

the prediction of erosivity than the portion of small raindrops.

Considering the relation of KE or M to soil properties for describing splash detachment, it has been shown that detachment rates are soil-type dependent (Assouline et al., 2007; Wainwright and Parsons, 2002). Contrary to that, Angulo-Martínez et al. (2012) could not detect any difference in splash detachment amounts between three different soil types (Cambisol, Gypsisol and Solonchak) and emphasized that the differences were only caused by different rainfall intensities. Supporting these findings, Salles et al. (1999) found no difference when fitting splash detachment rates of different soil types using M multiplied by drop diameter.

The influence of soil properties on the effect of KE and M is only roughly investigated (Al-Durrah and Bradford, 1982; Bradford et al., 1987). To analyze the influence of raindrops on splash detachment best, all studies transformed rainfall intensity into a DSVR and used one DSVR per rainfall intensity. DSVR can be turned into a mathematical formula consisting of rain drop mass and velocity exponentiated with different factors fitted to the observed soil loss (Salles and Poesen, 2000).

In this study we want to examine the influence of different substrates on splash detachment and their relationship to rain drop mass and velocity. Additionally, our objectives are to test if splash detachment is sufficiently described by one average parameter for the drop size and drop velocity relationship alone. Therefore, we divided it into specific intensities using the lower left and upper right quarter of the relationship graph. We may find distinct differences between these wide ranges.

We propose the following hypotheses:

1. The momentum of large drops (upper right quarter) is best suited to predict substrate detachment, given that substrate diameter is considered as covariate

2. Fine substrates respond to the kinetic energy of small drops, while coarse substrates respond more to the momentum of large drops.

3. Small and slow drops are more suitable to describe splash detachment amounts of

light substrates whereas big and fast drops describe splash detachment amounts of heavier substrates best.

2. Materials and methods

2.1. Rainfall simulation

Our study was conducted at the Soil Physics Laboratory, Wageningen University, Netherlands. We generated rainfall using an indoor rainfall simulator with a sprinkling height of 4.0 m and a Lechler nozzle type 461.008.17 CG. To control the flow rate a regulator valve and a flow meter were used and set up to 14 L per minute. Within the nozzles' heterogeneous sprinkling behavior we could produce seven different rainfall intensities ranging from 52 mm h^{-1} to 116 mm h^{-1} on an area of 2 m^2 . They were validated by three test runs of 15 min each and runs differ to a maximum of 5% error at each position. Every chosen position ensured no detached substrate splashing to the other positions (Legout et al., 2005; Leguédois et al., 2005). For measurements, we used intensities of 52, 60, 72, 80, 88, 100 and 116 mm h^{-1} . Since drop velocity decreases slightly with increasing intensity, we used inverse velocity for our calculations.

2.2. Measurement of drop-size-velocity relationship (DSVR)

We recorded the rain drop-size-velocity relationship by an optical disdrometer (Thies laser precipitation monitor, LPM) on every chosen intensity spot with two replicates (Bloemink and Lanzinger, 2005; Lanzinger et al., 2006; Salles and Poesen, 1998). From the DSVR, the distributions of drop mass and drop velocity were calculated. We derived three different distributions for each intensity:

1. the complete spectrum (all drops),

2. the lower left quarter (slow and small drops) and

3. the upper right quarter (fast and big drops) of the drop-size-velocity relationship

In total, we used 21 mean values of drop mass and drop velocity for further analysis. These distributions were extrapolated to be representative for a 1 min rainfall on a 1 m^2 area.

2.3. Splash cup measurements

We used the Tübingen Splash Cup (T-Cup, Scholten et al., 2011) to measure the mass of detached substrate. The T-Cup consists of three different parts: (1) water-filled polyethylene (PE) flask with a (2) carrier system connected by cotton wick to maintain stable moisture over long time and (3) a removable cup connected to the carrier system by a silk mesh that is in hydraulic contact to the carrier system and provides constant moisture. The cups themselves have a diameter of 4.6 cm and a height of 4 cm to exclude rim and wash-off effects during rainfall simulation, which was approved in field studies in China (Geißler et al., 2012). Splash cups were placed three times under every intensity spot for 15 min. We calculated the detached substrate by subtracting weight of dry material inside the cup after the rainfall event from weight of dry full-filled splash cup minus splash cup weight.

2.4. Substrates

We filled the T-Cups with five different substrates to cover a representative range of different particle sizes and densities (Table 1). All substrates were water-saturated before measurements. Detached substrate values were scaled to $g\ m^{-2}\ h^{-1}$ and standardized for further calculation.

2.5. Data analysis

Our objectives are to investigate the effect of drop size and velocity and substrate properties on particle detachment (1) for all substrates in one model, using substrate properties as covariates, and (2) for each substrate independently. For this we use the general formula

Table 1: Substrates and their characteristics (n = 21 for each substrate).

Substrate	Size (μm)	Density ($g\ cm^{-3}$)
Quartz sand (coarse)	1000–1200	1.413 ± 0.012
Quartz sand (medium)	400–600	1.420 ± 0.019
Quartz sand (fine)	125–200	1.412 ± 0.025
PE balls (artificial)	100–200	0.746 ± 0.012
Silt	2–100	1.113 ± 0.048

$$D_S = S_{dens,dia,type} \cdot m^x \cdot v^y$$

(with D_S = detached substrate and $S_{dens,dia,type}$ = substrate density, diameter or type). An effect size of 2 for y would indicate that KE explains detachment best, while an effect size of 1 would indicate, that M explains detachment best. Taking the logarithm of our model turns the formula into a linear model that can now be analyzed using mixed models (Pinheiro and Bates, 2000a,b). We focused on linear relationship since Salles and Poesen (2000) showed that there is no difference in the R^2 between linear and non-linear models when fitting erosivity functions to splash detachment rates. Differences in substrate detachment amounts were analyzed using students t-test. The relationship between substrate detachment amounts and rainfall intensity was investigated using linear models with F-statistics. For analysis with linear mixed effect models, substrate materials as well as rain simulation events were included as random factors. Models for deriving substrate-independent exponents (regarding all substrates together) were fitted including mean values of drop mass and drop velocity and the properties of the substrate (binary variable sand/no sand, continuous variables substrate particle density and mean particle diameter) using the following candidate set: (1) the full model including all substrate properties and their interactions, (2) all substrate properties without interactions, (3—6) each of the substrate properties as single covariate. Each of these 6 models was combined with (1) the overall mean drop size and velocity, and (2—3) the mean of the lower left or upper right quarter of the DSVR. Thus, our

candidate set included 18 models.

Models for deriving separate exponents for each substrate were fitted in the same way, but without using substrate qualities as covariates. The candidate set for each substrate thus included only three models, using mean values of drop mass and drop velocity calculated by (1) the complete spectrum, (2) the lower left quarter and (3) the upper right quarter of the DSVR.

From our models we can derive the exponents for mass and velocity of raindrops that best describe splash detachment rates. However, considering raindrops as globes and their density as constant, their mass is directly related to their diameter (with $d =$ drop diameter and $d_{dens} =$ drop density):

$$m = \frac{1}{6}\pi d^3 \cdot d_{dens}$$

Thus, we can use the exponent related to drop mass to derive an exponent for drop diameter.

We used maximum likelihood and compared our models based on the Akaike Information Criterion (AIC), since all models contain the same random variable structure. Out of the different candidate sets the model with the lowest AIC was identified. Restricted Maximum Likelihood was used to refit the best model. Goodness-of-fit was specified as conditional R2 (Nakagawa and Schielzeth, 2013). Model residuals did not show any violation of model assumptions (normality and homogeneity of variances). All analyses were accomplished using R 2.15.1 (R Core Team, 2013) together with the "lme4" (Bates et al., 2013) and "multicomp" (Hothorn et al., 2008) packages.

3. Results

3.1. Total amount of splashed substrate

The artificial substrate and silt show the highest splash detachment amounts whereas coarse sand shows the lowest amounts (Table 2). We found a significantly increasing splash detachment amount for all substrates with increasing simulated rainfall intensity except for fine sand and silt (Fig. 1, Table 3).

Table 2: Splash detachment amounts ($g\ m^{-2}\ h^{-1}$, n = 21) for each substrate). Small letters indicate significant mean differences.

Substrate	Mean	Standard deviation	Minimum	Maximum	Median
Quartz sand (coarse)	307 a	76	201	516	297
Quartz sand (medium)	980 b	301	568	1655	936
Quartz sand (fine)	3199 c	1314	1547	5863	2878
PE balls (artificial)	5858 d	421	5239	6589	5722
Silt	5787 d	871	4331	7588	5601

3.2. Rainfall characteristics

Our rainfall simulator produced drop sizes in the range of 0.18 mm to 6.25 mm with a mean drop size of 1.27 mm for the lowest rainfall intensity of 52 $mm\ h^1$ increasing to 1.50 mm for the highest rainfall intensity of 116 $mm\ h^1$. However, with increasing intensity we measured decreasing rain drop velocities, with 3.86–3.71 $m\ s^{-1}$ for high and low rainfall intensities, respectively. For lower intensities ($<88\ mm\ h^{-1}$) only our small drops (<0.5 mm) reach terminal velocity, for higher intensities only very small drops (<0.1 mm) do. Our drop-size-velocity relationship diagram follows a power law function for intensities below 100 $mm\ h^{-1}$ and changes to a negative linear relationship for intensities above 100 $mm\ h^{-1}$. All drop size distributions (DSD) were represented by a modified gamma probability function.
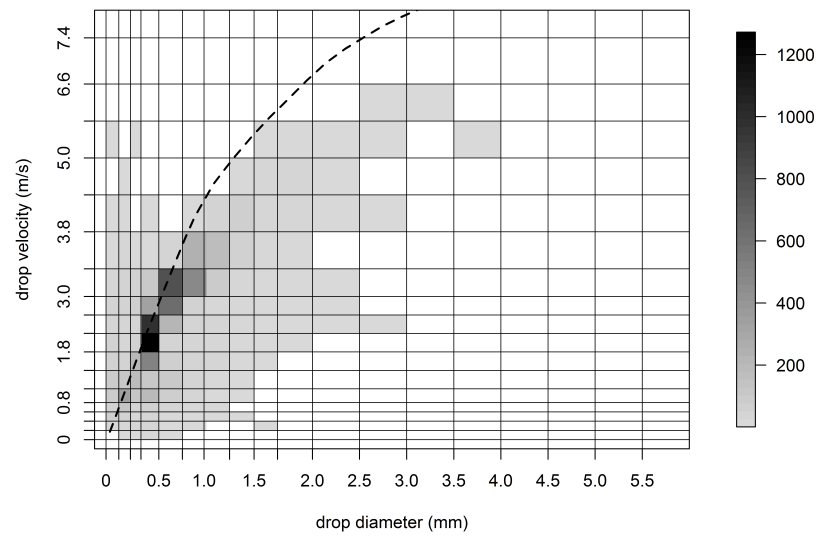
Figure 1: Drop-size-velocity relationship of intensity 80 mm h1 . Colored rectangles symbolize number of drop counts in one minute rainfall; dashed line symbolizes drop-size-velocity relationship under natural conditions measured by Gunn and Kinzer (1949).
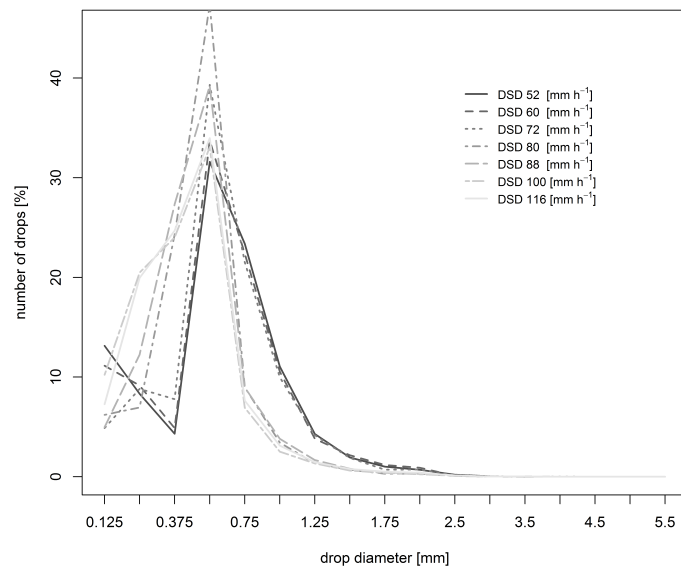
Figure 2: Drop size distribution of all intensities showing the shape of a modified gamma function.

3.3. Effect of rain properties on splash detachment (substrate-independent)

Our results show that the model including substrate diameter ($p < 0.05$), drop mass and velocity calculated from the lower left quarter of the DSVR as well as their interactions have the smallest AIC (268.89) and is therefore the preferred model. This model explains 45% of the total variance (conditional $R^2 = 0.45$).

Based on these results, the relationship between detached substrate (D_S), drop mass (m) and velocity (v) can be expressed by

$$D_S \sim m^{0.7} \cdot v^{1.0}$$

which is equivalent to

$$D_S \sim d^{2.1} \cdot v^{1.0}$$

(intercept and interaction of d (or m) and v with substrate diamter have been omitted in these equations for simplification).

Table 3: Overview of linear modeling results of splash detachment amounts in relation to rainfall intensity (with I = rainfall intensity).

Substrate	Equation	p-Value
Quartz sand (coarse)	$log(D_S) = 3.28 + 0.57 \cdot log(I)$	0.015 *
Quartz sand (medium)	$log(D_S) = 3.58 + 0.75 \cdot log(I)$	< 0.001 ***
Quartz sand (fine)	$log(D_S) = 5.19 + 0.65 \cdot log(I)$	0.066
PE balls (artificial)	$log(D_S) = 8.12 + 0.13 \cdot log(I)$	0.029 *
Silt	$log(D_S) = 8.12 + 0.12 \cdot log(I)$	0.333

3.4. Effect of rain properties on splash detachment of different substrates

Analyzing each substrate derives different parameter estimates of drop mass and drop velocity. Furthermore, depending on which substrate was used, not only mass and

velocity from the complete DSVR apply to the best model, but also the lower left and the upper right quarter of the DSVR. Therefore, five different relationships between detached amount of substrate and drop mass and drop velocity are resulting in five different equations.

Detachment of silt is best described by drop mass and velocity resulting from the lower left quarter of the DSVR as well as detachment of the artificial substrate and coarse sand. Contrastingly, fine sand is best described by the upper right quarter of the DSVR and medium sand by the complete DSVR (Table 4).

Table 4: Optimum DSVR and equation that were used to calculate the best fit of splash detachment rates for substrates with different diameters and densities (n = 21 for each substrate) and conditional $R^{2]}$-values (intercepts of model equations have been omitted due to simplification purposes).

Substrate	Optimum DSVR	Optimum equation	Cond. R^2
Quartz sand (coarse)	Lower left quarter	$D_S \sim m^{1.3} \cdot v^{0.2} \sim d^{3.9} \cdot v^{0.2}$	0.55
Quartz sand (medium)	Compl. spectrum	$D_S \sim m^{2.9} \cdot v^{3.5} \sim d^{8.7} \cdot v^{3.5}$	0.56
Quartz sand (fine)	Upper right quarter	$D_S \sim m^{1.3} \cdot v^{2.6} \sim d^{3.9} \cdot v^{2.6}$	0.75
PE balls (artificial)	Lower left quarter	$D_S \sim m^{0.4} \cdot v^{1.3} \sim d^{1.2} \cdot v^{1.3}$	0.22
Silt	Lower left quarter	$D_S \sim m^{0.5} \cdot v^{0.5} \sim d^{1.5} \cdot v^{0.5}$	0.50

4. Discussion

Is detachment of larger substrate better described by momentum than by kinetic energy and do small and slow rain drops account for better modeling results for lighter and smaller substrates? Our results indicate that the effect of rain drop mass on splash detachment is different, but rain drop velocity is as pronounced as in momentum. We could also see that not only mean values of drop size and velocity calculated from the complete DSVR apply best to splash detachment rate, but also small and slow drops alone do for specific substrates. In the following discussion we want to show reasons for the different behavior of substrates under simulated rainfall.

4.1. Total amounts of splashed substrates

As known from other erosion studies (Legout et al., 2005; Leguédois et al., 2005), fine substrate is more likely to be detached than coarse components. Our findings support these studies. Our lightest substrate (artificial PE balls) has splash detachment amounts almost twentyfold higher than our heaviest substrate (coarse sand) with a mean of 5858 $g\ m^{-2}\ h^{-1}$ compared to a mean of 307 $g\ m^{-2}\ h^{-1}$. Although results are widespread, total amounts compared to Angulo-Martínez et al. (2012) show similar results in total splash-detached substrate and prove that results are comparable to natural conditions. Although Cambisols with silty texture, Gypsisols with sandy-loam texture and Solonchaks with clay-loam texture differ in their density and grain size, Angulo-Martínez et al. (2012) could not detect any difference in splash behavior while our results show alteration.
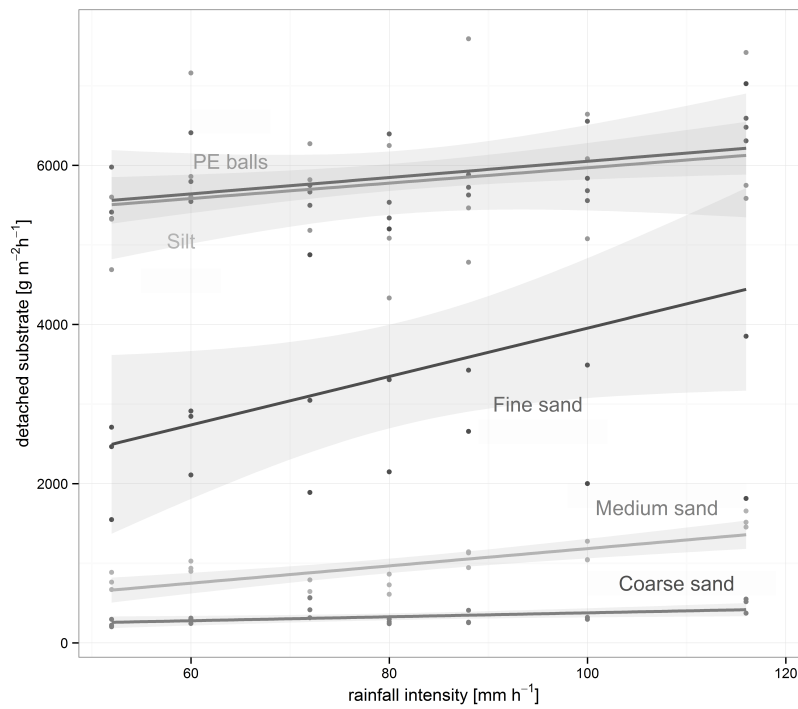

Figure 3: Detached substrate amounts per intensity with 95% conf. intervals

We assume this is caused by the use of a wider range of substrates (PE balls, sands) in our experiment. Additionally, previous studies investigated the linear relationship

between the amount of detached substrate and rainfall intensity and found similar results as in our study, where substrates follow a positive linear relationship except for small substrates like fine sand and silt (Mazurak and Mosher, 1968).

4.2. Rainfall characteristics in comparison to natural rainfall

The measurements show that not all raindrops produced by our rainfall simulator reached terminal velocity. Our drop velocities are about 18% below the calculation by Gunn and Kinzer (1949) (see Fig. 2), but can still be considered as natural conditions in this range although only small drops reach terminal velocity. Canopy interactions and understory in forests can cause such slower rain drop velocities (Nanko et al., 2008; Frasson and Krajewski, 2011). Simulated rain drop diameters represent measurements under natural conditions in an acceptable way (Willis and Tattelman, 1989; Assouline and Mualem, 1989). However, other measurements (Zanchi and Torri (1980) in Italy, Carter et al. (1974) in the USA) showed larger drops than produced by our rainfall simulator. This limitation can get crucial in the representation of our measurements considering findings under canopies by Nanko et al. (2008) who claim larger drops to appear more often due to the confluence of drops on leaves. Therefore, larger drops may play a more important role in rainfall erosivity and this means a limitation of our study. Contrary to that, Geißler et al. (2013) found a superimposing of this effect by drop retention and re-interception causing smaller drops under canopies in subtropical forests than in open field.

Drop size distribution and drop-size-velocity relationship (see Figs. 2 and 3) of our simulated rain also show typical behavior as under natural conditions. The modified gamma probability distribution (Ulbrich, 1983) of our rain drop size was measured under different conditions by many authors (Cerdà, 1997 under freefall; Frasson and Krajewski, 2011 under maize canopy; Sauvageot and Lacaux, 1995 in different latitudes). Our DSVR can be described by the function introduced by Gunn and Kinzer (1949) but with a lower limit (Wang and Pruppacher, 1977; Frasson and Krajewski, 2011) and again shows strong similarities to natural conditions.

4.3. Effect of rain properties on substrate-independent splash detachment - momentum or kinetic energy

Our results show that neither M nor KE best describe the splash effect. Our overall substrate-independent model derives from Eq. (3) which means that the predictor for splash detachment is M divided by drop diameter. This suggests that the drop diameter is less important than represented by momentum (0.9), and velocity is as important as in describing momentum. As reported in former studies (e.g. Torri et al., 1987), grain size distribution or in our case substrate diameter is the ideal parameter to explain splash detachment of different substrates, Therefore, hypothesis 1 can be affirmed for substrate diameter as most important substrate property (see Section 4.4), but not for momentum as best predictor for substrate detachment. For rain drops comparable findings have been reported by Abd Elbasit et al. (2010), Licznar et al. (2008), Salles et al. (1999), Salles and Poesen (2000), and Sanchez-Moreno et al. (2012) who suggested drop diameter exponents of 3 or 4 and velocity exponents of 1 or 2.

4.4. Different substrates account for different erosivity indices

Different to Salles et al. (1999) we used particle size distributions with a closer range of particle size for each substrate and detected distinct differences regarding the influence of drop mass and drop velocity on splash detachment. Additionally, it is not adequate to use only one equation in relation to drop size and drop velocity for different types of substrates. We could show that exponents in a splash-detachment-rate-describing equation of drop mass and of drop velocity differ between substrates, and within the same substrate between different particle sizes. The exponent of drop mass ranges from 0.4 for silt to 2.9 for medium sized sand. For velocity, the range is between 0.2 and 3.5. For light substrates we suggest the use of momentum divided by diameterto the power of 1.5 to describe splash detachment. These findings show less influence of drop mass than Sanchez-Moreno et al. (2012) and Abd Elbasit et al. (2010) had figured out.
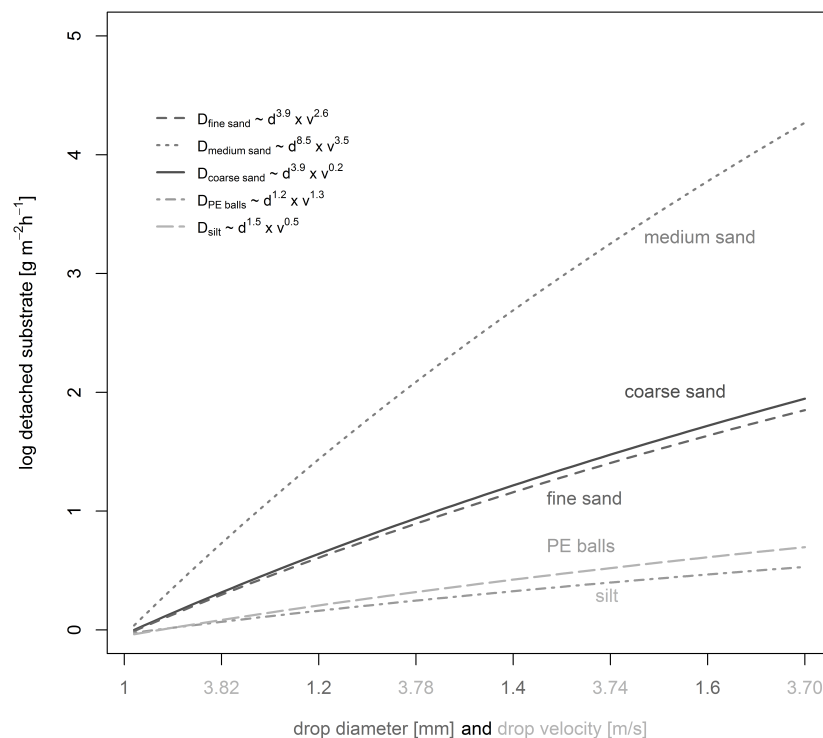
Figure 4: Splash detachment functions of different substrates (see Table 4) given by the product of drop diameter (dark grey) and drop velocity (light grey) for each substrate. After calculation, detached substrate amounts were log-transformed and intercept set to 0 for better comparison

Regarding bigger particles and denser substrates, our measurements confirm the use of kinetic energy multiplied by drop diameter (Fig. 4). Compared to Salles et al. (1999) and Salles and Poesen (2000) the influence of drop mass and drop diameter for medium sized sand is still more pronounced with exponents of 8.7 for drop diameter and 3.5 for drop velocity compared to 4 and 2 or 1, respectively. Hypothesis 2 has to be refused considering these findings.

Accordingly, we found that two groups of substrates show different behavior under simulated rainfall:

(A) small particles with medium density (diameter $< 100\ \mu m$, density $< 1.20\ g\ cm^{-3}$) like silt or medium sized particles (diameter $< 300\ \mu m$, density $< 0.80\ gcm^{-3}$) like PE balls with low density, and

(B) large particles with high density (diameter $> 170~\mu m$, density $> 1.40~gcm^{-3}$) like fine, medium or coarse sized sand.

Particles of group A show very low impact of raindrop mass, but relatively high influence of raindrop velocity. In contrast, particles of group B generally show stronger influence of drop mass and of drop velocity, with the exception that detachment of coarse sand is better described by lower velocities. Dissimilar to previous studies (e.g. Salles et al., 1999) we can assume that different soil substrates (group A and B) respond to rainfall properties like drop mass and drop velocity in a different way on how energy is transformed. Smaller sized substrates as silt are likely to have much higher cohesive forces due to their higher proportion of negatively charged clay minerals compared to sand. Therefore, more energy is needed to overcome those forces; hence less energy can be transformed into kinetic energy or momentum to detach substrate particles. This results in lower drop mass and drop velocity exponents.

Comparing our substrate-independent model with the substrate-specific models, we see that substrate type matters. Medium sized sand particles are detached much more efficiently by larger drops, indicated by an exponent of 8.7 as compared to the average over all substrate types of the full model given by 2.1. Thus, an increase in drop diameter is less important for detaching other substrates. This can be seen in group A where substrate particles show low influence of drop mass due to cohesiveness and in group B, where large substrate particles of our coarse sand show low influence of drop mass due to their size and weight. Raindrops need more energy to move these particles which again results in lower drop mass and drop velocity exponents.

4.5. Drop-size-velocity relationships and different substrates

Our results show that detachment of substrate is highly significant for the lower left and upper right quarter of the DSVR rather than for the complete drop size and velocity spectrum. The lower left quarter of the DSVR is best in describing splash detachment amounts independent from the type of substrate used in this study. One reason might

be the fact that rainfall simulators produce generally more small drops compared to natural conditions (Iserloh et al., 2013).

Because detachment amounts of small and light substrates (PE balls, silt) and coarse sand apply best to small and slow and fine sand applies best to large and fast raindrops, respectively, we suppose that the extremes of the DSVR apply better to the specific substrate detachment rates than the mean drop size and velocity. The reason for this behavior may be found in the energy that is needed to detach such substrates. On the other hand when considering only particles from group B, we assume that the fitted DSVRs show random alteration and consequently the shape of a DSVR cannot be used as an indicator in erosivity modeling for large substrates with high density.

5. Conclusions

Different from KE and M, we present a rainfall erosivity parameter which describes the splash effect by $\frac{mv}{d}$ which is equal to $\frac{Momentum}{d}$. This parameter yields best results for considering different substrates together with particle mean diameters ranging from 40 μm to 1100 μm and particle densities ranging from 0.7467 $g\ cm^{-3}$ to 1.4207 $g\ cm^{-3}$.

Moreover, our results show that specific erosivity parameters are needed in regard of the substrate that is detached. Our measurements show significant differences between lighter and heavier substrates and our model indicates strong influence of substrate diameter. Furthermore, we show that for heavier substrate like sand KE multiplied by diameter is best in describing splash detachment. Momentum divided by drop diameter to the power of 1.5 describes detachment amounts best for lighter substrate (silt or artificial substrate). The lower impact of drop size and drop velocity on smaller substrates can be related to higher cohesive forces between substrate particles. Further, alternations of drop-size-velocity relationships (lower left quarter with small and slow drops, upper right quarter with large and fast drops and complete DSVR) represent erosivity factors different for dissimilar substrates. Light substrate is best represented by the lower left quarter of the DSVR with slower and smaller drops, whereas for heavier

substrates, the influence of DSVR is indifferent. This should be taken into account when measuring splash erosion of contrasting substrates under different rainfall conditions.

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Kinetic energy of throughfall in subtropical forest ecosystems as a function of tree species richness and spatial variability

Philipp Goebes [a], Steffen Seitz [a], Peter Kühn [a], Ying Li [b], Pascal A. Niklaus [c], Goddert von Oheimb [d], Thomas Scholten [a]

[a] University of Tübingen, Department of Geosciences, Soil Science and Geomorphology, Rümelinstraße 19-23, 72070 Tübingen, Germany

[b] Leuphana University Lüneburg, Faculty of Sustainability, Institute of Ecology, Scharnhorststraße 1, 21335 Lüneburg, Germany

[c] University of Zürich, Institute of Evolutionary Biology and Environment, Winterthurstrasse 190, 8057 Zürich, Switzerland

[d] Technische Universität Dresden, Department of Forest Sciences, Institute of General Ecology and Environmental Protection, Chair of Biodiversity and Nature Conservation, Pienner Straße 7, 01735 Tharandt, Germany

Abstract

Soil erosion threatens ecosystem functioning by reducing soil organic carbon stocks or relocating nutrients. A common measure to protect soil against erosion is afforestation. Most of today's forest stands are monocultures due to economic reasons. However, monocultures have come under criticism due to their greater susceptibility to adverse environmental conditions and pathogens and their negative long-term impact on soil fertility. Furthermore, there is growing evidence that mixedspecies forest stands have beneficial effects on ecosystem functions and services (growth rates, nutrient cycling). Moreover, it is known that species-rich forests tend to have higher and denser crown cover and therefore, might affect soil erosion. This study investigates the role of tree species richness on throughfall kinetic energy (TKE) as an important part of the soil erosion process and examines the spatial variability of TKE in mixed-species forest stands.

The research was conducted within BEF-China, a large-scale forest biodiversity experiment in subtropical China. In summer 2013, 1,800 TKE measurements were carried out during five rainfall events. The impact of tree species richness on TKE was analyzed using a plot-level as well as a local neighborhood approach. The spatial variability of TKE at the plot-level was investigated using eight measuring positions differing in vegetation characteristics. TKE was measured using splash cups and related to the vegetation covariates tree height, crown base height, number of branches, leaf area index, stem ground diameter and crown area.

Our experiment shows that TKE was not influenced by tree species richness at the plot level. One reason might be the young age of the experimental forest where a dense and high tree canopy has not yet been developed. However, TKE was influenced by neighborhood tree species richness. In such young forests, tree species richness might only affect TKE on a small spatial scale within the direct neighborhood. Moreover, TKE showed a distinct spatial variability. Directly below the first branch of the tree individuals the lowest TKE was found (430 Jm^{-2}). This can be attributed to low rain drop velocities because of low falling heights. Measurements in the middle of four tree individuals showed the largest TKE (556 Jm^{-2}). This can be ascribed to a larger

crown area on which drops can confluence resulting in an increase of drop mass and, furthermore, to a low leaf area index increasing the throughfall amounts. The number of tree individuals that are affecting one measurement position are positively related to TKE with a 13 % increase of TKE from one surrounding tree individual to four surrounding individuals. Further investigation on TKE below grown-up trees and dense canopies is needed to confirm our findings for later successional stages.

1. Introduction

Soil erosion as an ecosystem function threatens ecosystem functioning by reducing soil organic carbon stocks, relocating nutrients and reducing the species diversity of plants, animals and microbes (Pimentel, 2006; Pimentel and Kounang, 1998). A common measure to overcome severe soil loss is afforestation, which increases ground cover and stabilizes soil aggregates by roots. However, especially rainfall erosivity is influenced by forests in many ways and only little research has been conducted on this part of the soil erosion process (Geißler et al., 2013). In general, rainfall erosivity is the product of kinetic energy and rainfall intensity (Renard and Freimund, 1994). In forests, throughfall kinetic energy (TKE) is a widely used measure to describe the power of raindrops to erode soil. Main determinants controlling TKE in forests are abiotic factors such as rainfall amount, drop size distribution and drop fall velocity as well as biotic factors such as height and density of the canopy, crown cover, leaf traits, leaf area index and branch architecture (Cao et al., 2008; Geißler et al., 2012b; Gómez et al., 2001; Hall and Calder, 1993; Herwitz, 1987; Nanko et al., 2008; Staelens et al., 2008; Tsukamoto, 1966). For instance, higher crown cover and density can 85 alter TKE by creating slower, but larger rain drops and additionally change throughfall amount. Moreover, these transformation processes can lead to higher TKE in forests than in open field (Geißler et al., 2012a; Nanko et al., 2004), yet this might be detected only in advanced succession (Geißler et al., 2010). Increasing TKE can be attributed to a drop size increase by confluence of drops on leafs and branches. Drop velocity, however, decreases in forests due to shorter falling heights. This suggests that rain drop mass has more impact on erosivity than

rain drop velocity (Goebes et al., 2014).

For several reasons huge efforts are currently made in many regions of the world to increase the forested area by means of afforestation. Most often afforestation takes place by the establishment of easily manageable monocultures. Besides the increase of timber, fuel and pulp wood production, the reduction of atmospheric CO_2 by carbon sequestration in forest soils, or the stabilization of regional climate conditions (Dixon and Wisniewski, 1995; Houghton et al., 2012), one important motive force is the improvement of erosion control. However, TKE as main driver of the erosion process is highly species-specific. For instance, TKE below Castanea henryi and Quercus serrata was higher compared to that of Schima superba, Elaeocarpus decipiens and their mixture (Geißler et al., 2012b). These differences can be attributed to species-specific differences regarding the number of branches and the angle of the first branch. Branches transfer throughfall water lateral and release it as indirect throughfall (André et al., 2011). Furthermore, even within a monoculture below a single tree, TKE is spatially variable (Clements, 1971; Staelens et al., 2008; Stout and McMahon, 1961). Nanko et al. (2011) showed a distance to stem effect, where TKE increases below a single Japanese cypress Chamaecyparis obtusa with increasing distance to the stem. In addition, TKE under this tree species is negatively affected by canopy thickness (Nanko et al., 2008).

In recent years, monocultures have increasingly come under criticism due to their greater susceptibility to adverse environmental conditions, pathogens (Hantsch et al., 2013) or herbivores (Jactel and Brockerhoff, 2007), and their negative long-term impacts on soil fertility (Puettmann et al., 2008). There is growing evidence that mixed-species forest stands have beneficial effects on ecosystem functions and services (e.g., growth rates, biomass production, nutrient cycling, light harvesting, plant nutrition, crown cover; (Forrester et al., 2006; Forrester, 2014; Gamfeldt et al., 2013; Kelty et al., 1992; Loreau et al., 2001; Richards et al., 2010). Species-specific differences in growth and biomass allocation patterns as well as plant architecture are due to niche separation. As a result, stratified canopies with a high degree of crown overlap and, thus, an increased mean vegetation cover and greater biomass density can be found in mixtures

compared to monocultures (Lang et al., 2010; Lang et al., 2012; Menalled et al., 1998; Pretzsch, 2014). Concerning soil erosion, it is known that in particular TKE reacts strongly to these parameters (Geißler et al., 120 2013; Nanko et al., 2006; Nanko et al., 2008). As a consequence, tree species richness might affect soil erosion processes. However, only very few studies yet reported tree species richness effects on TKE. In tropical conditions, a negative correlation between plant diversity and soil erosion was found (Shrestha et al., 2010). In contrast, a positive tree diversity effect on TKE was observed in a subtropical secondary forest along a range of successional stages (Geißler et al., 2013). This effect can be attributed to an increase of both, tree species richness and canopy height with increasing stand age. Throughfall drops are more likely to be re-intercepted by a thicker vegetation layer with different heights resulting in changing TKE (Geißler et al., 2013). These structural biodiversity effects can level out an increase of TKE with increasing stand height and therefore, keep TKE constant (Brandt, 1988; Wiersum, 1985).

Such biodiversity effects on rainfall erosivity were mostly assessed by using a plot-level approach (Geißler et al., 2013). However, in mixed-species stands it has been shown that local neighborhood interactions strongly influence individual-tree growth and architecture (Biging and Dobbertin, 1992; Getzin et al., 2008) and hence, might affect TKE. Therefore, in structurally complex forest stands with a heterogeneous mixture of species, spatially explicit approaches are needed to analyze the effect of biodiversity or rather tree species richness on TKE on subplot-level.

In this study we present new approaches for assessing TKE in subtropical forests at an early successional stage. We investigated the influence of tree species richness as a proxy for biodiversity on TKE by making use of a high number of replicates at the plot-level. Local neighborhood tree species richness was examined at the subplot-level. Furthermore, investigations of several spatial-specific effects on TKE have been combined to analyze these effects among a wide range of species. We developed a sampling design that can assess the influence of several vegetation parameters on TKE, for instance the distance to stem effect and the first branch effect. Additionally, we analyzed how

the spatial 145 distribution of TKE is affected by different numbers of tree individuals. Moreover, freefall kinetic energy (FKE) was compared to TKE. Our experiment relates those effects to the high number of 24 different species and provides more general, non-species-specific results. With this approach, we will test three hypotheses:

(1) TKE increases with increasing tree species richness at plot and local neighborhood scale.

(2) TKE is spatially variable due to differences in vegetation cover characteristics.

(3) TKE is higher than FKE.

2. Materials and Methods

2.1. Study site

The study site is located at Xingangshan, Jiangxi Province, PR China (N29°08–11, E117°90–93) and is part of the "Biodiversity and Ecosystem Functioning (BEF-) China" project (Bruelheide et al., 2014) with a total size of 26.7 ha (Yang et al., 2013). Elevation of the study site ranges from 108 m to 250 m with a mean of 190 m a.s.l. Slopes range from 0 to 45 degrees. The climate in Xingangshan is typical of subtropical summer monsoon regions with an average annual temperature of 17.4 °C and a mean annual rainfall of 1635 mm (own measurements, supplement: Figure 7). The wet season lasts from April to August whereas winters are relatively dry.

The experimental area holds 261 plots with seven richness levels of 0, 1, 2, 4, 8, 16 and 24 tree species (Bruelheide et al., 2014). Trees were planted after harvest of the previous stand in 2008. The plot size is 25.8 m x 25.8 m and 400 tree individuals were planted with a horizontal distance of 1.29 m. Species were randomly assigned to individual planting positions within the plots, and treatments (i.e. species richness) were randomly assigned to the plots. Further details on the general design and establishment of the BEF-China experiment are provided by Yang et al. (2013) and Bruelheide et al. (2014).

2.2. Experimental design

A total of 40 plots was used for TKE measurements during five rainfall events. 17 monocultures, 10 2-species mixtures, six 4-species mixtures, four 8-species mixtures, one 16- species mixtures and two 24-species mixtures plots have been sampled. Each plot has a core area, which consists of the central 6 x 6 tree individuals. The core area with these 36 individuals was divided into 9 sections (Figure 1).
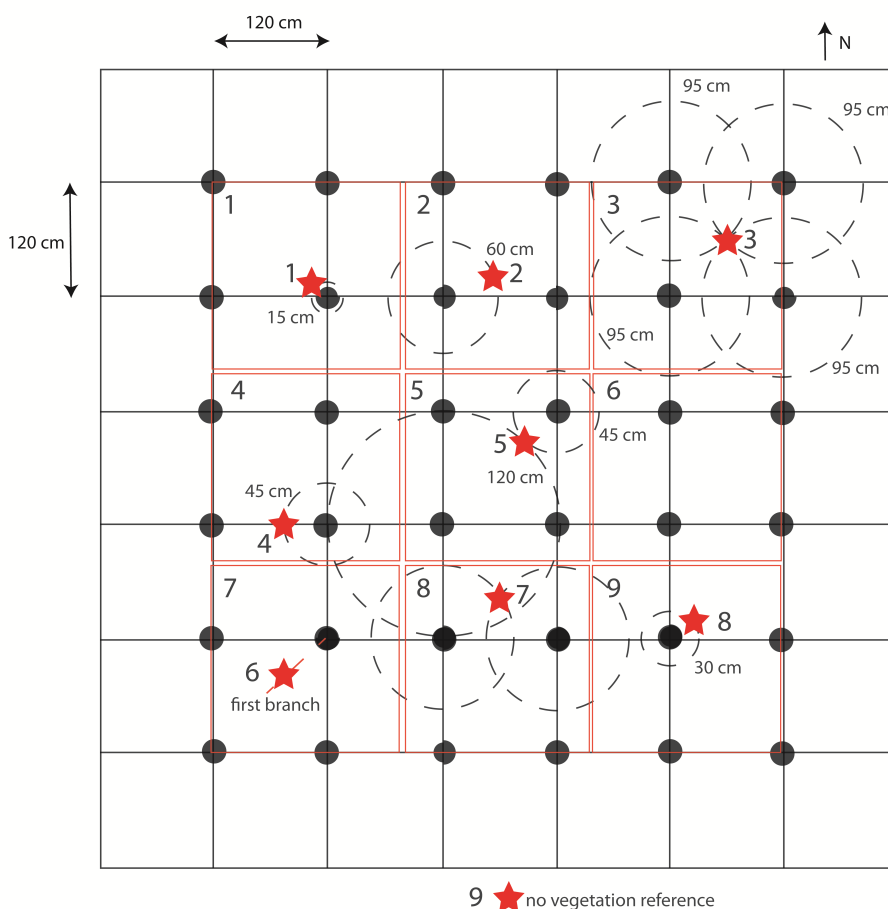
Figure 1: Sampling design with nine measurement positions. The positions have been (1) 15 cm from the stem (2) in the middle of two tree individuals, (3) in the middle of four individuals, (4) 45 cm from tree stem, (5) at the 45 cm x 120 cm intersection between two individuals, (6) the 75 cm x 75 cm intersection between two individuals, (8) 30 cm from tree stem and (9) outside the plot control (no-vegetation reference). Black dots symbolize tree individuals and red stars throughfall kinetic energy measurement position with rainfall gauge.

In eight out of the nine sections, a specific TKE measurement was located. The positions were (1) 15 *cm* away from tree stem, (2) in the middle of two tree individuals, (3) in the middle of four individuals, (4) 45 *cm* away from tree stem, (5) at the 45 *cm* x 120 *cm* intersection between two individuals, (6) below the first branch of a tree individual, (7) at the 75 *cm* x 75 *cm* intersection between two individuals, and (8) 30 *cm* away from tree stem. In each plot, these positions were randomly assigned to the eight sections. Furthermore, a ninth position was placed outside the plot as a control without vegetation. The data from the measurements on the eight positions within the plot core area was used for tree species richness and spatial analysis, and the control was used to determine FKE (see below) to compare TKE with FKE. The sampling design allows a high replication of plot-level, which is important for diversity measurements, with a satisfying number of measurement positions within a plot (subplot-level).

2.3. Throughfall kinetic energy measurement

Kinetic energy of rainfall was measured using designed by Scholten et al. (2011). Splash cups were filled with uniform fine sand (0.125 *mm*). We calculated the detached sand by subtracting weight of dry sand inside the cup after the rainfall event from weight of the dry full-filled splash cup minus splash cup weight. The detached sand can be converted into kinetic energy of rainfall ($J \ m^{-2}$ for each rainfall event) using a modified function provided by Scholten et al. (2011) and accounting for one square meter:

$$KE_{rainfall} = detached \ sand[g] \cdot 0.1455 \cdot (\frac{10,000cm^2}{\pi r^2_{splash \ cup}})$$

In general, splash cups allow a high number of replications with low costs and an easy handling in the field. In total, 1,800 splash cups were used and measured from May to July 2013 (i.e. 40 plots x 9 measurement positions x 5 rainfall events).

2.4. Measurement of rainfall

In total, five rainfall events have been registered. Rainfall amount, intensity, duration and peak intensity were determined based on 5 minutes-interval measurements at the

BEF-China climate station at our study site. Additionally, rainfall characteristics such as drop size distribution and drop size velocity relationship have been recorded by a Laser precipitation monitor by Thies (Lanzinger et al., 2006). For a higher spatial resolution, rainfall gauges (diameter 4.6 cm) have been placed next to each splash cup to measure the throughfall amount.

2.5. Measurement of of vegetation parameters

To specify the influence of vegetation on TKE, total tree height, stem diameter at 5 cm above ground (GD), crown diameters, crown base height and the number of branches of neighboring trees of measuring points were measured or counted as co-variables. Total height was measured with a measuring pole as the length from stem base to the apical meristem. GD was measured with a caliper to the nearest millimeter. Crown diameters were determined with a linear tape along two directions (north-south and east-west). Based on the measured crown diameters, crown area was calculated as an area of ellipse. Crown base height was measured as the distance up to bifurcation point of the lowest living crown branch. Additionally, LAI was determined above every splash cup position using a Nikon F50 with a Nikon AF G DX 180°and HemiView V8 (Kundela, 2009). Photos were taken under diffuse radiation conditions. In cases when more than one tree individual had an impact on the splash cup measurement, mean values of the tree individuals involved have been calculated.

2.6. Data analyses

The effects of tree species richness on TKE and the spatial variability of TKE below vegetation were tested by fitting linear mixed effect models with maximum likelihood. For the tree species richness analyses, we used the complete dataset except for the control measurements outside the plot (n = 1,600 splash cups). Out of these, 189 splash cups were not covered by trees and these splash cups were omitted for the analyses of the spatial variability of TKE (n = 1,411 splash cups).

Models concerning plot-level tree species richness effects included rainfall event, measurement position, species richness and the interaction of species richness with rainfall event as fixed effects. Species richness was split into a log-linear and a factorial term to test for both, a linear and deviation from a non-linear trend. Species composition, plot and the interaction of composition with rainfall event and position were used as random factors. The interaction of species richness with rainfall event allowed us to test whether species richness affects TKE differently during different rainfall events. The interaction between species richness and position eliminates spatial differences within one plot. To test the TKE differences across the different tree species richness levels, we introduced contrasts in our models that were fitted before species richness (monocultures against mixtures, each tree species richness levels against mean of all tree species richness levels).

To test the tree species richness effect at the neighborhood level, we used rainfall event, plot, number of neighboring tree individuals and a log-linear and factorial neighborhood species richness term as fixed effects. Composition of tree neighbors and its interaction with rainfall event were used as random factors. We included plot as a fixed effect to remove the variance between plots. Thus, the species richness effect of neighboring trees was tested within plots. To test for neighborhood species richness, only splash cups affected by two or more tree individuals on mixed-species plots were used (n = 436).

The spatial variability of TKE was analyzed using species composition and plot as random factors. Rainfall event and position as well as their interaction were used as fixed effects. Further, the eight splash cup positions per plot were assigned to three classes (further referred to as influencing individuals) consisting of splash cups influenced by one (position 1, 4, 6, 8), two (position 2, 5, 7) and four tree individuals (position 3). To investigate the mechanisms underlying the spatial variability, we firstly added vegetation parameters (total tree height, GD, number of branches, crown base height, crown area, LAI) before fitting the measurement positions. Secondly, we constructed linear mixed effect models consisting of these covariates as dependent variable and the position contrast or the individual classes as explanatory variables to distinguish between

spatial positions and their interactions with vegetation.

Pearson's correlation coefficient (r) was used to analyze rainfall parameters and to avoid multicollinearity (dismissing covariates with $r > 0.8$). The distinction between FKE and TKE was investigated using Student's t-test. Vegetation covariates have been added separately to the models to avoid underrepresentation and multicollinearity. TKE data was log-transformed before modeling. Model residuals did not show any violation of model assumptions (normality and homogeneity of variances). All analyses were conducted using R 2.15.3 (R Core Team, 2013) together with the "asreml" package (Butler, 2009).

3. Results

3.1. How tree species richness affects TKE

Our results showed no significant effect of plot-level tree species richness on TKE ($F_{1,21} = 0.2, P = 0.94$) (Figure 2). The highest TKE occurred in the 8-species mixture, being 41% higher than the lowest TKE (occurring in the 16-species mixture). However, no statistical evidence could be found by comparing these two levels ($F_{1,1} = 0.68, P = 0.56$). During rainfall event 1 TKE exhibited the widest range of values between species richness levels (increase of 83 % from the 16- to the 8-species mixture). Tree species richness had no significant effect on TKE neither at each rainfall event ($F_{1,75} = 0.30, P = 0.99$), nor by focusing on one measurement position ($F_{1,114} = 1.00, P = 0.51$). Although monocultures showed slightly lower TKE (6%) than species-mixtures, this was not statistically significant ($F_{1,21} = 0.04, P = 0.55$).

On the neighborhood level, tree species richness significantly influenced TKE ($F_{1,45} = 4.30, P < 0.05$; supplement: Figure 8). Evaluating the difference between neighborhood species richness level 1 and ¿1 showed no significant relationship to TKE. However, after accounting for these mono-mixture differences, a positive linear relationship between the different species richness levels 2, 3 and 4 was found ($F_{1,50} = 3.00, P < 0.1$). Nevertheless, neighborhood species richness analyses could not distinguish between position

effects within one plot and the plot effects because we could not realize a within-plot neighborhood species richness replication with our sampling design.
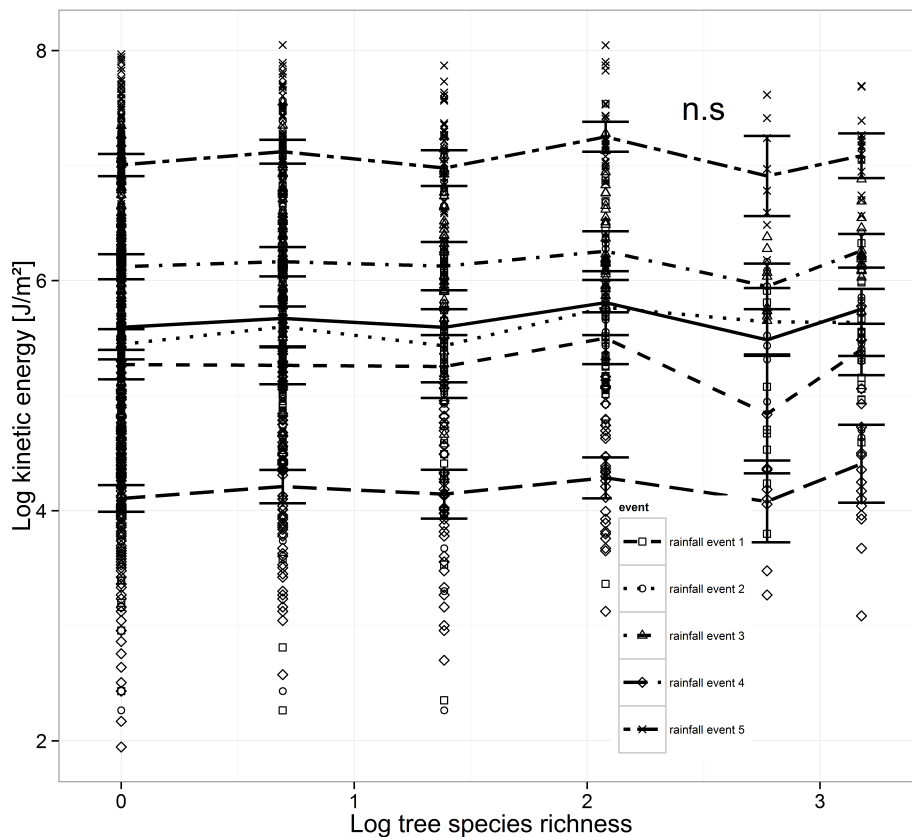
Figure 2: Log throughfall kinetic energy versus diversity treatment during five rainfall events. Black solid line symbolizes mean of all events. Different symbols show different rainfall events and dashed lines connect mean values of each tree species richness level for each rainfall event.

3.2. How tree individuals affect spatial distribution of TKE

TKE showed a significant spatial variability (Figure 3; $F_{1,119} = 1.90, P < 0.1$). Investigating each rainfall event separately, this pattern was strong at rainfall event 1 ($F_{1,237} = 2.44, P < 0.05$) and 5 ($F_{1,237} = 2.00, P < 0.05$), whereas no significant spatial variability was found at the rainfall events 2, 3 and 4. At each event, splash cups placed below the first branch showed on average 20 % less TKE than on the other positions ($F_{1,237} = 7.90, P < 0.01$; P6 in Figure 3). TKE was significantly 13

% higher in the middle of four individuals (P3 in Figure 3) compared to the mean of all other positions ($F_{1,237} = 4.30, P < 0.05$). This effect was strongest at rainfall event 5 ($F_{1,237} = 8.00, P < 0.01$). Furthermore, the effect of the spatial position on TKE was influenced by the number of tree individuals covering the splash cup (Figure 4). Overall, TKE was positively affected by the number of influencing tree individuals ($F_{1,119} = 6.20, P < 0.05$). TKE increased on average by 13 % from one to four influencing individuals. Regarding the single rainfall event, this pattern is only significant at rainfall event 1 ($F_{1,237} = 3.04, P < 0.05$) and rainfall event 5 ($F_{1,243} = 4.80, P < 0.01$).
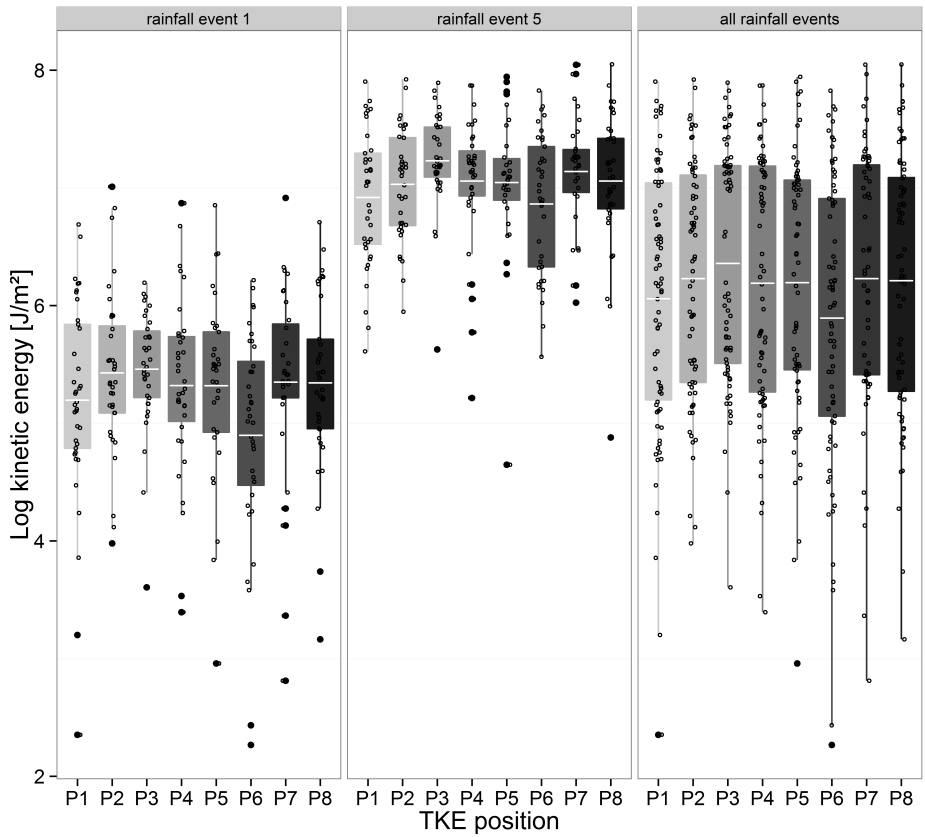
Figure 3: Log throughfall kinetic energy (TKE) and spatial position of TKE measurement at rainfall event 1 (left), at rainfall event 5 (middle) and in all five rainfall events (right). Different colors indicate different positions (see Figure 1) and white lines represent means.

Our data showed a positive trend for a distance to stem effect when considering only splash cups influenced by one tree individual in a line of 15 cm, 30 cm, 45cm and

60 cm away from the tree stem. TKE was positively affected by stem distance with a mean of 4% higher TKE per distance increment. Nevertheless, no significant relationship ($F_{1,107} = 0.40, P > 0.1$) was found.
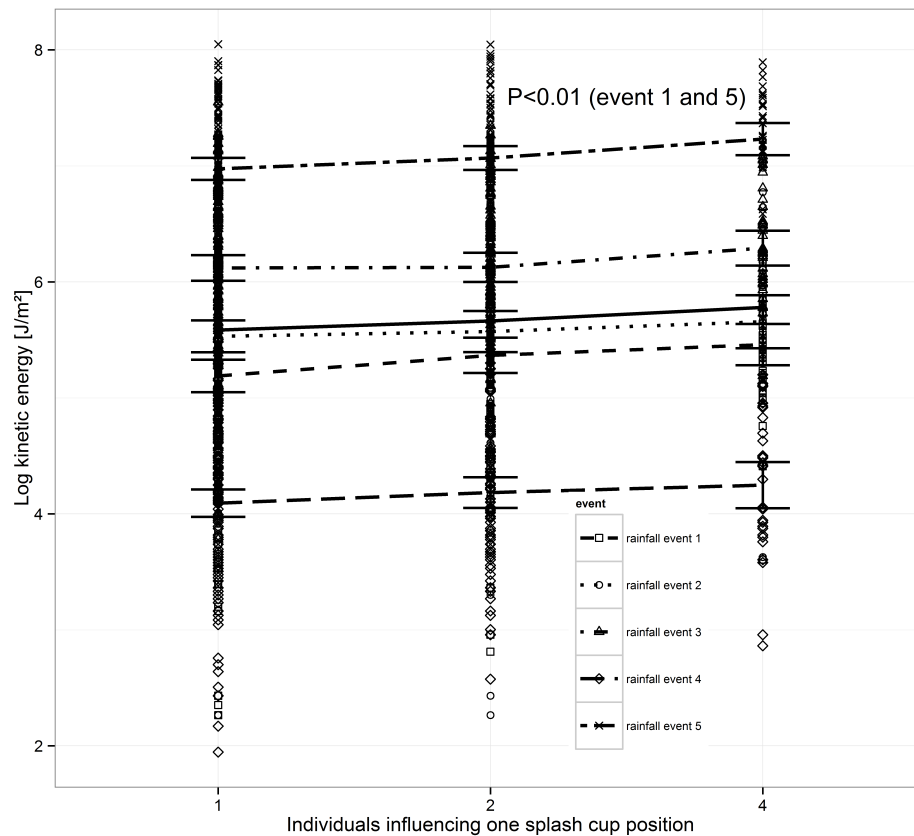
Figure 4: Log throughfall kinetic energy and "number of individuals" treatment of five rainfall events. The eight splash cup positions per plot that were covered by tree (Figure 1) were assigned to three classes: 1: splash cup is5 influenced directly by one tree individual; 2: the splash cup is influenced by two individuals; 4: the splash cup is influenced by four individuals. Black solid line symbolizes mean of all events. Different symbols show different rainfall events and dashed lines connect mean values of each treatment level for each rainfall event.

TKE was significantly positively affected by crown base height ($F_{1,85} = 9.4, P < 0.01$), tree height ($F_{1,193} = 2.8, P < 0.1$), LAI ($F_{1,211} = 12.3, P < 0.001$), crown area ($F_{1,215} = 4.7, P < 0.05$), and rainfall amount ($F_{1,164} = 2126, P < 0.001$), and significantly negatively affected by the number of branches ($F_{1,211} = 9.6, P < 0.01$) at all

rainfall events (Figure 5 only shows rainfall event 5 for simplification). In contrast, GD had no significant effect on TKE ($F_{1,211} = 1.2, P > 0.1$). However, the influence of LAI on TKE changed with the magnitude of the rainfall event ($F_{1,252} = 22, P < 0.001$ at the high magnitude event 5 to $F_{1,192} = 1.40, P > 0.1$ at the low magnitude event 4).
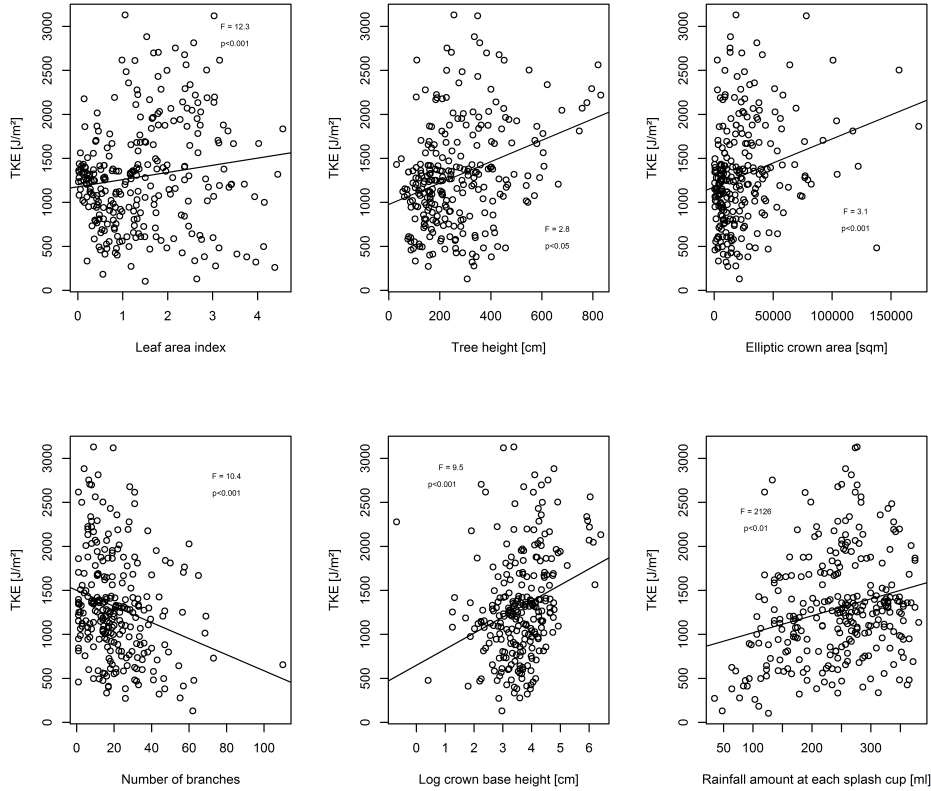
Figure 5: Throughfall kinetic energy (TKE) and vegetation covariates at rainfall event 5 (all plots and all measurement positions). Black solid line symbolizes the linear trend.

3.3. Rainfall characteristics and TKE

The characteristics of the five rainfall events are given in Table 1. All characteristics are highly positively interrelated ($r > 0.7$). This is also true for the correlation with FKE. TKE increases with increasing rainfall amount ($r = 0.99, P < 0.001$), rainfall intensity ($r = 0.95, P < 0.05$) and rainfall duration ($r = 0.73, P = 0.16$). TKE was 80 $\pm$ 50 $J\ m^{-2}$ for rainfall event 4 characterizing the lowest rainfall amounts and 1290 $\pm$

$600\ J\ m^{-2}$ for rainfall event 5 with highest rainfall amounts. Rainfall/throughfall ratio was 1.27 of all rainfall events.

Our results showed that FKE was not significantly different from TKE by considering all data. When separating the tree individuals by height, it became obvious that only for trees exceeding 330 cm height, TKE is significantly higher than FKE ($t(465) = 2.19, P < 0.05$).

Table 1: Characteristics of the five rainfall events registered from May to July 2013.

Rainfall events	Rainfall amount $[mm]$	Rainfall duration $[h]$	Mean rainfall amount in open field (ml)	Mean through-fall amount $[ml]$	Rainfall intensity I_{5min} $[mm\ h^{-1}]$	Rainfall intensity of total event $[mm\ h^{-1}]$
Event 1	23.3	10.16	40.73	35.88	12.1	2.29
Event 2	39.3	11.50	70.90	41.91	22.8	3.42
Event 3	61.2	14.50	104.25	93.77	44.4	4.25
Event 4	6.6	2.33	5.72	5.84	25.2	2.83
Event 5	185.7	30.58	303.88	246.57	127.2	6.07

4. Discussion

4.1. Effects of tree species richness on TKE

No significant relationship between TKE and plot-level tree species richness was found and, therefore, hypothesis 1 has to be rejected. However, this contradicts other studies (Geißler et al., 2013; Martin et al., 2010), which showed significant effects of biodiversity on TKE and sediment discharge. The main reason for the absence of a tree species richness effect in this study may be the young age of the plantation. In such an early successional stage, crown cover, canopy or vegetation layering have not yet fully developed (Li et al., 2014) and therefore, plot-level TKE effects based on these forest structures might not (yet) be detectable. Nevertheless, structural effects inside the stand at the individual tree level (e.g. LAI, number of branches, crown base height, tree height,

and rainfall amount) may overlay plot-level biodiversity effects (Brandt, 1988; Wiersum, 1985). This might indicate that vegetation parameters of one tree individual solely affect TKE much more at this early stage than a fully developed and interacting crown layer or tree height at plot-level. Therefore, only at the subplot-level diversity effects on TKE might be found in young stands. We, however, expect that the impacts of tree species richness on TKE will change with the further development of the experimental plantation (Geißler et al., 2010).

In accordance with the second aspect of hypothesis 1 we observed a positive tree species richness effect at the local neighborhood level on TKE. In the experimental young succession forest, direct neighbors and their diverse composition as measures of subplot scale are much more influencing TKE than plot-scale effects (see supplement: Figure 8). However, this effect is rather weak. A main reason for the occurrence of this effect might be the positive relation between neighborhood species richness level and certain vegetation characteristics, i.e. tree height, crown area, and number of branches (Figure 6).

It has been often found that the local neighborhood interactions strongly influence tree growth (in this study tree height) and tree architecture (crown area and number of branches) (Biging and Dobbertin, 1992; Getzin et al., 2008; Lang et al., 2012; Schröter et al., 2012). These differences in vegetation structure as a response to the local neighborhood species richness might influence TKE. For instance, higher tree height in more diverse neighborhoods might lead to faster drop velocities as well as higher crown base heights (Geißler et al., 2013; Nanko et al., 2004). A higher crown area might lead to a higher TKE by creating bigger rain drops through confluence. However, in our study the effects of the local neighborhood species richness cannot be completely separated from the plot-level species richness effects. Higher local species richness is more likely to occur in plots with higher tree species richness. In addition, plot-level tree species richness interacts with local neighborhood species richness, if both are fitted in one model. Nevertheless, TKE of specific neighborhood richness (e.g. 2) did not vary among different plot tree species richness levels.
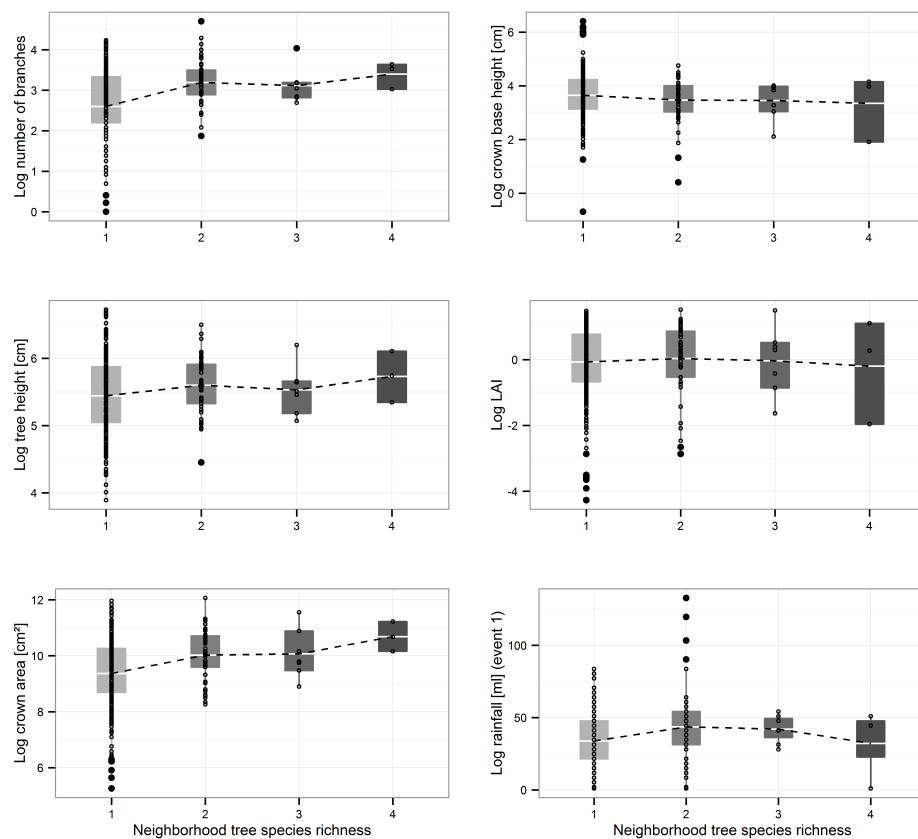
Figure 6: Vegetation covariates and neighborhood tree species richness. White lines indicate mean values and dashed black lines connect mean values of each tree species richness level.

To improve the investigation of TKE on plot- and subplot-level, changes of the sampling design have to be made. For analyzing the effects of local neighborhood diversity, only one position (P3) could be used at which tree species richness levels of 3 and 4 were realized. More investigations at the subplot level have to be carried out to strictly isolate the local neighborhood diversity effects from the plot-level effects.

4.2. Spatial variability of TKE

We found that TKE had a strong spatial variability below forests and, therefore, hypothesis 2 can be confirmed. Our findings strengthen the assumption that different mechanisms cause a high TKE spatial variability within forests. In particular, the positions directly below the first branch of a tree and in the middle of four tree individuals

showed distinct differences in TKE. Furthermore, we observed a trend towards a positive distance to stem effect (Bochet et al., 2002; Nanko et al., 2008), which appears at all rainfall events with rainfall amounts $> 20\ mm$. This increase of TKE towards the crown perimeter is caused by concentrated dripping like that from a peaked roof (Clements, 1971).

First branch effect

We demonstrated that the first branch effect results in significantly lower rainfall erosivity (Figure 3). This can be explained by three crucial components of this effect: firstly, the breaking of drops in smaller ones when they hit these branches. Secondly, a shorter falling height leading to lower rain drop velocity and thirdly, interception of throughfall water and transfer to tree stems without release (Herwitz, 1987). Moreover, the least number of branches, high LAI, and low rainfall amounts compared to all other measurement positions in our study mediate this effect (supplements: Figure 9). High LAI values can be the reason for higher re-interception and thereafter, evaporation from leaves (Brandt, 1988). This leads to decreasing throughfall amount and therefore, lower TKE (Aston, 1979). Additionally, few branches prevent drops from confluence resulting in lower TKE due to lighter drop mass. Despite these vegetation parameters, the first branch is the last barrier for drops before reaching the soil surface (Nanko et al., 2008). Hence, low rain drop velocity occurs more often leading to low TKE.

Position of splash cup in the middle of four tree individuals

The middle position between four tree individuals showed the highest TKE. In our study, we attribute this effect to a high number of branches, a low LAI, a large crown area, and, most importantly, high rainfall amounts at this position (supplement: Figure 9). Branches at this measurement position might also function differently than under the first branch. A high number of branches increase the number of dripping points on the sheltered underside. It generates drop sizes of almost the same volume as coalescence drops from leaves and, thus, is responsible for a higher TKE (Herwitz, 1987). Low LAI leads to high throughfall amounts by less interception and, thus, high TKE (Geißler

et al., 2013). Additionally, larger crown areas strengthen the important role of drop confluence on leaf tips by creating larger drops (Geißler et al., 2012a). Interestingly, only horizontal parameters (number of branches, crown area, LAI) and not vertical parameters (such as tree height or crown base height seem to differ between the positions. It could be that in such young forest stands horizontal vegetation parameters are of greater influence than vertical ones. This can also support the key role of raindrop mass for rainfall erosivity over drop velocity which is very low for small trees (Foot and Morgan, 2005; Goebes et al., 2014).

Moreover, the number of surrounding tree individuals (and their different composition, see chapter 4.1) affected TKE positively. This increase can be ascribed to increasing rainfall amounts, a greater number of branches, higher heights, lower LAI, and larger crown area with increasing surrounding individuals directly beneath the measurement position (supplement: Figure 10). Since there is no typical positive correlation of tree height and LAI, we have to assume that both effects are counteracting. This might indicate that rainfall amount, crown area, and the number of branches are largely controlling this effect by the mechanisms described above. Additionally, we assume that if LAI - as prominent controlling factor of throughfall (Levia and Frost, 2006) - increases below the positions between tree individuals due to total plant cover growth, more re-interception and transpiration will occur resulting in less TKE.

4.3. Rain characteristics and TKE

Our study showed a very weak difference between FKE and TKE when compared to Geißler et al. (2010). Therefore, we have to reject hypothesis 3. Since the afforestation started in 2008, the forest was in an early successional stage. Results might be different in the future, when the experimental forest becomes higher and denser. Then, drops re-intercepted by the canopy have higher falling heights, and higher velocities will lead to increasing kinetic energy while drop size will stay constant (Geißler et al., 2013; Nanko et al., 2006; Nanko et al., 2008). The significant difference between FKE and TKE we found for trees exceeding 330 cm in height might be used as an indication for the

process. Nevertheless, throughfall below vegetation was reduced by 11–18 % compared to open field. This decrease is at the bottom line of results published in previous studies (Brandt, 1988; Nanko et al., 2004; Reid and Lewis, 2009; Ziegler et al., 2009) and generally supports the weak difference between FKE and TKE.

The spatial, individual and neighborhood diversity effect are mainly evoked by the abiotic factor rainfall intensity, calculated from 5 min rainfall amount and from total rainfall amount of every event. Thus, only very low intensities (rainfall event 1) and very high intensities (rainfall event 5) registered at study site-scale induce these effects on TKE. Consistent to that, a study on throughfall volume suggests similar abiotic factors (Staelens et al., 2008).

4.4. Vegetation parameters and TKE

In general, several vegetation parameters influence TKE without regarding spatial distribution and diversity treatments (Figure 5). The branch number negatively influenced TKE. More branches led to lower TKE due to a higher probability of drops being re-intercepted, dripping and breaking into smaller ones (Geißler et al., 2012b; Herwitz, 1985). Increasing stand height lead to faster raindrops below the canopy and increase TKE (Geißler et al., 2010). However, a higher canopy may increase the space for vegetation layering which can mask the height effect (Wiersum, 1985). It can be assumed that stand height seems to be a very important factor only in young forest plantations (Geißler et al., 2013). If the sufficient stand height for rain drops reaching terminal velocity has been achieved, further height gain will not affect rain drop velocities. The same applies to the crown base height. The crown area affected TKE positively by increasing the surface for coalescence of rain drops and creating more dripping points. Interestingly, LAI also affected TKE positively. This is in contradiction to previous studies in which canopy storage is positively and throughfall amount negatively affected by LAI (Geißler et al., 2013; Park and Cameron, 2008). However, in our study a higher LAI seems to promote confluence of rain drops by larger crown and leaf area and, thus, increases TKE. Rainfall intensities might explain this shift. Canopy storage might play

a minor part in this process when medium rainfall intensities were considered (rainfall event 2, 3, and 4, Table 1). Then, TKE reacts negatively to LAI related to very high and very low rainfall intensities, because especially in heavy rains, a high LAI can enhance water storage (Herwitz, 1985) and hence, affect TKE. Studies on throughfall volume identified almost the same parameters (tree height, LAI), but showed no dependency on crown area (Park and Cameron, 2008). As abiotic factor, throughfall amount affected TKE positively which is consistent with other studies (Scholten et al., 2011).

Magnitude of rainfall events

The magnitude of a rainfall events leads to different impacts of vegetation parameters on TKE. LAI loses its influence on TKE in low magnitude rainfall events, because canopy interception is not as important with less rainfall amount than with high amounts. During low rainfall events, drops can easily confluence on leaves and release more continuous drop sizes (Calder et al., 1996); (Levia and Frost, 2006); (Nanko et al., 2006). Non-saturated canopies generate lower TKE than those sufficiently saturated (Nanko et al., 2008). During high magnitude rainfall events larger and more drops are hitting the canopy and lead to indifferent drop formations affecting TKE (Levia and Frost, 2006).

5. Conclusion

Our research focused on plot and subplot diversity effects on TKE and the spatial distribution of TKE in forests. Measurements were carried out in 40 communities varying in species richness from 1 to 24. Results show that TKE was not influenced by plot-level tree species richness, at least not in such an early successional stage. This can be attributed to a typical absence of a species richness effect in early stages of succession and to the overemphasizing of site parameters such as crown area or LAI. Nevertheless, indications of a diversity effect on TKE can be seen by regarding the neighborhood diversity. TKE is positively influenced by neighborhood tree species richness. This suggests that at early forest succession stages diversity is affecting TKE only at local scale rather than at plot-level, which emphasizes the need to examine the erosion process

at local neighborhood scale.

Focusing on the spatial distribution of TKE, we can see distinct positions that decrease TKE (below the first branch) or increase it (in the middle of four individuals). Moreover, the numbers of individuals, which are affecting a measuring spot, positively affect TKE. Furthermore, the tree species richness of these individuals positively influenced TKE. Independent of tree species richness and spatial treatments, number of branches, crown base height, tree height, LAI, crown area, and the rainfall amount at each measuring position influence the amount of TKE. Finally, TKE is only larger than FKE for spatial spots below trees exceeding 330 *cm*.

For future research, it will be beneficial to further improve the sampling design in order to give more weight to the positions influenced by four tree individuals. This will allow for more detailed investigations on the local neighborhood diversity effects and on the mechanisms leading to the highest TKE in the middle of four tree individuals. Moreover, further investigation on TKE in this experimental forest under full-grown trees and dense canopies is needed.

Acknowledgements

Supplement
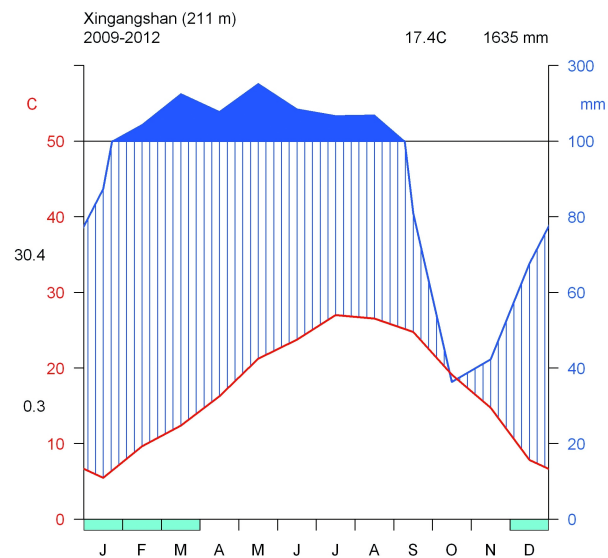
Figure 7: Walter and Lieth climate diagram of the monthly average temperature (red solid line) and precipitation (blue solid line) at Xingangshan, PR China (2009 - 2012).
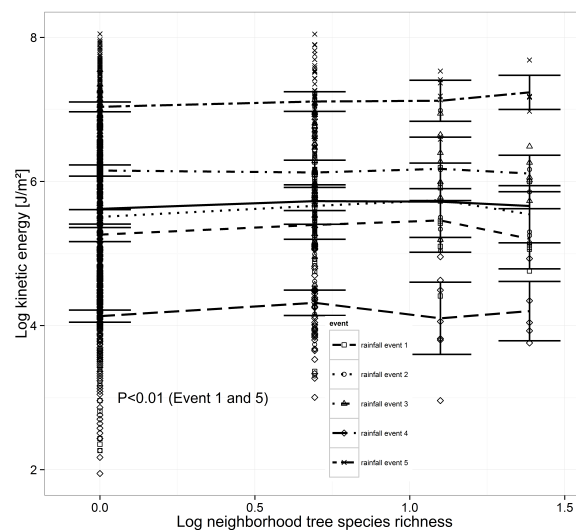
Figure 8: Throughfall kinetic energy and neighborhood tree species richness of five rainfall events. Black solid line symbolizes mean of all events. Different symbols show different rainfall events and dashed lines connect mean values of each diversity level for each rainfall event.
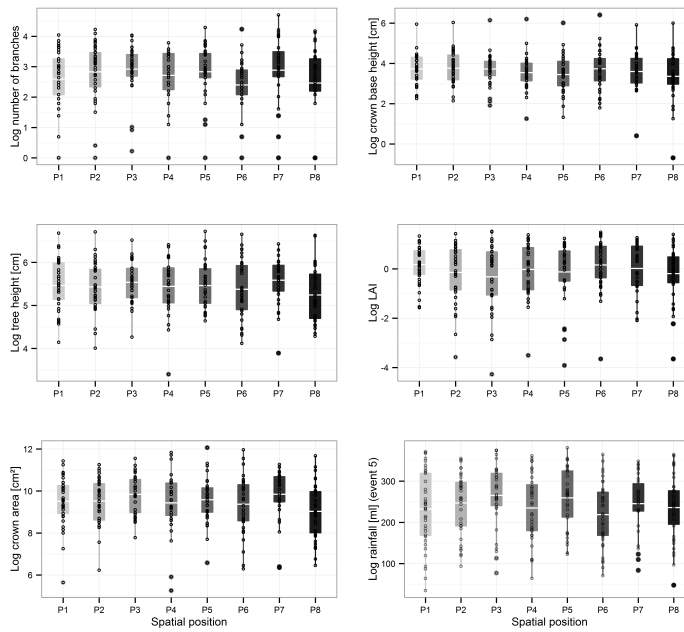
Figure 9: Vegetation covariates and spatial positions of TKE measurements. White lines indicate mean values.
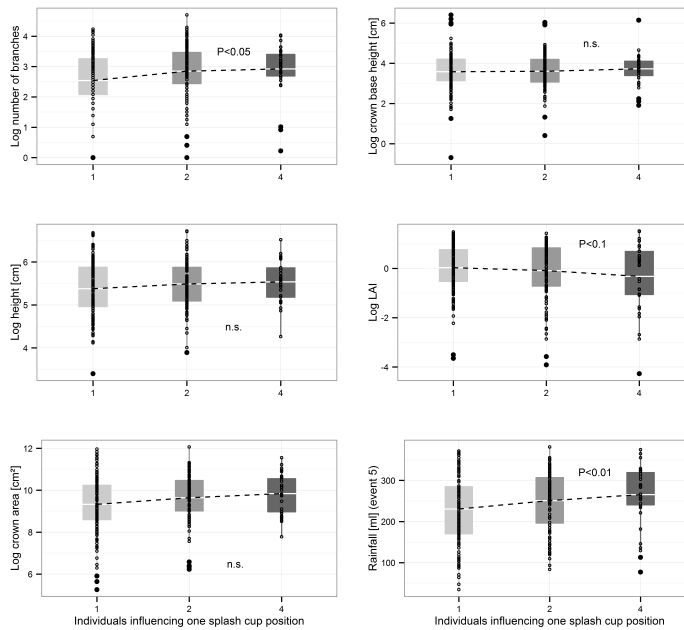
Figure 10: Vegetation covariates and "number of individuals" treatment. White lines indicate mean values and dashed black lines connect mean values.

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Manuscript 3 (under review)

Species-specific effects on throughfall kinetic energy in subtropical forest plantations are related to leaf traits and tree architecture

Philipp Goebes [a], Helge Bruelheide [b,c], Werner Härdtle [d], Wenzel Kröber [b], Peter Kühn [a], Ying Li [d], Steffen Seitz [a], Goddert von Oheimb [e], Thomas Scholten [a]

[a] University of Tübingen, Department of Geosciences, Soil Science and Geomorphology, Rümelinstraße 19-23, 72070 Tübingen, Germany

[b] Martin-Luther-University Halle Wittenberg, Geobotany, am Kirchtor 1, 06108 Halle, Germany

[c] German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Deutscher Platz 5e, 04103 Leipzig, Germany

[d] Leuphana University Lüneburg, Faculty of Sustainability, Institute of Ecology, Scharnhorststraße 1, 21335 Lüneburg, Germany

[e] Technische Universität Dresden, Institute of General Ecology and Environmental Protection, Pienner Str. 7, 01737 Tharandt Germany

Abstract

Soil erosion is a key threat to many ecosystems, especially in subtropical China where high erosion rates occur. While the mechanisms that induce soil erosion on agricultural land are well understood, soil erosion processes in forests have rarely been studied. Throughfall kinetic energy (TKE) is influenced in manifold ways and often determined by the tree's leaf and architectural traits. We investigated the role of species identity in mono-specific stands on TKE by asking to what extent TKE is species-specific and which leaf and architectural traits account for variation in TKE.

We measured TKE of 11 different tree species planted in monocultures in a biodiversity-ecosystem-functioning experiment in subtropical China, using sand-filled splash cups during five natural rainfall events in summer 2013. In addition, 14 leaf and tree architectural traits were measured and linked to TKE. Our results showed that TKE was highly species-specific. Highest TKE was found below Choerospondias axillaris and Sapindus saponaria, while Schima superba showed lowest TKE. These species-specific effects were mediated by leaf habit, leaf area (LA), leaf pinnation, leaf margin, stem diameter at ground level (GD), crown base height (CBH), tree height, number of branches and leaf area index (LAI) as biotic factors and rainfall amount as abiotic factor. Among these, leaf habit, tree height and LA showed the highest effect sizes on TKE and can be considered as major drivers of TKE. TKE was positively influenced by LA, GD, CBH, tree height, LAI, and throughfall amount while it was negatively influenced by the number of branches. TKE was lower in evergreen, simple leaved and dentate leaved than in deciduous, pinnated or entire leaved species. Our results clearly showed that soil erosion in forest plantations can be mitigated by the appropriate choice of tree species.

1. Introduction

Soil erosion negatively influences ecosystems widely, especially in regions with high erosion rates such as subtropical China [1]. Soil erosion brings about high economic costs due to declining agricultural productivity, reduced soil organic matter, relocation of nutrients, and off-site effects that influence human safety and food security [2–4].

Therefore, soil erosion plays an important ecological and economic role [5]. Reducing soil erosion is often achieved by afforestation [6], due to a high surface cover and stabilized soil aggregates in forests [7]. Afforestation in subtropical regions is dominated by mono-specific stands [8], primarily in order to optimize wood production in terms of quantity and quality by planting fast-growing species and to allow for a simple and standardized management [9]. Afforestations are well acknowledged for their great contribution in meeting the increasing demand for wood products and in carbon sequestration, thus having strong implications for climate change mitigation [10].

Soil erosion in forests is highly influenced by throughfall kinetic energy (TKE) [11]. TKE is a combination of throughfall amount, drop size distribution and drop velocity. It is known that forests highly influence the kinetic energy of rainfall as first step towards erosion occurrence by their structure and species composition [12,5,13]. Many studies on throughfall have been conducted [14,15], but there can be different mechanisms if TKE is examined. Even though soil erosion is generally reduced in forests [7], TKE can be higher in forests than in open fields [16,17]. In particular, with a sparse understory vegetation and leaf litter cover TKE can strongly increase soil erosion under forest.

In open field sites, kinetic energy of rainfall is only affected by abiotic factors (i.e., rainfall intensity and amount; [18,19]. Below forest canopies, however, biotic factors come into play with the potential to alter throughfall and TKE considerably. As a result, large species-specific differences have been found [16,20–23]. Species-specific effects on TKE are evoked by plant traits such as leaf area index [13,21,24], leaf habit [5], tree height [12], canopy thickness [25,18], branch characteristics [26] and the first branch of a tree individual [25,5]. The mechanism of the latter is that rain is channeled by leaves and branches to drop at specific spatial points above the ground surface resulting in smaller or larger rain drops [26]. Hence, this is one of the reasons for concentrating TKE on spatially confined soil patches and increasing the soil erosion potential drastically at the micro scale. As an example of species-specific differences evoked by leaf traits, species with broad leaves and a rough cuticle produced larger drops than species with smaller and wax-coated leaves and might, thus, increase TKE [27]. For this reason, TKE

under the canopy of Schima superba with evergreen leaves was found to be lower than under that of Castanea henryi and Quercus serrata with deciduous leaves [5]. However, most preceding studies have only dealt with at maximum four different species [16,5,15], precluding cross-species comparisons of TKE-trait relationships. One exception is the study of [27], who investigated nine different species with regard to their leaf drips but without considering plant traits. However, several studies have disregarded both the mediating effects of most biotic [28–31] and abiotic factors such as rainfall intensity and throughfall amount on TKE [18,19].

As a consequence, little is known about how and to what extent species-specific leaf and architectural traits mediate soil erosion processes under tree canopies. This in turn means that a broader set of species (covering a wide range of leaf and tree architectural traits) needs to be analyzed to reveal species identity effects on TKE. Therefore, it is essential to study TKE under a multitude of species that vary in leaf traits and morphology. Moreover, the investigation of several traits factors allows a comparison and identification of the major drivers for variations in TKE, independent of species identity. Major drivers for variations in TKE have been identified in intraspecific comparisons [32] and could be tested for their interspecific validity. However, literature reporting on TKE distribution under forest canopies remains scarce (both generally and in subtropical regions), underlining the need to further investigate TKE variation below broad-leaved tree species.

We set out to close this knowledge gap by quantifying relationships between TKE and leaf and architectural traits of 11 different tree species typical of subtropical broad-leaved forest ecosystems of China. Trees were grown in monocultures that were established in the context of a large-scale biodiversity-ecosystem functioning experiment (henceforth referred to as BEF-China; [33]. Specifically, we tested the following hypotheses:

H1 TKE below forest canopies is highly species-specific.

H2 Leaf traits and tree architectural traits mediate species-specific effects on TKE.

2. Materials and Methods

2.1. Study site

The BEF-China experiment is located near Xingangshan Township, Jiangxi Province (N29°08-11, E117°90-93), P.R. China. The mean annual temperature is 17.4 ℃ and mean annual rainfall is 1635 mm. The climate of the study area is characterized by subtropical summer monsoon with a wet season from May to July and a dry winter. After the clear-cut of a Cunninghamia lanceolata plantation in 2008, an experimental forest was planted on a plot-level based approach with 400 tree individuals per plot ($25.8m$ x $25.8\ m$; planted in 20 rows each of which with 20 tree individuals), using a planting distance of 129 cm and including a total of 24 tree species on 261 plots to investigate biodiversity effects on ecosystem functions (see [33] and [34] for detailed explanations). This study focuses only on monoculture plots of trees that had an average minimum height of 100 cm in 2013. Trees were six years old. No specific permissions were required for these locations and activities. The field studies did not involve endangered or protected species.

2.2. Experimental design and data sampling

TKE was measured during five rainfall events with an event-based approach for a total of 11 species in 17 monoculture plots in 2013. Within the central part of each plot (including 6 x 6 trees), eight randomly assigned positions with distinct distances to the tree stems were used to measure TKE (1) 15 cm away from tree stem, (2) in the middle of two tree individuals, (3) in the middle of four individuals, (4) 45 cm away from tree stem, (5) at the 45 cm x 120 cm intersection between two individuals, (6) below the first branch of a tree individual, (7) at the 75 cm x 75 cm intersection between two individuals, and (8) 30 cm away from tree stem). TKE was measured using splash cups [35] and representative values of $J\ m^{-2}$ were obtained. Next to each splash cup, a rainfall collector was installed to quantify the rainfall amount (throughfall) with a high spatial resolution. Rainfall events were registered by the BEF-China climate stations and classified by rainfall intensity, duration and total amount (Supp. Table 5). A total of nine leaf traits and five architectural traits were analyzed. Leaf traits included leaf area

(LA), specific leaf area (SLA), leaf pinnation (simple or pinnate), leaf margin (entire or dentate), trichome cover of upper leaf surface, leaf thickness, leaf toughness, leaf habit (deciduous or evergreen) and leaf area index (LAI). These traits except for LAI were measured on individuals planted in the experiment [36,37]. LAI was registered at each TKE measuring point below diffuse radiation conditions, using a Nikon D100 with a Nikon AF G DX 180° and HemiView V8 (Delta-T). Architectural traits examined were total height, elliptic crown area, number of branches, stem diameter at ground level (GD) and crown base height (CBH) of each tree individual were measured [40]. Table 1 gives an overview of all tree species with leaf and architectural traits influencing TKE.

2.3. Data analyses

Species-specific variation of TKE was investigated using linear mixed-effect models fitted by restricted maximum likelihood. Rainfall event, species identity and the interaction of species identity with rainfall event were included as fixed factors. Plot, measurement position within each plot, interaction of plot with rainfall event and interaction of plot with position entered the model as random effects. For testing effects within each rainfall event, rainfall event was not used as fixed factor. Contrasts were fitted before species identity to detect species which had significantly higher or lower TKE than mean of all others. Significant effects were detected using Wald Test statistics with Type I SS ANOVAs. In total, 625 data points entered the analyses (5 events x 17 plots x 8 positions – 55 failed measurements). To specify possible effects of species identity, mediation analysis were constructed by fitting mediation trait variables before the species identity term. Mediation variables were detected as such, if significance of species identity was changed from significance to non-significance and if the mediation variable itself significantly influenced TKE. To identity the most important mediation variable, categorical levels were predicted and ranked by their magnitude of TKE differences (effect size). For continuous mediation variables, the difference in TKE was evaluated when increasing mediation variable by one standard deviation. Each model was only fitted with a single mediation variable to avoid multicollinearity among traits.

Table 1: Leaf and architectural traits of the tree species included in the present study according to a significant influence on throughfall kinetic energy. Values represent means of the variables measured. Abbreviations: D = deciduous, E = evergreen, S = simple, P = pinnate, D = dentate, E = entire.

Species name	Abbr.	Leaf area index	Leaf area	Leaf habit	leaf pinnation	Leaf margin	Tree height	Number of branches	Crown base height	Throughfall amount
Castanea henryi Rhed. & Wils.	cah	2.77	3,128	D	S	D	488	19	81.9	70.0
Choerospondias axillaris (Roxb.) Burtt & Hill	cha	2.31	35,484	D	P	D	576	12	268.5	93.7
Cyclobalanopsis glauca (Thunb.) Oerst.	cyg	0.29	2,474	E	S	D	143	16	29.3	83.7
Koelreuteria bipinnata Franch.	kob	0.27	30,727	D	P	D	119	1	58.7	98.3
Liquidambar formosana Hance	lif	1.06	5,051	D	S	D	225	32	23.9	87.7
Lithocarpus glaber (Thunb.) Nakai	lig	0.77	1,956	E	S	E	192	27	30.0	63.4
Quercus fabri Hance	quf	0.55	1,912	D	S	D	166	24	35.9	82.5
Quercus serrata Murray	qus	0.41	1,972	D	S	D	110	23	16.4	98.2
Sapindus saponaria Linn.	sas	1.13	42,231	D	S	E	233	5	68.4	94.4
Triadica sebifera Small	trs	1.20	2,108	D	S	E	265	19	32.9	88.6
Schima superba Garder & Champion	scs	3.06	3,230	E	S	D	338	47	42.3	49.9

Additionally, a model was constructed consisting only of leaf traits (fitted first to avoid underrepresentation by larger effects) and architectural traits to test for their influences on TKE. In this model, plot and rainfall event were considered as random effects. Model simplification was done using step-wise backward selection with the maximum likelihood approach [38]. Hence, the final model only contained significant effects ($P < 0.05$). Prior to the analyses, all covariates have been checked for collinearity (correlations were not allowed to exceed $R = \pm 0.7$). Hence, leaf toughness, leaf thickness and crown area did not enter the final model due to multicollinearity. Predictions were used to identify the effect size according to the method described above.

If a measuring position was influenced by more than one tree individuals, mean values of leaf and architectural traits of surrounding individuals have been calculated.

TKE data was log-transformed to ensure normal distribution. Model residuals did not show violation of model assumptions (normality and homogeneity of variances). Analyses were conducted using R 2.14.1 [39]. Linear mixed effects models were analyzed with R package "asreml" [41] and "lme4" [42].

3. Results

Across all rainfall events, species and plots, TKE was highly variable ranging from $7\ J\ m^{-2}$ to $2{,}882\ J\ m^{-2}$. Mean TKE was $490 \pm 534\ J\ m^{-2}$ and differences between rainfall events were considerable. Rainfall event 4 and 5 yielded the lowest ($74 \pm 54\ J\ m^{-2}$) and the highest mean TKE ($124 \pm 61\ J\ m^{-2}$), respectively. In all models, TKE was strongly positively correlated with rainfall event ($F_{4,22} = 731, P < 0.001$). TKE was species-specific and strongly depended on rainfall event (Fig. 1, Supp. Table 3). Species identity significantly affected TKE at rainfall events 1 and 2 ($F_{1,6} = 6.3, P < 0.05$ and $F_{1,6} = 4.6, P < 0.05$, respectively), whereas it was not significantly related to TKE at rainfall events 3, 4, and 5, all of which had higher rainfall intensities. TKE below the canopy of *Choerospondias axillaris* and *Sapindus saponaria* were significantly higher (58 %, $F_{1,6} = 11.89, P = 0.013$, and 62 %, $F_{1,6} = 10.11, P = 0.019$, respectively) and TKE

below the canopy of *Schima superba* was significantly lower (42 %, $F_{1,6} = 8.63, P = 0.026$) than the mean TKE of all other species.
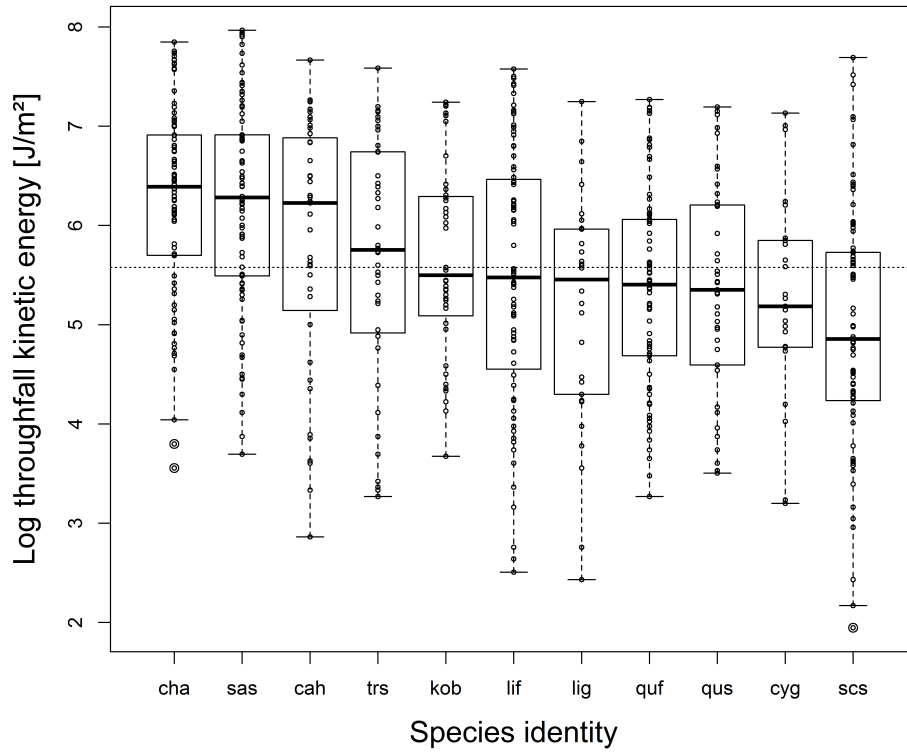
Figure 1: Throughfall kinetic energy (TKE, log-transformed) of the 11 species analyzed. Dotted line represents the total mean TKE. For abbreviations of species names see Table 1.

The effect of species identity on TKE was mediated by leaf habit, leaf pinnation, LA, tree height, LAI, SLA, rainfall amount, CBH, GD, crown area and number of branches (Table 2). Regarding categorical traits, the highest difference between factor levels occurred between different leaf habits (with a 92 % increase of mean TKE from evergreen to deciduous). Increase of mean TKE for pinnated leaves was 60 %. Considering vegetation continuous traits, high effect sizes were found in LA (+ 92 %), tree height (+ 33 %), LAI (- 25 %), SLA (+ 17 %), rainfall amount and CBH (each + 16 %). Effect sizes were small for GD and the number of branches (all < 7 %).

Table 2: Effect sizes of mediation variables (leaf and tree architectural traits). Values are predicted from mixed effect models for throughfall kinetic energy (TKE) with basic design structure (not shown, see Supp. Table 3). For abbreviations of traits see Table 1.

		Change in TKE $[J\ m^{-2}]$ by changing mediation variable by one SD
Mediation variables	LA	+199 **
	Leaf habit	+146 **
	Leaf pinnation	+141 *
	Tree height	+91 ***
	LAI	–65 **
	CBH	+46 **
	Throughfall amount	+42 ***
	GD	+16 .
	Number of branches	–13 **

In general, TKE was significantly positively related to LA, CBH, height, and rainfall amount, but negatively influenced by LAI and the number of branches. Moreover, deciduous species ($+\ 13\ J\ m^{-2}$), species with pinnate ($+\ 32\ J\ m^{-2}$) and entire margined ($+\ 20\ J\ m^{-2}$) leaves displayed higher TKE than evergreen species, species with simple leaves and species with dentate leave margins, respectively (Fig. 2, Supp. Table 4).

4. Discussion

This study compared TKE of 11 tree species in monocultures typical of subtropical forest ecosystems in China. Further, it complemented former analyses by deepening our understanding of leaf traits and tree architecture effects on TKE [5,27]. Mediation analyses linked leaf and tree architectural traits to varying TKE induced by different tree species, and major biotic drivers of TKE variability were detected by comparing effect sizes. Finally, this study aimed to support the selection of appropriate tree species for tree plantation in order to minimize TKE and thus to counteract soil erosion in

subtropical regions resulting from high monsoon precipitation (particularly in areas with steep terrain).
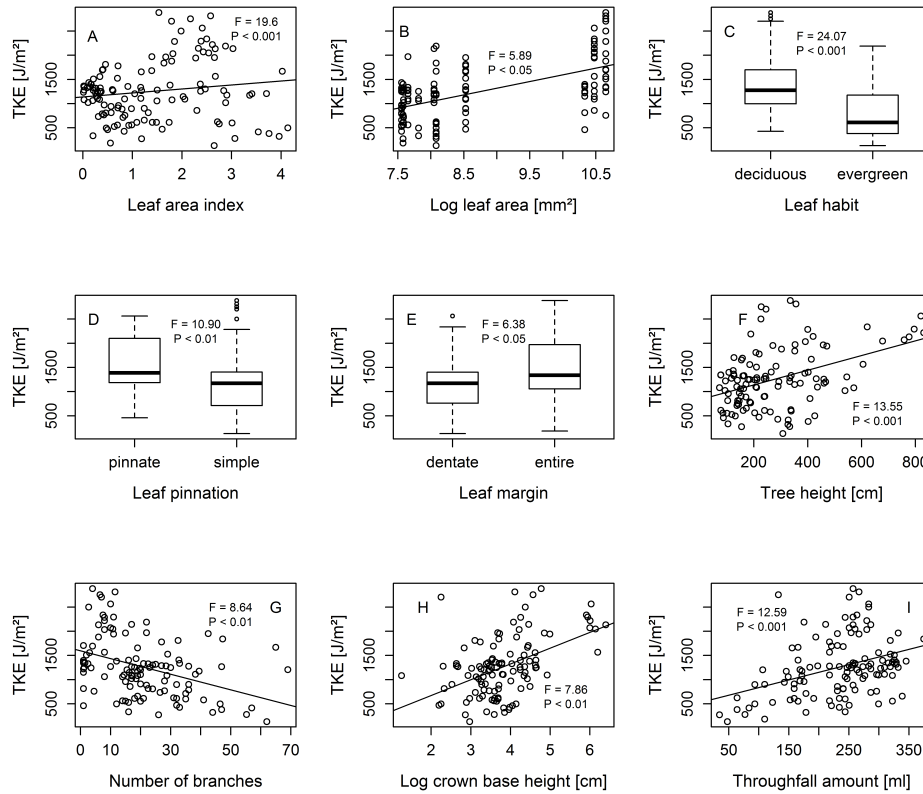
Figure 2: Throughfall kinetic energy (TKE) versus leaf traits (A-E), tree architectural traits (F-H) and abiotic covariates (I) of rainfall event 5. Black solid lines indicate linear trend.

4.1. Species-specific TKE variation (H1)

Our first hypothesis was confirmed by the significant influence of species identity on TKE. However, only three out of 11 species showed distinct differences in TKE compared to overall means. Among these, two species positively (*Choerospondias axillaris* and *Sapindus saponaria*) and one species negatively (*Schima superba*) affected TKE (Fig. 1). Species-specific differences of throughfall amount or interception have been frequently reported [43,18]. Moreover, drop size distribution as an important driver of TKE has been found to be species-specific [27]. Nevertheless, preceding studies found

no significant difference in TKE among certain species [5,16,21,44,43], which is in line with our findings. Furthermore, the highly significant interaction of species identity with rainfall event emphasizes the importance of abiotic characteristics in TKE distribution [18]. A profound influence of species identity on TKE was found at low peak intensity rainfall, whereas TKE at high rainfall intensities was not species-specific. Higher intensity rainfall usually results in considerable canopy vibration, through which the drop sizes are reduced [20]. Therefore, the variation of TKE at high intensity rainfall could be much less than that at low intensity rainfall leading to no species-specific differences. However, this effect often is superimposed by an increase of total throughfall amount with higher rainfall intensities.

The species-specific effects of canopies of *Choerospondias axillaris*, *Sapindus saponaria* and *Schima superba* have strong implication for managing TKE. Planting *Schima superba*, which negatively affected TKE, has the potential to decrease soil erosion in early successional stages. *Schima superba* is also well-known for high values of canopy interception during rainfall [45]. This could be partially attributed to the high LAI and re-interception of rainfall by lower canopy layers [25,30]. Low TKE below *Schima superba* was also reported by [5]. These findings are as much more relevant as *Schima superba* represents one of the dominant tree species in the regional species pool [46,47]. *Choerospondias axillaris* increased TKE which is consistent with high runoff volumes found for this species in comparison to peanut crops [48]. However, despite a TKE increase, higher soil loss with *Choerospondias axillaris* can be counteracted by an intact litter cover [29].

4.2. Leaf and tree architectural traits mediate species-specific variation (H2)

First, the strong impact of rainfall event on TKE suggests that the TKE variation is pre-determined by the characteristics of rainfall events, such as duration, total rain amount and rainfall intensity. Within a specific rainfall event, the redistribution patterns of TKE differ among tree species. This effect of species identity was mediated by a range

of leaf traits and by tree architecture. LA, leaf habit, leaf pinnation, GD, CBH, tree height, number of branches and LAI as biotic factors were found to be responsible in mediating species-specific TKE (Table 2). Moreover, the significant effect of rainfall amount measured at each splash cup position on TKE showed the influence of biotic and abiotic factors on TKE [18].

In our study, TKE varied at the most between deciduous and evergreen species where deciduous species showed higher TKE. Similarly, [5] found that *Castanea henryi* and *Quercus serrata* as examples of deciduous species yielded higher TKE than the evergreen species *Schima superba.* Leaf habit represents a dominant segregation for many leaf traits and has been found to influence core functional and physiological processes specifically in the study species [46] as well as globally [49–51]. Deciduous species tend to have leaves with higher SLA [52], which we found to positively affect TKE. In addition, evergreen species tended to have a larger crown length ratio (ratio of crown length to the total tree height). Two mechanisms might elucidate the great variation between deciduous and evergreen species: (i) A lower tree height decreases falling height of raindrops and thus, results in lower TKE; (ii) a larger crown area with lower tree height (higher crown length ration) may increase LAI which results in higher interception, leading to decreasing throughfall. Moreover, leaf pinnation (pinnate or simple) can alter drop sizes. On the basis of higher margin circumference in relation to total leaf area [53], pinnate leaves create more dripping points. However, different leaf margins contributed only marginally to species-specific changes in TKE. Pinnate leaves showed the highest leaf area (see Table 1) with the exception of *Sapindus saponaria.* Higher leaf area can increase the gathering of rain water and thus may cause larger drops resulting in higher TKE [13,26,20]. In contrast, many studies have reported on the positive influence of leaf area on interception [43], which leads to decreasing throughfall amount and decreasing TKE. Therefore, in our study variation of interception might only play a minor role in explaining species-specific differences in TKE, since all rain events lasted long enough to compensate the effect of canopy storage at the beginning of each event. However, the high effect size of LA in our study might be an overestimation, since leaf

areas of *Choerospondias axillaris* and *Sapindus saponaria*, both with largest TKE, were almost twice of the standard deviation above the mean. This is due to the fact that for measurements of leaf area, the leaflets of pinnate leaves are traditionally added up to a total value per pinnate leaf [54]. Furthermore, water might gather at the branch, where each leaflet splits, which in turn may result in increased drop size and thus TKE. As demonstrated in former studies [13,28], tree height was the most important tree architectural parameter to describe species-specific differences in TKE. Increasing tree height can contribute to higher TKE by several processes: (i) higher drop velocity due to higher falling heights [55], (ii) larger crown width [40] that increases drop size through increased confluence, and (iii) larger crown width is associated with higher LAI, which creates more dripping points [26,28]. LAI negatively mediated species-specific differences in TKE. It is known that high canopy thickness increases drop splitting by dripping on branches and leaves [25,20], which in turn may decrease raindrop sizes. Moreover, higher canopy thickness in young forest stands might decrease space between vegetation and surface resulting in lower rain drop velocities [5]. Additionally, with denser and thicker crown cover water storage in the canopy increases, but this effect can be neglected with regard to rainfall durations longer than a day.

CBH (with half of the effect size of tree height) contributed to species variances as indirect factor, as it is usually related to tree height. CBH may constitute "the last barrier" in releasing throughfall drops, determines the falling height and thus drop velocity. Yet, our data showed that CBH contributed to interspecific TKE much less as compared to tree height. One reason might be that the same CBH might occur at trees along a large range of tree height.

GD positively and branch number negatively mediated species identity of TKE, but only to a smaller extent (< 7 % difference). This suggests that GD mediated species-specific changes as an indirect effect of tree growth characteristics (tree height and LAI). Furthermore, the number of branches might affect TKE through an indirect effect via LAI. Branches gather throughfall and release it at any random position or transfer it directly to the stem, which decreases throughfall and increases stemflow [26]. However,

our results indicated that this was a weak effect and water might both, be distributed along the branches and transferred to the stem in equal proportions. Moreover, the greater effect size of LAI demonstrated that leaves are much more important than the branches as regards the impacts of species-specific TKE.

Besides the significant effect of plant traits on TKE, throughfall amount was also highly correlated with TKE, but showed smaller effect sizes than the findings from other studies [19]. In most studies, throughfall amount was found to be the major driver of spatial variability of TKE [35,16]. However, our species comparison revealed that shifts in drop formation and drop velocity within a specific rainfall event might have a higher impact on TKE than the total amounts of rainfall. Thus higher throughfall amounts do not necessarily lead to higher TKE at rainfall event level.

5. Conclusion

This study aimed to contribute to a better understanding of mechanisms underlying the relationships between TKE-and leaf and tree architectural traits, taking 11 tree species of subtropical forests in China as example. In conclusion, the optimal trait combination a tree should have to minimize TKE would be a low leaf area index and leaf area, simple pinnated leaves, dentated leaf margins, low tree height, high number of branches and a low crown base height. Furthermore, evergreen species showed lower TKE as compared to deciduous ones.

Our results showed that TKE distribution among different species is much more complex than throughfall distribution solely. TKE sensitively responded to the amount of throughfall, but also to the transformation of throughfall amount (in terms of drop size and drop velocity) by leaf and tree architectural traits (Fig. 2). Thus, this study helps to understand the interaction between these vegetation characteristics, species identity and TKE as a basis for erosion modeling and the mitigation of soil erosion by means of an optimized selection of appropriate tree species in the context of afforestation programs.

Acknowledgements

Supporting Information

Table 3: Results from the basic mixed-effects model for throughfall kinetic energy response.

		Df	DenDf	F	Pr
Fixed effects	Intercept	1	6.2	17760	$1.2 \cdot 10^{-11}$ ***
	Event	4	22.4	731.4	$2.2 \cdot 10^{-16}$ ***
	Position	7	101.3	1.3	0.2510
	Species identity	6.3	6.3	3.0	0.0936 .
	Species identity:Event	44	21.5	3.0	0.0037 **

		Gamma	Component	Std. error
Random effects	Plot	0.4120	0.0797	0.0588
	Plot:Event	0.0013	0.0003	0.0081
	Plot:Position	0.6095	0.1180	0.0224

Table 4: Effect sizes of leaf and tree architectural traits. Values are predicted from mixed effect models for throughfall kinetic energy (TKE) with basic design structure (not shown, see Supp. Table 3). For abbreviations of traits see Table 1.

		Change in TKE $[J\ m^{-2}]$ by changing mediation variable by one SD
Full model	Height	+114 ***
	LA	+34 *
	Leaf pinnation	+31 **
	LAI	–24 ***
	Throughfall amount	+20 ***
	Leaf margin	+20 *
	Leaf habit	+13 ***
	Number of branches	+12 **
	CBH	+3 **

Table 5: Characteristics of the five rainfall events.

Rainfall events	Rainfall amount $[mm]$	Rainfall intensity [5min intensity]	Rainfall intensity of total event $[mm\ h^{-1}]$
Event 1	23.3	12.1	2.29
Event 2	39.3	22.8	3.42
Event 3	61.2	44.4	4.25
Event 4	6.6	25.2	2.83
Event 5	185.7	127.2	6.07

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Manuscript 4 (ready for submission)

Rule-based analysis of throughfall kinetic energy to evaluate leaf and tree architectural trait thresholds to mitigate erosive power

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Philipp Goebes [a], Karsten Schmidt [a], Steffen Seitz [a], Felix Stumpf [a], Thomas Scholten [a]

[a] University of Tübingen, Department of Geosciences, Soil Science and Geomorphology, Rümelinstraße 19-23, 72070 Tübingen, Germany

Abstract

Throughfall kinetic energy (TKE) as measure of rain power below vegetation plays an important role in erosion occurrence. TKE can directly influence soil erosion with the absence of a litter cover on the soil surface. It is known that TKE is influenced by abiotic factors such as throughfall amount and rainfall intensity as well as by biotic factors such as tree height, crown base height, crown area, leaf area index, leaf area, plot and neighborhood diversity or the number of branches.

This study seeks out to investigate importance of these leaf and tree architectural traits in classifying TKE and to identity vegetation thresholds to prevent erosion by an optimal set of traits. Data of 1405 TKE measurements using splash cups during five rainfall events in a subtropical Chinese tree plantation of six year age were analyzed by using Random Forests for feature importance evaluation and by using Classification and Regression Trees for rule construction.

Our results showed that leaf area, tree height, leaf area index and crown area are the most prominent vegetation traits to classify TKE. To mitigate the soil erosion potential based on TKE, the optimal set of leaf and tree architectural traits would be a leaf area lower than 70 cm^2, a tree height lower than 290 cm combined with a lower crown base height than 60 cm, a leaf area index smaller than 1, more than 47 branches per tree and using single tree species neighborhoods. Rainfall characteristics like intensity and amount further classify high or low TKE. Although these results were obtained in a young tree plantation without all trees reaching full height and canopy thickness, they are, nevertheless, another step in TKE modeling and in setting thresholds for erosion occurrence.

1. Introduction

Soil erosion is a major threat to natural ecosystems and agricultural land. Among slope, slope length, soil erodibility or vegetation, rainfall erosivity is one important driver in predicting soil erosion rates by empirical [Renard et al., 1997] or process-based models

[Morgan et al., 1998]. Rainfall erosivity is most commonly expressed by the EI30 which combines rainfall energy (E) and rainfall intensity per 30 min interval (I30). While there are numerous studies investigating and modeling rainfall intensity and its processes [van Dijk et al., 2002], research is lacking on the processes determining rainfall energy. This is especially true if rainfall energy is examined below vegetation (throughfall kinetic energy, TKE). Below vegetation, the drop size distribution of rain drops is changed due to leaf and tree architectural traits resulting in complex processes. The drop size distribution change can result in higher TKE than rainfall energy at open field sites [Geißler et al., 2012; Nanko et al., 2004], which strengthens the influence of TKE in inducing soil erosion processes below vegetation. Moreover, if a litter cover at the soil surface is missing, TKE is directly influencing soil erosion. Therefore, the development of models predicting TKE is essential to avoid soil erosion below vegetation. Several studies have been conducted to model the role of rainfall kinetic energy in soil erosion at open sites in different regions of the world [Salles and Poesen, 2000; Assouline and Mualem, 1989; Assouline, 2009; van Dijk et al., 2002], but literature is rare on rainfall kinetic energy models below vegetation. Brandt, C. [1990] developed one model incorporating tree height as most important vegetation variable while Calder [1996] used interception processes to model TKE by evaluating the drop size distribution. However, Foot and Morgan [2005] suggested that it is sufficient to model TKE by only using tree height and canopy area. These varying approaches motivate to model TKE using a variety of leaf and tree architectural input variables to clarify their influence and importance among each other.

A positive effect on TKE has been reported for leaf area [Goebes et al.,2015b under review], throughfall amount [Brandt, 1988; Scholten et al., 2011; Geißler et al., 2012], tree height [Geißler et al., 2013; Foot and Morgan, 2005], crown area [Brandt, 1988; Nanko et al., 2008] and crown base height [Nanko et al., 2008; Brandt, C., 1990]. Contrary, TKE is negatively influenced by leaf area index (LAI) [Nanko et al., 2008; Nanko et al., 2006] and number of branches [Herwitz, 1987]. Moreover, deciduous tree species showed higher TKE [Goebes et al.,2015b under review] and a spatial variability of TKE exists [Nanko et

al., 2011; Finney, 1984]. Further, type and intensity of a rainfall event determine if TKE is erosive or not [Zhou et al., 2002; Brandt, 1989]. However, it is not clear to what extend these variables result in erosive TKE and if leaf and tree architectural trait thresholds exist below which only low TKE occurs. For instance, Moss and Green [1987] reported a maximum crown base height of 30 cm below which TKE is non-erosive. Though, literature reporting leaf and tree architectural trait thresholds remains scarce. In the recent 15 years, TKE has been measured in different regions, under different rainfall conditions and below different vegetation [Zhou et al., 2002; Nanko, 2007; Nanko et al., 2008; Nanko et al., 2011; Sanchez-Moreno et al., 2012].

In the last decades, geoinformatics, statistical and machine-learning methodologies made a huge progress. In soil erosion research, Random Forests [Breiman, 2001] are a such a new technique. For instance, Märker et al. [2011] used Random Forests to model erosional response units and to identify major controlling factors of erosion. In general, Random Forests yield high prediction accuracies and are able to detect important input variables with its incorporated feature importance measurement [Breiman, 2001]. However, random forests are typically treated as a black box. Indeed, a forest consists of a large number of deep trees, where each tree is trained on bagged data using random selection of features, so gaining a full understanding of the decision process by examining each individual tree is infeasible. The evaluation of a tree can be achieved by using classification and regression trees (CART) [Cutler et al., 2007; Breiman et al., 1984]. Thus, we want to evaluate a step-wise decision tree approach to establish a rule-based system for estimating TKE. Finally, we want to test two hypotheses:

(i) TKE can be modeled by a distinct set of leaf and tree architectural traits.

(ii) TKE is lower for a smaller leaf area, a lower tree height and less throughfall than mean of all species.

2. Data collection and Modeling

2.1. Study site and experimental design

The study was conducted within the framework of the large-scale biodiversity-ecosystem functioning experiment "BEF-China" [Bruelheide et al., 2014] at Xingang-shan, Jiangxi Province, PR China (N29°08-11, E117°90-93). The climate in Xingangshan is typical of subtropical summer monsoon regions with a mean annual temperature of 17.4 °C and an average annual rainfall of 1635 mm [Goebes et al., 2015a under review]. The experimental area holds 70 ha with a plot-based tree diversity treatment including 24 tree species on 261 plots. Trees were planted after harvest of the previous stand in 2008. For this study, 40 plots were selected including 17 monocultures, 10 2-species mixtures, six 4-species mixtures, four 8 species-mixtures, one 16-species mixtures and two 24-species mixtures to cover a wide range of species and compositions. Within one plot, eight measurements were realized by selecting eight different positions in order to cover a wide range of spatial variability (see Fig. 1). Depending on the experimental design all trees have the same age.

2.2. Measurement of throughfall kinetic energy and rainfall

TKE was measured using Tübingen Splash Cups [Scholten et al., 2011] filled with uniform fine sand (diameter 0.125 mm). In total, 1411 splash cups were measured during five rainfall events (see Supplement Table 5 for rainfall characteristics) from May to July 2013. Sand loss in splash cups was used to calculate TKE ($J\ m^{-2}\ mm^{-1}$) by a modified version of the function given by Scholten et al. [2011] and the rainfall amount of each rainfall event.

Reviewing literature on TKE measurements of the past 30 years (Table 1), four different classes were calculated based on class means of 2 SD subtracted from mean (very low TKE, mean = 7.5), 1 SD subtracted from mean (low TKE, mean = 14.1), mean (average TKE, mean = 20.7) and mean plus 1 SD (high TKE, mean = 27.3). By comparing these classes, TKE was evaluated and classified.
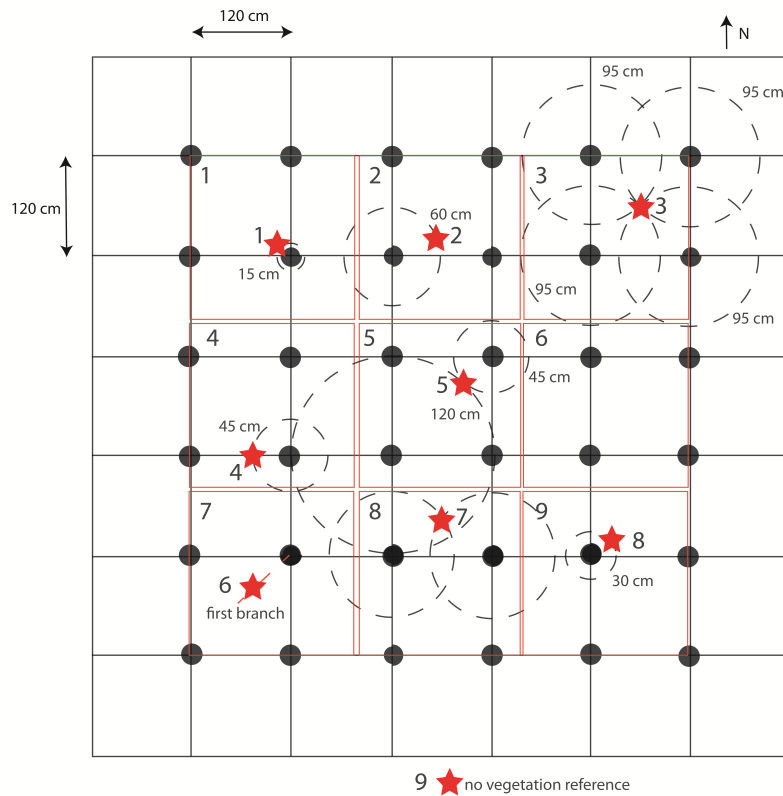
Figure 1: Sampling design with nine measurement positions. The positions have been (1) 15 cm from the stem (2) in the middle of two tree individuals, (3) in the middle of four individuals, (4) 45 cm from tree stem, (5) at the 45 cm x 120 cm intersection between two individuals, (6) the 75 cm x 75 cm intersection between two individuals, (8) 30 cm from tree stem and (9) outside the plot control (no-vegetation reference). Black dots symbolize tree individuals and red stars throughfall kinetic energy measurement position with rainfall gauge.

2.3. Measurement of model input variables

Plot-level diversity was evaluated based on the experimental design and neighborhood diversity specified by the composition of direct neighboring tree species of a measurement position. The number of individuals was determined by counting direct tree neighbors that were influencing one splash cup. We measured total tree height, ground diameter (GD), crown base height (CBH), crown area, number of branches as tree architectural characteristics [Li et al., 2014] and determined leaf habit (deciduous, evergreen and in mixtures both), leaf area and specific leaf area as leaf traits [Kröber and Bruel-

heide, 2014; Kröber et al., 2014]. Throughfall amount was measured using rainfall gauges and LAI as well as ground coverage were measured using hemispherical photographs. Elevation and aspect were measured at plot-level scale. All splash cup positions were covered by vegetation. If a splash cup was influenced by more than one tree individual, mean values of leaf and tree architectural traits were used.

Table 1: Mean, minimum and maximum rainfall amount based TKE ($Jm^{-2}mm^{-1}$) measured in different studies. Abbreviations: TF=throughfall, FF=freefall, art=artificial, SD=standard deviation. Rainfall characteristics show amount of annual precipitation or simulated rainfall intensity and type of rainfall.

Study	Rainfall characteristics	Mean	Minimum	Maximum
Sanchez-Moreno et al. 2012	300 - 500 mm, FF	21	4	70
Nanko 2007	2300 mm, TF + (FF)	27 (11)	23.8	32.2
Finney 1984	61 mm h^{-1} (art.), TF	7	0.4	10.5
Brandt 1987	?? mm, TF	21.8	3	40
Nanko et al. 2008	40 mm h^{-1} (art.), TF+(FF)	17.5 (12.7)	15.9	20.7
Nanko et al. 2011	40 and 85 mm h^{-1}, TF	16.2	11.8	21.2
van Dijk et al. 2002	0.4 - 372 mm h^{-1}, FF	21	3.4	36.8
Brandt 1988	2478 mm, TF + (FF)	27 (18)	13.6	40.2
Zhou et al. 2002	1454 mm, TF	28	21	33
All 9 studies combined		20.7 (SD 6.6)	0.4	70
This study	**1642 mm, TF**	**9.6**	**0.3**	**54.8**

2.4. Modeling

We used a set of 6 categorical and 13 continuous variables to model TKE (Table 2). Plot-diversity treatment, spatial variability (position 1-8), number of influencing individuals, monoculture-mixtures contrast, leaf habit and rainfall event were used as categorical variables. Rainfall amount, LAI, coverage, GD, CBH, number of branches,

crown area, tree height, leaf area, specific leaf area and neighborhood diversity were used as continuous variables. Additionally, we used plot-diversity and number of influencing individuals as continuous variables to account for relationships using appropriate distance between factor levels.

We used the feature importance measurement of the Random Forest (RF) for variable selection of two feature subset types (i) n variables for all rainfall events and (ii) m variables for all single events. The selected variables were used in six CART models (subset for all rainfall events and subsets for all single events). All models were analyzed using R 2.15.3 [R Core Team, 2013] with the packages randomForest [Liaw, A., Wiener, M., 2002] and rpart [Therneau, T., Atkinson, B., Ripley, B., 2013] and were validated using the caret package [Kuhn, 2014].

2.4.1. Variable elimination

Prior to the Random Forest analyses, recursive feature elimination with incorporated resampling was used to identify model performance in dependency of the numbers of input variables [Kuhn, 2014]. This approach leads to a distinct number of input parameters necessary for model calibration beside the specification of non/or less important variables by number. The model approach is based on the following steps: (1.1) Tune/train the model on the training set using all predictors, (1.2) Calculate model performance, (1.3) Calculate variable importance or rankings, (1.4) for Each subset size Si, i = 1 . . . S do, 1.5 Keep the Si most important variables, (1.6) Pre–process the data, (1.7) Tune/train the model on the training set using Si predictors, (1.8) Calculate model performance, (1.9) Recalculate the rankings for each predictor, (1.10), (1.11) Calculate the performance profile over the Si, (1.12) Determine the appropriate number of predictors, (1.13) Determine the final ranks of each predictor, and (1.14) Fit the final model based on the optimal Si. Variables occurring after the optimal input variable number were dismissed in the RF models. These pre-processing step prior model building enables the possibility to eliminate non-relevant input variables for subsequent rule-based model interpretations. Model performance was evaluated by using the root mean square

error (RMSE) and the explained variance (R^2).

Table 2: Predictors used as the independent variables in the CART models. Mean values (and standard deviation (SD)) are calculated as mean (SD) of all five rainfall events.

	Indicators	Abbr.	Mean (SD)	Unit
Abiotic factors	Throughfall amount	A	87.37 (93.93)	ml
	Rainfall Event	B	–	–
Leaf traits	Leaf habit (deciduous vs. evergreen)	C	–	–
	Leaf area	D	13,898 (13,214)	mm^2
	Specific leaf area	E	11.61 (1.27)	$g\ mm^{-2}$
Tree characteristics	Height	F	271.60 (156.42)	cm
	Leaf area index (LAI)	G	1.43 (1.07)	–
	Crown area	H	24,132 (26,462)	cm^2
	Coverage	I	0.62 (0.28)	–
	Number of branches	J	21.41 (16.15)	–
	Ground diameter	K	3.92 (2.03)	cm
	Crown base height	L	56.74 (75.10)	cm
Spatial factors	Position	M	–	–
	Number of individuals (c and n)	N, O	–	–
Diversity treatment	Tree species richness (c and n)	P, Q	4.00 (5.63)	–
	Neighborhood tree species richness	R	1.24 (0.55)	–
	Mono-Mixture contrast	S	–	–

2.4.2. Variable importance using Random Forests

As we cannot identify the less relevant parameter name by the variable elimination algorithm [Kuhn, 2014], the variable importance feature of RF was used. RF are optimal

suited to identify relevant features [Breiman, 2001] based on mean increased modeling performance (%IncMSE) via randomized feature and instance sampling. RF allow for analysis of non-parametric and non-linear effects and give no need to transform data before modeling. They provide high prediction accuracy by fitting many classification trees to a data set and combining the predictions from all trees [Cutler et al., 2007].

In this study, six RF models were constructed (one subset for all rainfall events and five subsets for all single events). The variable importance feature of RF was used to dismiss all input variables that do not lead to a better model performance due to the feature elimination approach. We used TKE as dependent target variable and the variables listed in Table 2 as independent variables. Rainfall event was used as input variable only in the RF of all data. mtry and mnodesize were tested with 1, 2, 3 and 4 and finally set to 3. We constructed 1500 trees per model using regression.

2.4.3. Rule construction using CART

Classification rules for TKE were constructed using CART. CART build the rule by splitting the continuous response into two groups (resulting into nodes which are the sample means of each group) by using an optimal threshold of a predictor (splitting) variable. The optimal split (threshold) is defined as the largest drop to reduce the residual sum of squares between the two groups of the target variable fitted with an ANOVA to the predictor evaluated at this split. The splitting process is iterated in a recursive way for each of the two sub-regions and for each of the predictor variables [Breiman, 1984]. Vertical location of a predictor defines its importance in predicting the target variable TKE. In this study, TKE ($J\ m^{-2}\ mm^{-1}$) was used as response variable and input variables were selected due to RF feature importance measurements. CARTs were constructed using the ANOVA method. Due to the simplification of the model structure by dismissing non/or less relevant input variables, no tree pruning was needed. Fivefold repeated 10-fold cross-validation was used to validate the single trees by $RMSE$ and R^2, as well as the model stability/robustness.

3. Results

Recursive feature elimination results in dismissing the least important five variables (mean of dismissed variables of the six models; Figure 2 dashed line).
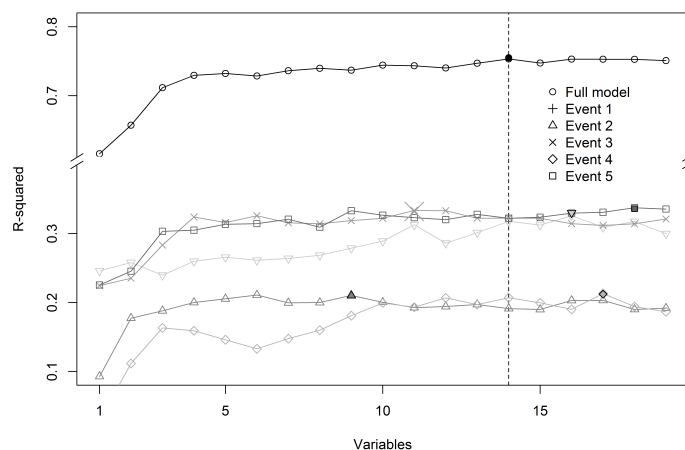

Figure 2: Results of the recursive feature elimination with data from each event and combining all events (full model). Big symbols indicate best variable set for each subset (5 single events and 1 combining all events) and dashed line indicates best variable set by calculating the mean of all subsets.

Selected and dismissed variables in all models based on the RF results are shown in Table 3.

Table 3: Select input variables based on Random Forest feature importance. For variable abbreviations, see Table 3.

Model	Variables selected	Variables dismissed
Complete	A, B, C, D, E, F, G, H, I, J, K, L, P, Q	M, N, O, R, S
Event 1	A, C, D, E, F, G, H, I, J, K, L, M, S	N, O, P, Q, R
Event 2	A, C, D, E, F, G, H, I, J, K, L, P, S	M, N, O, Q, R
Event 3	A, C, D, E, F, G, H, I, J, K, L, P, S	M, N, O, Q, R
Event 4	A, C, D, E, F, G, H, I, J, K, L, P, N	M, O, Q, R, S
Event 5	A, C, D, E, F, G, H, I, J, K, L, P, Q	M, N, O, R, S

The final CART models of all events combined and of event 2 are displayed in Figs. 3 and 4, respectively (for all other events, see Supplement Figs. 6, 7, 8 and 9).
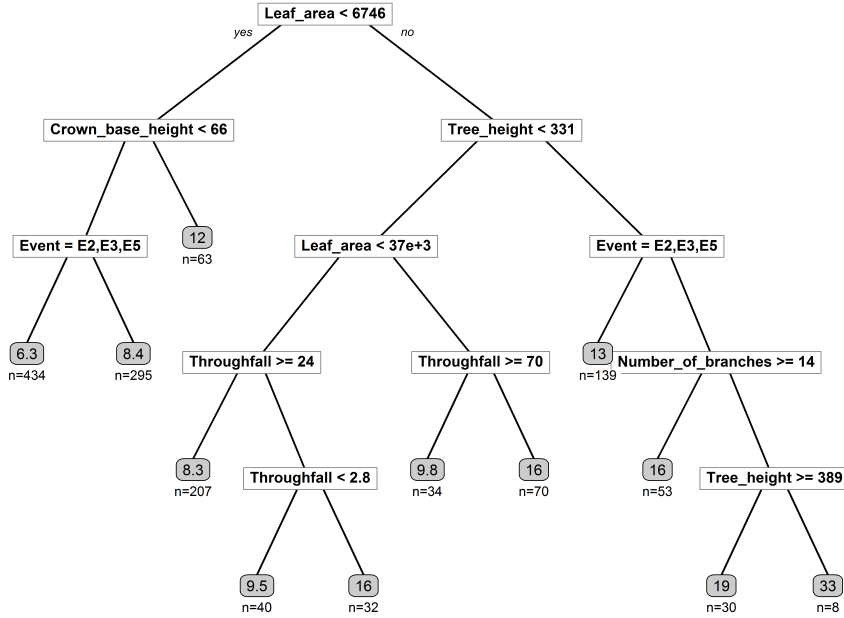

Figure 3: Regression Trees of all events combined. Target variable was throughfall kinetic energy (TKE) and input variables are listed in Table 3. TKE was measured as $J\ m^{-2}\ mm^{-1}$ (n=1405).

Leaf area and throughfall amount occurred in all six CARTs. Tree height and LAI were second prominent with five times occurrence. Position, coverage, specific leaf area, ground diameter and neighborhood diversity occurred only once though. The CART of all rainfall events showed six input variables, five split levels and 12 terminal nodes. The CARTs of rainfall event 2 and 4 showed eight different variables, five split levels and 13 and 12 terminal nodes, respectively. Leaf area was the most prominent variable in first splits. Throughfall amount, tree height and LAI were most prominent in second splits while leaf area, throughfall amount, LAI, number of branches and crown base height appeared most important in third splits. The thresholds of each variable depended on the rainfall event.
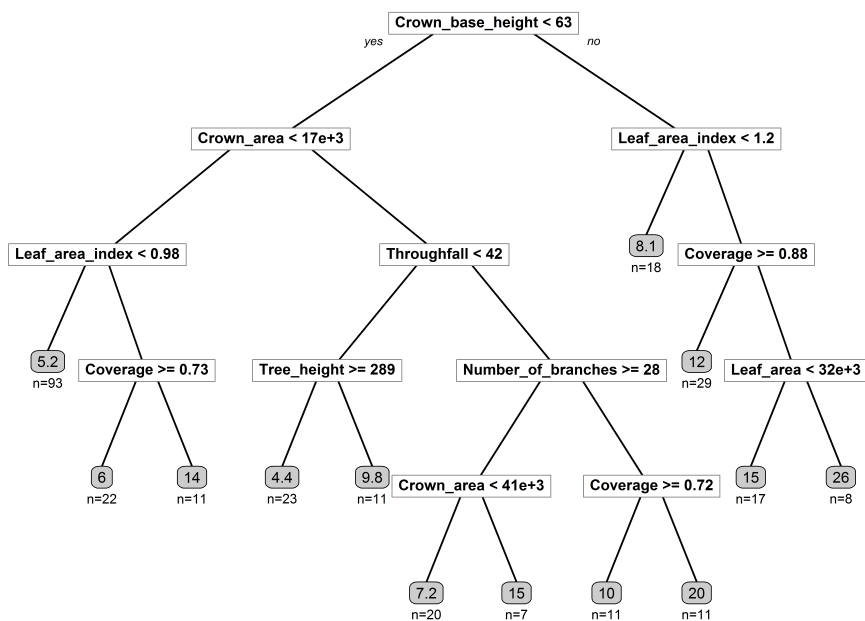
Figure 4: Regression Trees of rainfall event 2. Target variable was throughfall kinetic energy (TKE) and input variables are listed in Table 3. TKE was measured as $J\ m^{-2}\ mm^{-1}$ (n=281).

To monitor very low TKE, thresholds are set by leaf area, throughfall and tree height as the most prominent variables. Leaf area, throughfall, LAI and crown area are most prominent in building splits to yield low TKE while specific thresholds of leaf area, throughfall, crown area, number of branches and crown base height lead to average TKE. High TKE can be monitored with splits occurring by leaf area, throughfall, and LAI. TKE always was higher than the thresholds to detach sediment of various grain sizes reported in literature [Kerenyi, 1981; Morgan et al., 1988; Salles et al., 2000]. CART model performance was $R^2 = 0.68\ 0.45,\ 0.37,\ 0.46,\ 0.41$ and 0.43 and $RMSE = 32.0,$ 16.0, 25.7, 26.5, 4.9 and 52.7 for the full model and rainfall events 1, 2, 3, 4 and 5, respectively.

4. Discussion

We investigated the influence of 19 leaf and tree architectural traits on TKE using an step-wise approach of RF and CART. We showed rules induced by leaf and architectural

traits to obtain very low, low, average or high TKE compared to nine studies which investigated TKE in different regions. Leaf area, throughfall, tree height, LAI and crown area affected TKE as most prominent variables in the tree models.

Ensemble approach using RF variable importance and CART to predict TKE

We detected the effect of biotic and abiotic factors on TKE that are consistent with previous studies. Thus, hypothesis 1 can be confirmed. CARTs showed influence on TKE by leaf area [Goebes et al., 2015b under review], throughfall amount [Brandt, 1988; Scholten et al., 2011; Geißler et al., 2012], tree height [Geißler et al., 2013; Foot and Morgan, 2005], LAI [Nanko et al., 2008; Nanko et al., 2006], crown area [Brandt, 1988; Nanko et al., 2008], number of branches [Herwitz, 1987], crown base height [Nanko et al., 2008; Brandt, C., 1990], spatial variability [Nanko et al., 2011; Finney, 1984] and type and intensity of rainfall event [Zhou et al., 2002; Brandt, 1989]. Further, feature elimination and selection before using CART left no need for pruning or modifying the final trees. A typical pruned RT has three to 12 terminal nodes [Cutler et al., 2007], which is consistent with 9 to 14 terminal nodes in this study. Moreover, prediction results with R^2 =0.68 emphasize the suitability of this approach.

TKE comparison with previous studies

In this study, TKE was twofold lower compared to the mean of other studies investigating rainfall kinetic energy in open fields and below vegetation (Table 2). The age of the subtropical tree plantation can be considered as main reason for this behavior. Many trees did not yet reach full tree height which leads to low fall velocities and thus, lower TKE [Gunn and Kinzer, 1949]. Furthermore, a dense and thick crown cover was not developed in some plots in the previous six years this plantation existed. LAI and number of branches as major variables in modeling high TKE emphasized the importance of a thick crown cover (Fig. 6). To our knowledge, only one study measured similar TKE [Finney, 1984]. Comparable to our study, relatively low vegetation heights

were used that did not allow rain drops to reach terminal velocity. In contrast, Nanko et al. [2008], Nanko et al. [2011] and Sanchez-Moreno et al. [2012] measured average to high TKE which might be caused by high-intensity rainfall above 40 $mm\ h^{-1}$. These intensities exceed those of four events measured in our study. Since throughfall amounts are similar to or lower than our measurements, rainfall intensity might function as the major abiotic factor leading to high TKE throughout all studies [Levia and Frost, 2006]. However, TKE can be stable among different rainfall intensities ranging from 1 to 46 $mm\ h^{-1}$ [Zhou et al., 2002]. In this case, throughfall amount might be a better predictor for TKE differences.

Thresholds of leaf and tree architectural traits as well as throughfall to model TKE

In general, results obtained from data of all events can be found in more detail by examining each event (Fig. 3-8). Since TKE is standardized by rainfall amount, rainfall intensity and duration might change the optimal set of leaf and tree architectural traits and their thresholds. Leaf area was the most important trait in our CARTs to describe different TKE. It was of major importance to yield very low, low, average or high TKE. With a leaf area higher than 32,000 mm^2 average to high TKE occurred while a leaf area below 7,000 mm^2 led to very low TKE. The latter size was most prominent in all species and showed that only species with large leaf area cannot function as erosion inhibitors. A higher leaf area might create a larger surface for rain drop gathering as well as confluence and hence, a release of larger rain drops [Herwitz, 1987]. For instance, leaves of Schima superba (38,090 mm^2) increased sand loss in splash cups by 30 % compared to leaves of Castanopsis eyrei (12,920 mm^2) which led to TKE (converted out of sand loss with a linear function by Scholten et al. [2011]) within the range of one standard deviation of natural rainfall [Geißler et al., 2012]. This shows that the erosion potential below vegetation can be dramatically reduced to that of natural rainfall with small leaf sizes.

Our study showed an indifferent effect of throughfall on TKE and contradicts a positive effect reported in previous studies [Brandt, 1988; Levia and Frost, 2006; Scholten

et al., 2011]. Nonetheless, throughfall amount as abiotic factor was second prominent to describe TKE differences, but with a positive and a negative effect. Throughfall amounts lower than 229 mm led to low TKE while throughfall amounts higher or lower than 189 mm led to very low TKE in high rainfall amounts per event. However, very low throughfall amounts like 2.8 mm can also lead to high, average or low TKE. This neither positive nor negative effect can be ascribed to the standardization of TKE by the rainfall amount fallen at each event, which let biotic factors emerge. Thus, throughfall amount might play an important part in classifying TKE but to what extend remains unclear. This was especially visible when analyzing data of all events combined (Fig. 3).

A tree height shorter than 290 cm resulted in very low to low TKE (7.5 – 14.1 $J\ m^{-2}\ mm^{-1}$) due to shorter falling heights and hence, slower rain drop velocities [Gunn and Kinzer, 1949]. This threshold leads to TKE only about 2 J m-2- mm-1 below literature reported amounts [Brandt, J. 1990; Nanko et al., 2008]. Brandt [1990] emphasized in her model that tree height changes affect TKE more with lower heights. Fig. 3 highlights that only tree heights above 389 cm led to high TKE, although 60 cm less height led to very low to low TKE. This suggests that there is critical height approximately at 330 cm, above which TKE becomes highly erosive. However, this height is close to the mean of all species and shows that especially young trees are non-erosive.

A LAI higher than 1 led to average to high TKE while a lower LAI led to very low to low TKE This threshold results in a positive effect of LAI on TKE which is contrary to previous studies [Nanko et al., 2008; Geißler et al., 2013]. However, these studies dealt with LAI ranging from 1.5 to 11. Therefore, the positive effect of LAI might occur only for low LAI due to a close connection to canopy openness or crown area. Within these low values, a higher LAI represents a higher coverage and throughfall creation without creating more rainfall interception and breaking points by different canopy layers.

A crown area higher than 40,000 cm^2 never led to very low or low TKE and thus, symbolizes a maximum size below which the erosive potential of TKE can be contained. We ascribe this positive effect on TKE by gathering of rain drop and creating a higher

area at which throughfall occurred. However, low rainfall intensities (rainfall event 1) counteract this effect when TKE is examined at 15 cm, 30 cm and 60 cm away from the tree stem (Fig. 4). Nanko et al. [2008] showed this negative effect of crown area on TKE examining areas larger than 85,000 cm^2. Nevertheless, the effect shift remains unclear.

Crown base height was the fourth most classifier of TKE. Rain drops falling from a crown base height lower than approximately 60 cm created very low and low TKE. Moss and Green [1987] showed in their study that the height-velocity relationship for rain drops increased rapidly over the first two meters and stated a threshold of 30 cm below which rain drops are non-erosive. This threshold represented the mean crown base height in this study and is another argument to consider low- and slow-growing tree species as erosion inhibiting.

The importance of the number of branches to classify TKE can be considered mediate. While less than 14 branches at low rainfall amounts (event 3 and 4) led to average or high TKE, more than 47 branches led to very low and low TKE. We ascribe this negative effect to the higher probability for raindrops to break at branches and hence, decrease in drop size and velocity resulting in low TKE [Herwitz, 1987].

The effect of spatial variability on TKE remains indistinct as its importance in the RT was low and it occurred only in combination with crown area. Positions below vegetation where very low or low TKE appeared remain unclear. This absence of a spatial variability of TKE can be found in literature [Nanko et al., 2011]. Nevertheless, 30 cm away from the stem below or at margins of the canopy high TKE can be achieved which was also reported by Finney [1984].

If the surrounding trees consist of one species, very low TKE occurred. Species-mixtures, however, led to low TKE. A diverse neighborhood might lead to more complex tree structures which can positively affect throughfall by creating different canopy layer height at which drops can confluence [Getzin et al., 2008; Schröter et al., 2012]. Nevertheless, a classification by neighborhood tree diversity as well as ground diameter

and specific leaf area was not prominent (low importance in CART).

5. Summary

Our study linked leaf and tree architectural traits to TKE and set thresholds below which low TKE and above which high TKE occurred. Fig. 5 provides a graphical summary of all relevant traits investigated in this study.
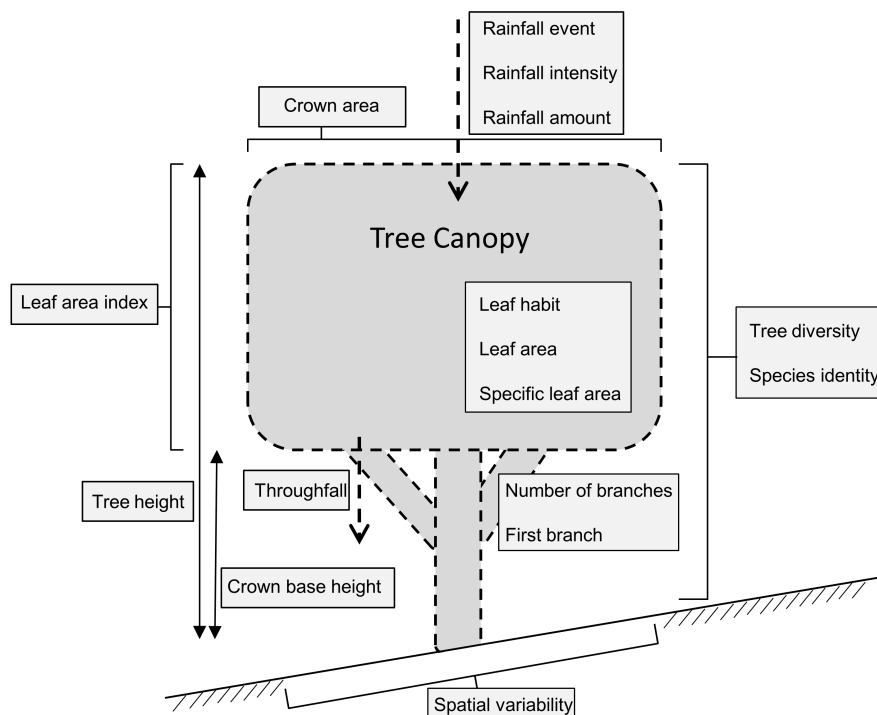

Figure 5: Graphical summary of relevant tree architectural and leaf traits affecting TKE based on Classification and Regression Trees.

With the set of species, tree architectural and leaf traits used in this study, the erosive potential of TKE can be mitigated by a smaller leaf area than 70 cm^2, a lower tree height than 290 cm combined with a lower CBH than 60 cm, a LAI smaller than 1, more than 47 branches and by using single tree species neighborhood while the amount of throughfall can vary. Although these models have been calibrated with data of a young tree plantation, they are, nevertheless, another step towards identifying the importance of leaf and tree architectural traits and most of all, setting thresholds for erosion occurrence based on TKE.

Acknowledgements

Supplement

Table 4: Characteristics of the five rainfall events.

Rainfall events	Rainfall amount [mm]	Rainfall duration [h]	Mean throughfall amount [ml]	Rainfall intensity [5min intensity]	Rainfall intensity of total event [mm h^{-1}]
Event 1	23.3	10.16	35.88	12.1	2.29
Event 2	39.3	11.50	41.91	22.8	3.42
Event 3	61.2	14.50	93.77	44.4	4.25
Event 4	6.6	2.33	5.84	25.2	2.83
Event 5	185.7	30.58	246.57	127.2	6.07

Figure 6: Classification and regression tree of rainfall event 1. Target variable was throughfall kinetic energy (TKE) and input variables are listed in Table 3. TKE was measured as $J\ m^{-2}\ mm^{-1}$ (n=279).

Figure 7: Classification and regression tree of rainfall event 3. Target variable was throughfall kinetic energy (TKE) and input variables are listed in Table 3. TKE was measured as $J\ m^{-2}\ mm^{-1}$ (n=282).

Figure 8: Classification and regression tree of rainfall event 4. Target variable was throughfall kinetic energy (TKE) and input variables are listed in Table 3. TKE was measured as $J\ m^{-2}\ mm^{-1}$ (n=281).
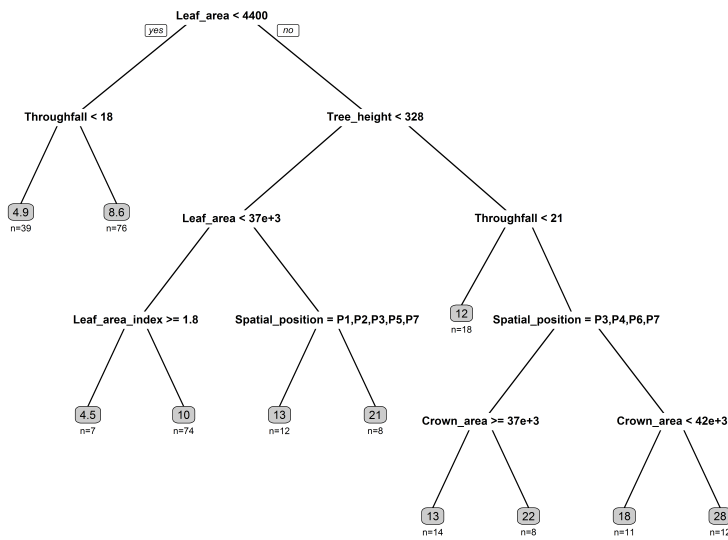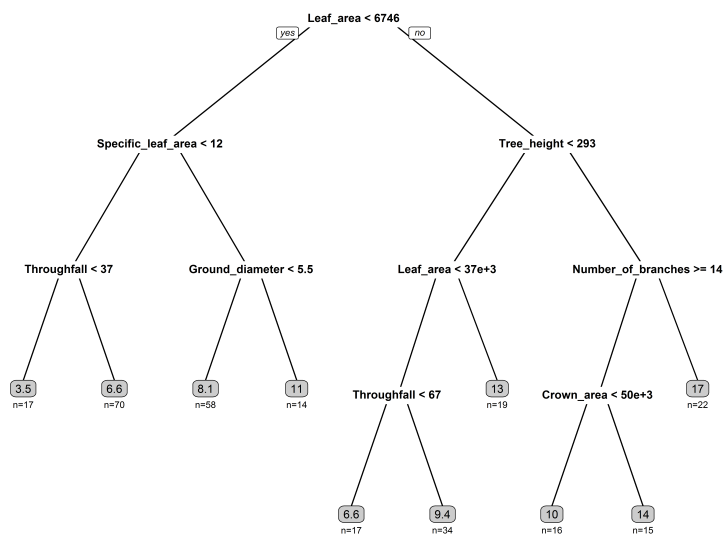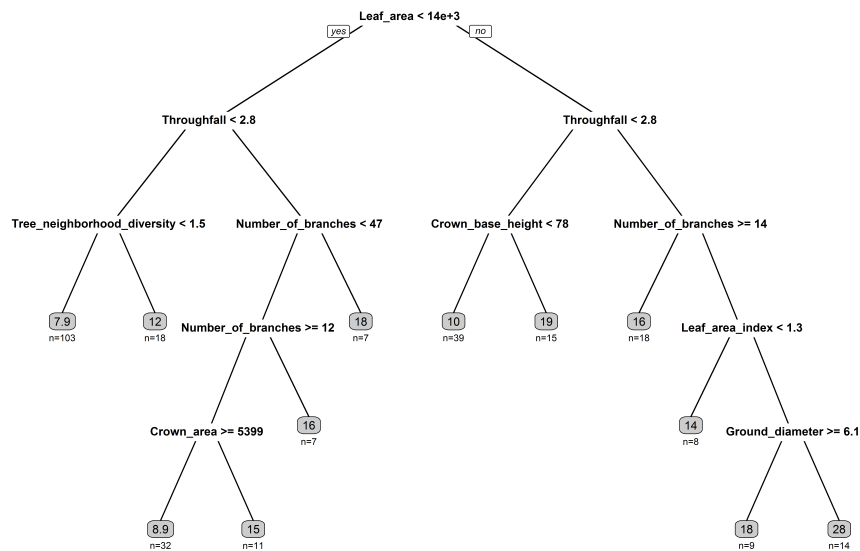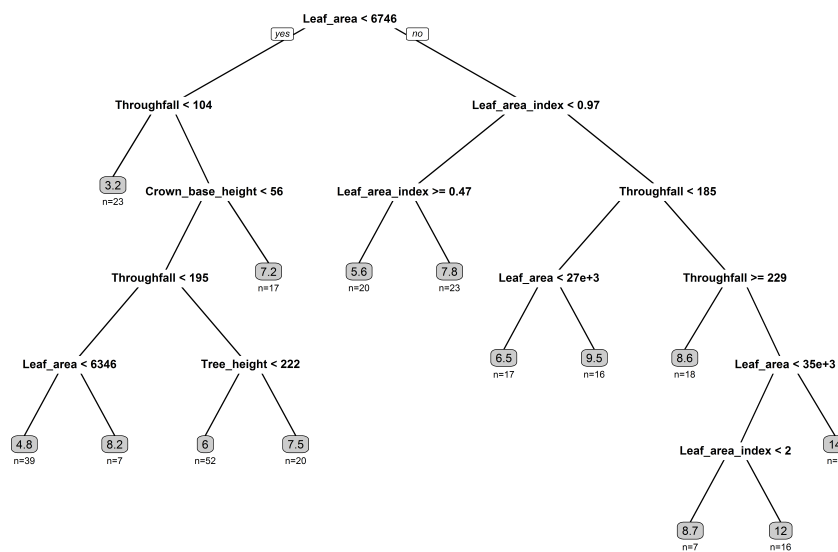

Figure 9: Classification and regression tree of rainfall event 5. Target variable was throughfall kinetic energy (TKE) and input variables are listed in Table 3. TKE was measured as $J\ m^{-2}\ mm^{-1}$ (n=282).

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Manuscript 5 (accepted)

The influence of leaf litter diversity and soil fauna on initial soil erosion in subtropical forests

Steffen Seitz [a], Philipp Goebes [a], Pascale Zumstein [b], Thorsten Assmann [b], Peter Kühn [a], Pascal A. Niklaus [d], Andreas Schuldt [b], Thomas Scholten [a]

[a] University of Tübingen, Department of Geosciences, Soil Science and Geomorphology, Rümelinstraße 19-23, 72070 Tübingen, Germany

[b] Leuphana University Lüneburg, Institute of Ecology, Scharnhorststraße 1, 21335 Lüneburg, Germany

[c] University of Zürich, Institute of Evolutionary Biology and Environment, Winterthurstrasse 190, 8057 Zürich, Switzerland

Abstract

Although the protective role of leaf litter cover against soil erosion is known for a long time, little research has been conducted on the processes involved. Moreover, the impact of soil meso- and macrofauna within the litter layer on erosion control is not clear. To investigate how leaf litter cover and diversity as well as meso- and macrofauna influence sediment discharge in subtropical forest ecosystems, a field experiment has been carried out in South-East China. A full-factorial random design with 96 micro-scale runoff plots and 7 domestic leaf species was established and erosion was triggered by a rainfall simulator.

Our results demonstrate that leaf litter cover protects soil from erosion (-82 % sediment discharge on leaf covered plots) by rainfall and this protection is removed as litter decomposes. This protective effect is influenced by the presence or absence of soil meso- and macrofauna. Fauna presence increases soil erosion rates significantly by 58 %, while leaf species diversity shows a non-significant negative trend. We assume that the faunal effect arises from arthropods slackening and processing the soil surface as well as fragmenting and decomposing the protecting leaf litter covers. Even though the diversity level did not show a significant influence, single leaf species in monocultures show rather different impacts on sediment discharge and thus, erosion control. In our experiment, runoff plots with leaf litter from *Machilus thunbergii* showed the highest sediment discharge (68.0?$g\ m^{-2}$) whereas plots with *Cyclobalanopsis glauca* showed the smallest rates (7.9?$g\ m^{-2}$).

1. Introduction

Soil erosion is one of the principal environmental problems worldwide, especially in regions with high human impacts on the ecosystems (Morgan, 2005). In subtropical parts of China, for example, high rainfall intensities cause severe and continuous losses of soil and thus, important disservices in ecosystems (Wang et al., 2005; Shi et al., 2008). Soil erosion reduces soil organic matter (SOM), relocates nutrients, changes the

water-holding capacity and can reduce the biodiversity of soil flora and fauna (Durán-Zuazo and Rodríguez-Pleguezuelo, 2008). The degradation of soils will remain one of the principal environmental problems as an augmentation of extreme weather events and changes in mean precipitation are stated in future (IPCC, 2007; Xu et al., 2007).

Besides soil erodibility, rainfall erosivity and inclination, vegetation is regarded as a main attribute to describe the intensity and kind of erosion caused by water (Thornes, 1990). Forest in general reduces the risk of considerable soil loss and especially the litter cover is known to reduce the erosivity of rainfall by absorbing the impact of raindrops, leading to a lower sediment discharge and runoff volume compared to bare ground (Morgan, 2005). Nevertheless, leaf exudates and low sunlight in dense forest plantations can lead to a declining shrub and herb layer and so to bare ground, thus increasing runoff and sediment discharge (Onda et al., 2010). Geißler et al. (2012) showed that the erosive power of raindrops is significantly higher under subtropical forest than under fallow land due to changes in drop sizes. It has been demonstrated that leaf litter quality is an important ecosystem factor in temperate climates with direct impact on soil characteristics (Kooijman and Cammeraat, 2010). Leaves of different species vary in their sizes, shapes, decomposition rates (Cornelissen, 1996) and water storage capacities within a litter layer (Kim et al., 2014), which has an important influence on ground coverage and surface runoff. Sidle et al. (2007) described a shallow preferential flow in soiloverlaying organic horizons ("biomat flow"), which is not initiating soil erosion. It is suggested that plant species and functional diversity as well as a highly structured and diverse litter cover is an important factor for soil erosion control on mountain slopes (Martin et al., 2010; Körner and Spehn, 2002). Although the protective role of litter cover against soil erosion has been known for a long time (e.g. Smith, 1914), only little research has been conducted on the processes involved.

In general, quality and quantity of litter determines decomposer communities ranging from microbes and fungi to animals of different size classes (Hättenschwiler et al., 2005). Leaf litter provides habitats, maintains a favourable microclimate for soil fauna and further on, it is an important food source (Sayer, 2006). Although the main part of

litter decomposition is performed by microbes (Bardgett, 2005), the meso- and macro-fauna constitutes the dominant physical litter transformers. It is consequently essential for promoting both, litter decomposition (Hättenschwiler and Gasser, 2005) and physical-chemical soil parameters (Gabet et al., 2003). By that, these organisms have the potential to influence geomorphological processes like soil erosion (Butler and Sawyer, 2012; Wheaton et al., 2011; Butler, 1995). Allen et al. (2014) recently linked ecological principles to geomorphological aspects in general. However, our knowledge about how these principles affect soil erosion is still rudimentary. Cammeraat and Kooijman (2009) consider both, soil fauna and tree type as important ecosystem engineers. At the same time, most of the relevant studies on faunal effects deal with bioturbation and illustrate the role of one or few functional groups of soil meso- and macrofauna as geomorphic agents (Hupp et al., 1995; Viles, 1988). For instance, the crucial role of earthworms influencing soil structure and related soil physical properties is relatively well studied (Blanchart et al., 2004). Earthworms can decrease surface water runoff by increasing soil porosity (Edwards and Bohlen, 1996). Porosity is indirectly influenced by leaf litter and SOM, as they are a major food supply to earthworms, but also arthropods (Sayer, 2006). Ants and termites can also have an effect on soil turnover (Butler, 1995). For example, Cerdà and Jurgensen (2011) indicated that the presence of ant nests decreases surface runoff but increases sediment loss owing to unconsolidated soil mounds. Nevertheless, the impact of other soil meso- and macrofauna on soil erosion, especially in ecosystems lacking the important influence of earthworms, is not yet clear.

Focusing on initial soil erosion which is triggered by rain splash striking the soil surface (e.g. Goebes et al., 2014) and shallow overland flow transporting soil particles (e.g. Shi et al., 2010), our research concentrates on how litter cover and litter diversity as well as meso- and macrofauna influence sediment discharge. From a hypothetical point of view, full leaf covered soil surfaces might be better protected against soil erosion by greater overlap and gap-filling in highly diverse leaf litter mixtures. At the same time, highly diverse leaf litter mixtures may lead to faster leaf decomposition caused by more active decomposer communities and thus, soil surfaces will get bared quicker.

As a consequence, this effect could lead to an inferior conservation of soil surfaces and therefore, to higher erosion rates. At last, we hypothesize that soil meso- and macrofauna will have an impact on leaf litter cover and sediment discharge.

Based on these hypotheses, our research questions are:

I. Does higher leaf litter species diversity lead to decreasing sediment discharge, when soil surfaces are fully covered and to increasing sediment discharge, when soil surfaces are partly covered?

II. Does the presence of soil meso- and macrofauna lead to a faster decomposition of leaf litter cover and thus, increasing sediment discharge?

To examine the influence of leaf litter in forest ecosystems, experimental approaches are widely used, but mostly performed in temperate climates (Sayer, 2006). Runoff plots are a common mean in soil erosion research to investigate sediment discharge and surface runoff (Hudson, 1993). To standardize rainfall conditions for those erosion measurements, rainfall simulators are widely used (Iserloh et al., 2013b). In order to investigate the role of litter diversity and meso- and macrofauna decomposers on soil erosion, we established a full factorial replicated field experiment that manipulated the amount and diversity of leaf litter and decomposer abundances in a subtropical forest system in South-East China.

2. Materials and methods

2.1. Study site

The study took place in a Castanea mollissima plantation (established in 1996) near Xingangshan, Jiangxi Province, P.R. China (N 29°05.193' and E 117°55.533', 125 m a.s.l., Figure S1), which is part of the Biodiversity and Ecosystem Functioning project "BEF China" (Bruelheide et al., 2014; Bruelheide et al., 2011). The climate in Xingangshan is characteristic for subtropical summer monsoon regions with a mean annual temperature of 17.4°C and a mean annual rainfall of 1635 mm (Köppen-Geiger classification: Cwa). In summer 2012 meteorological data showed typical monsoon patterns

with increasing mean temperature from May (21.8°C) to August (27.4°C) and a mean monthly precipitation of 200 mm. In September temperature decreased (22.5°C) and the end of the monsoon season led to considerably lower precipitation (116 mm). The plantation covers an area of 1200 m^2 with an elevation difference of 11 m and is characterized by moderately steep to steep slopes (14°- 38°) without an ectorganic layer. Within a distance of 5-10 m, it is surrounded by region-specific secondary forest. The soil is an Endoleptic Cambisol (cf. IUSS Working Group WRB, 2006) developed on saprolite weathered to silt loam (sand=24 %, silt=50%, clay=26 %). It does not change considerably within the study site. The bedrock consists of non-calcareous slates. Mean bulk soil density is low (1.15 g cm^{-3}).

2.2. Runoff plots (ROP)

Sediment discharge and runoff volume were measured with micro-scale ROPs (0.4 m x 0.4 m) to determine initial soil erosion. The ROPs were made of stainless steel panels and connected to a covered runoff-gutter at the lower end. In this particular experiment we incorporated four holes to the side panels (circular, diameter 50 mm). Those holes were equipped with mesh (size 20 mm) to exclude bigger animals (e.g. mice and toads), but allow access to litter decomposing meso- and macrofauna. Half of the plots were additionally equipped with pitfall traps (diameter 0.09 m, depth 0.15 m, capacity 0.55 l) and fine mesh (size < 0.1 mm) to exclude or at least strongly reduce soil meso- and macrofauna from ROPs (fauna treatment). The traps were filled with 0.15 l of preserving solution (40 % ethanol, 30 % water, 20 % glycerol, 10 % acetic acid, some drops of detergent to reduce surface tension), which has shown its reliability in subtropical climates (Schuldt et al., 2011). In between the measuring campaigns all ROPs have been provided with 20-mm-mesh to fix the experimental leaves against moving downslope and to exclude falling leaves from *Castanea mollissima* (Figure 1). Micro-scale ROPs were chosen to establish a maximum number of replicates within a factorial random design and to assure a high level of maintenance and control (c.f. Hudson, 1993).
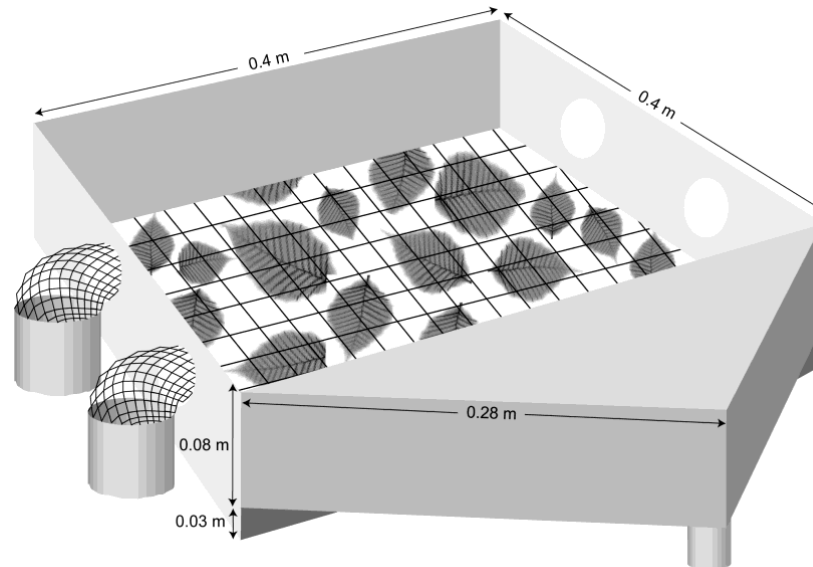
Figure 1: Runoff plot (ROP) with fauna treatment. ROPs (0.4 m · 0.4 m) consist of stainless-steel side panels and a triangular covered runoff gutter. Falling leaves are separated from experimental leaf mixtures by a 20-mm-mesh. Pitfall traps (2 at each side) are installed to exclude soil meso- and macrofauna.

Compared to small-scale ROPs and field plots, they are easier to handle and monitor in greater number, especially in rough terrain and climate conditions. Although ROP measurements in general are strongly influenced by arbitrary natural and measurement variability (Wendt et al., 1986), micro-scale ROPs allow focusing on initial soil erosion. Rilling processes do not occur on such short distances and the parameters of the erosion process can be controlled closer than on larger plots (Stroosnijder, 2005; Mutchler et al., 1994). The stability of soil aggregates influenced e.g. by SOM or meso- and macrofauna are of major importance at this scale (Morgan, 2005). Nevertheless, the use of such short ROPs raises certain constraints. Rim and boundary effects like the movement of splashed particles in and out of the plot have to be considered (Mutchler et al., 1994). The average splash distance for silt loam at every plot is approximately one quarter of the ROP-length (0.12 m, c.f. Legout et al., 2005). The length of the ROPs is another aspect, which affects erosion measurements (Bagarello and Ferro, 2004). Several studies showed that short slopes lead to higher runoff volume per surface area than longer slopes (e.g. Joel et al., 2002; Van de Giesen et al., 2000), which further leads to higher

sediment discharge. Yet, Thomaz and Vestena (2012) compared microscale plots (1 m^2) with larger plots (10 m^2) in a subtropical environment and found that runoff volume was higher in smaller plots, but soil loss was similar. We assume that our experimental erosion rates are overestimated compared to natural erosion rates and values should be extrapolated with caution. Nevertheless, interplot comparison is reasonable.

2.3. Experimental design

Leaf litter of seven domestic tree species (*Liquidambar formosana* (Hance, species A), *Machilus thunbergii* (Sieb. et Zucc., B), *Quercus serrata* (Thunb., C), *Schima superba* (Gardn. et Champ., D), *Castanopsis eyrei* (Champ. et Benth., E), *Castanea henryi* (Rehd. et Wils., F), *Cyclobalanopsis glauca* (Thunb., G), author and abbreviation for given species in parentheses) was collected in Gutianshan National Nature Reserve close to our study site (Geißler et al., 2013). Species were organised in two pools with one overlapping species (pool I: species A, B, C, D and pool II: species D, E, F, G) and distributed into the ROPs. Using one, two and four species mixtures as well as a bare ground feature (diversity 0), we obtained 24 ROPs (12 ROPs for each species pool). To investigate the meso- and macrofaunal influence, we applied a fauna exclusion feature using to different types of ROPs (see above) which doubled the number to 48 ROPs. Moreover, we replicated all plots and hence, achieved a total number of 96 ROPs (Figure 2). ROPs were placed randomly on the study site in four blocks (species pool I + replication and species pool II + replication).
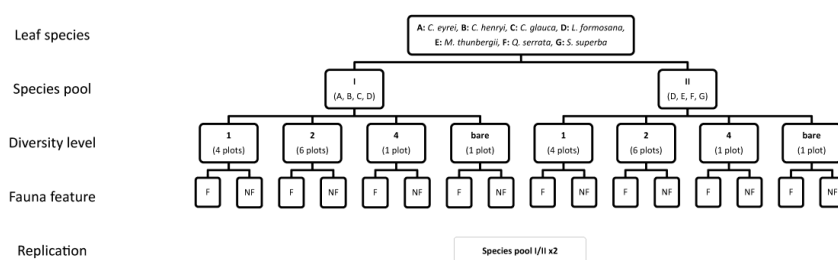

Figure 2: Experimental design with seven leaf species, two species pools (I, II), four litter diversity levels (bare ground, 1, 2, 4 species), fauna feature (F=Fauna, NF=No Fauna) and replication (96 ROPs in total).

Leaf litter blends were mixed before deployment to avoid local patches of individual species (Burghouts et al., 1998) and distributed randomly among the ROPs (60 g for each ROP). Prior to this, alien leaves, twigs and loose stones (> 2 mm) have been removed from the plot surfaces. Remaining stone cover was recorded photogrammetrically. The distribution was conducted six weeks before the first measurement to minimize plot installation effects and allow local leaf decomposer communities to adapt to the used leaf species. Soil meso- and macrofauna are mostly food generalists and can adapt quickly to changed food sources (Hättenschwiler et al., 2005). Leaf decomposition in general is largely influenced by litter quality determined by nutrient concentrations and the C/N and lignin/N ratio (c.f. Purahong et al., 2014; Wang et al., 2009). Dependent on the quality, the adaptation by microbes and bacteria can be fast, which is also true for our study plots (Seidelmann and Scherer-Lorenzen 2014, personal communication).

2.4. Rainfall simulation and sediment discharge

The rainfall simulation was carried out at two timesteps (May and September 2012) with the portable Tübingen rainfall simulator (Iserloh et al., 2013a). It was modified by a Lechler 460.788.30 nozzle and adjusted to a falling height of 3.5 m (pressure at nozzle: 150 hPa). The sprinkle area was 1 m^2 and protected from outer influences by a light frame tent (16 m^3). Rainfall intensity was set to 60 mm h^{-1} for all simulation runs according to a typical regional rain storm event, as monitored in Xingangshan (2009-2012) about 5 km northeast of our experimental site. Drop size spectrum and intensity of the simulator were calibrated using a "Laser Precipitation Monitor" by Thies (Lanzinger et al., 2006) to obtain homogeneous characteristics. Rainfall was simulated for 20 min at each ROP. To consider the effect of different water saturations, we applied a first 20 min run on actual field water saturated ground and a second run 15 min later, when soils had higher water saturation. Sediment discharge was separated from runoff by vacuum filtration (fibreglass filters). The solid subsample was oven dried (40℃) before weighing. Measurements were carried out when ROPs were fully covered (May 2012, 128 mm of natural rainfall during timestep 1) and after decomposition had led to reduced

leaf litter coverage (September 2012, no natural rainfall during timestep 2). Leaf covered ROPs have not laid bare completely in the second timestep. No rills were present in the experimental plots.

2.5. Soil properties

We recorded 48 soil profiles to assure that conditions are equal for every pair of ROPs. Bulk soil density (depth $0.05 \ m$) was measured with the mass-per-volume method ($100 \ cm^3$ intact core). The pH was determined in KCl ($10 \ g$ soil on $25 \ ml$ $1 \ M$ KCl) with a WTW pH-meter and Sentix 81 electrodes. Soil organic carbon was measured with an elemental analyzer (purge and trap chromatography, Elementar vario EL III). During the experiment we assessed soil moisture at both timesteps and every ROP with a Delta-T Device Wet2-Sensor (TDR). Leaf litter cover of the plots was recorded photogrammetrically at the beginning and at the end of the experiment. Meso- and macrofauna from pitfall traps were counted, identified and classified to higher taxonomic levels.

2.6. Data analysis

We used linear mixed effects (lme) models with species pool and block fitted first as fixed effects, followed by litter diversity, fauna treatment and their interactions. Species composition and plot as well as their interactions with the faunal exclusion treatment were fitted as random effects. For the analysis of the repeated measures, we also included the interactions of composition with the replicated rainfall simulations and the timestep of the rainfall event. These random terms ensure that effects of diversity and of diversity with the respective interactions are tested based on the correct number of replicates.

Since bare ground is different in quality from the other diversity levels, a binary contrast variable "litter cover" was fitted before litter diversity. When there were indications of trends, we tested whether specific diversity levels were different from others using linear contrasts (e.g. whether monocultures were different from mixtures). Functional diversity can sometimes be a more important determinant of ecosystem functions

than the number of species (Scherer-Lorenzen, 2005). We determined functional diversity sensu Petchey and Gaston (2006) using leaf traits (leaf area, leaf mass per area, C/N ratio and plant family). Leaf traits were recorded on green leaves sampled in the Gutianshan National Nature Reserve (Kröber et al., 2012). Leaf decomposition rates were calculated as remaining leaf mass at timestep 2 compared to timestep 1. Influences of site conditions were tested using the covariables slope, pH, soil moisture, soil organic carbon and bulk density. Runoff volume was used as covariable when fitting sediment discharge. All data (except runoff volume and leaf decomposition) were log- transformed to achieve normal residual distributions. All mixed models were fitted using R 2.15.3 (R Development Core Team, 2013) and ASReml (Butler, 2009).

3. Results

3.1. Effects on initial soil erosion

The result of the lme modelling for sediment discharge is shown in Supplement Table 1 on 206. Mean sediment discharge and runoff volume were calculated per m^2 and 20 minutes run (Supplement Table S2).

Mean sediment discharge was 60 % higher in September than in May (Figure 3). In May mean sediment discharge decreased from bare plots (diversity level 0) to leaf covered plots by 82 % ($P < 0.001$). A slight decrease was still visible in September but no longer significant with reduced litter cover (Supplement Table 2). Mean runoff volume was higher in the rainy season (timestep 1) than at the end of summer (timestep 2) and bare plots showed 28 % ($P < 0.01$) more runoff in May and 13 % (n.s.) more runoff in September than leaf covered plots (Supplement Table 2). Sediment discharge was on average lower at high than at low diversity levels, but at both timesteps no significant effect of litter diversity on sediment discharge could be found. Likewise, functional diversity had no significant effect. Furthermore, no effect of mono-species plots against mixed species plots and single species within their species pool on sediment discharge could be found.
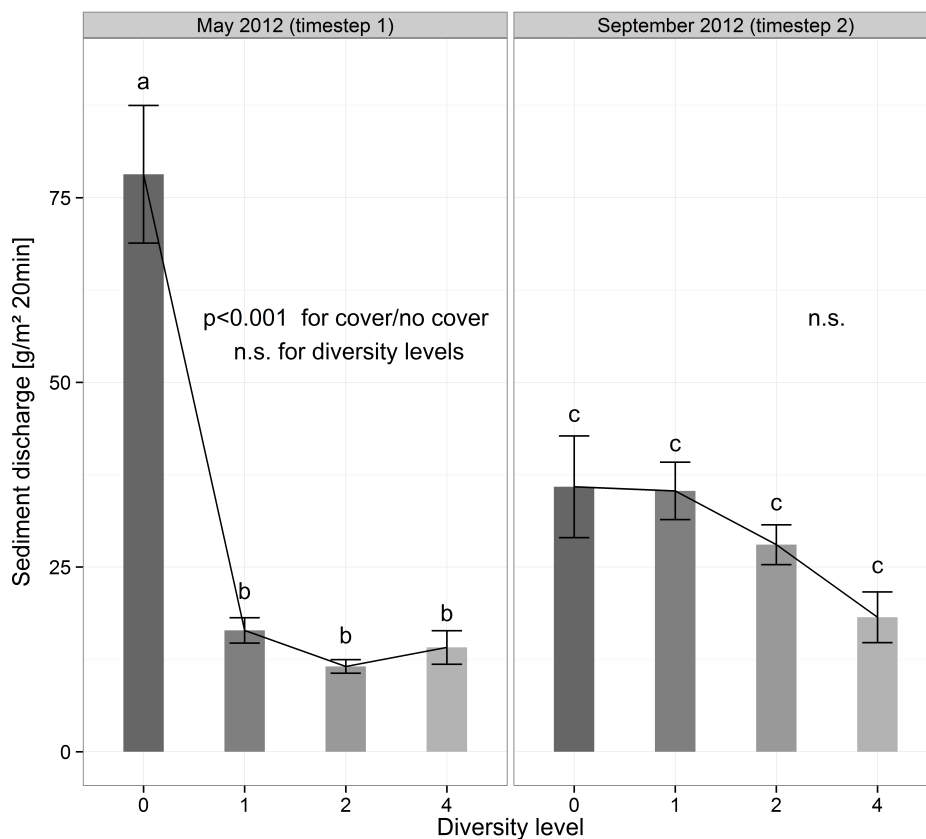
Figure 3: Effect of diversity levels and bare ground (diversity = 0) on sediment discharge at timestep 1 (May 2012) and timestep 2 (September 2012). Small letters indicate significant mean differences.

A clear difference between fauna and no-fauna treatment was evident at both timesteps (Figure 4) and sediment discharge was significantly influenced by the fauna treatment in May ($P < 0.001$) and September ($P < 0.05$). Discharge was 58 % higher with fauna than without. This effect is decreasing from timestep 1 (60 %) to timestep 2 (56 %).

All monocultures showed slightly different effects on sediment discharge and several species (species A and B: $P < 0.001$, species G: $P < 0.01$) showed significant deviation compared to the overall mean in timestep 2 (Figure 5). These differences did only occur in September, where influences of different leaf litter species were more heterogeneous than in May.
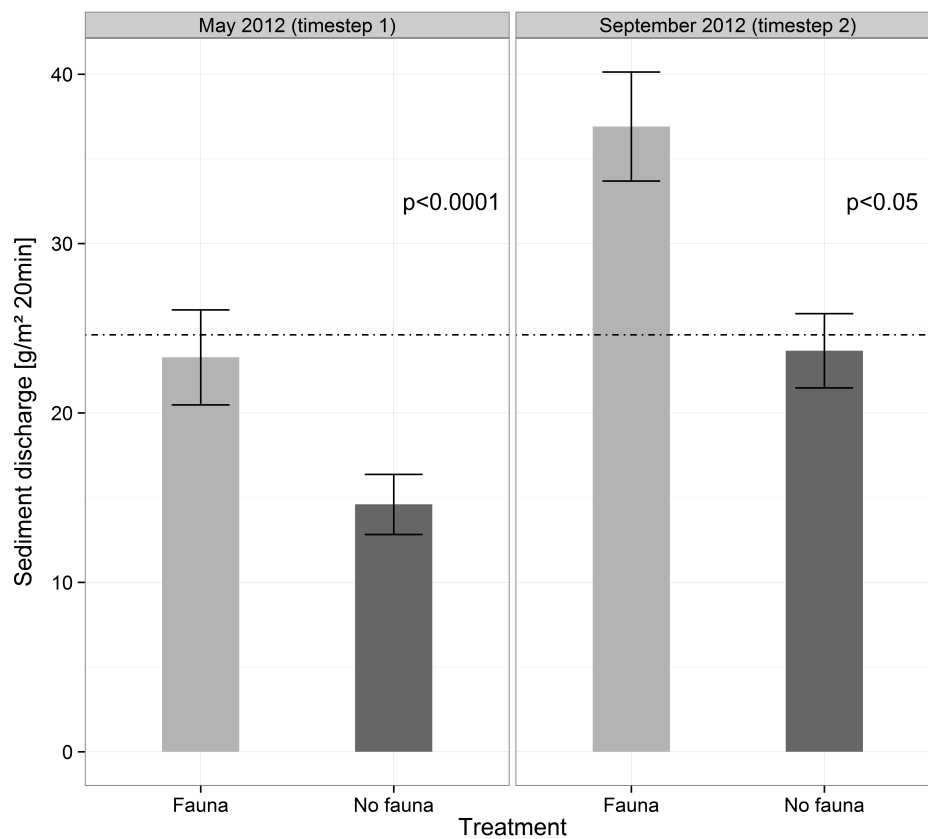
Figure 4: Effect of the fauna treatment on sediment discharge at timestep 1 (May 2012) and timestep 2 (September 2012).

Slope was not affecting sediment discharge at any time. Litter cover had a negative effect on sediment discharge ($P < 0.001$) and bulk soil density became significant in timestep 2 ($P < 0.05$). Moreover, soil moisture showed a negative effect on sediment discharge ($P < 0.001$) and mean moisture was 45 % in the rainy season (timestep 1) compared to 26 % at the end of summer (timestep 2). Mean moisture at the second rainfall simulation run (41 %) was 24 % higher than at the first run (31 %). Mean soil organic carbon content was low (1.6 %) and mean pH value was acidic (3.7). Both parameters did not affect soil erosion. Surface sealing and crusting could be seen on all plots during the rainfall simulations, but conditions were equal for all plot surfaces. No signs for a significant role of water repellency have been found. Basic data on soil parameters and soil moisture is presented in Supplement Table 3.
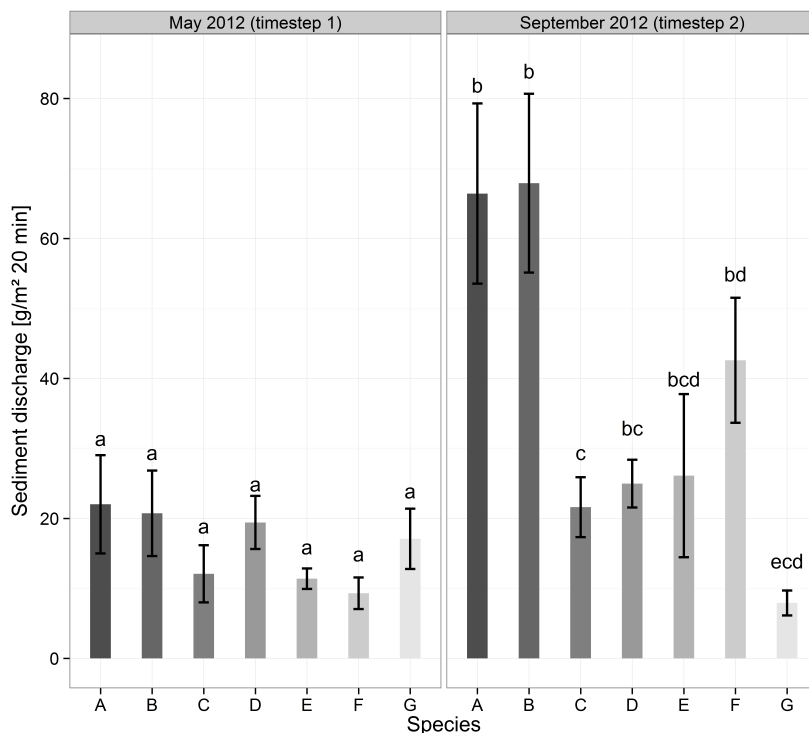
Figure 5: Relation between sediment discharge and monocultures of leaf litter species at timesteps 1 and 2. Small letters indicate significant mean differences.

3.2. Meso- and macrofauna abundance

In the ROPs with fauna exclusion we found 2101 individuals belonging to the mesoand macrofaunal size class. Springtails (Collembola) were the dominating taxon in the catches on the study site with 1038 individuals. Mites (Acari, 496 individuals), were the second largest group. Further taxa, which have a proved influence on soil structure and particles, were ants (Formicidae, 300 individuals), worms (Oligochaeta, 145 individuals) and beetles (Coleoptera, 49 individuals). Additionally, 73 larvae of unidentified insects were found. No ant mounds could be identified within the ROPs. Anecic earthworms, which are known to build vertical passages, were not found in the pitfall traps and are rare in the given study area (own observation) and under those acidic soil conditions.

3.3. Leaf litter cover and decomposition

The time between measurements was 19 weeks and none of the litter covered plots have laid bare completely within this timespan. Mean litter cover was 91 % (min=80 %, max=100 %) in May, when litter was brought out and 38 % (min=4 %, max=65 %) in September, when coverage was reduced due to litter decomposition. Leaf litter mass was 60 g in every ROP in May and 8.2 g (min=1 g, max=17 g) in September. On average, one tenth of leaf litter mass brought out in timestep 1 was still remaining in timestep 2. Differences in soil surface coverage due to different diversity levels could not be detected ($P > 0.1$).

Nevertheless, different leaf species showed rather different decomposition rates and thus, developments of surface litter cover. Species A (Liquidambar formosana) showed the fastest decomposition and low surface cover (2 % remaining leaf mass (rlm), 10 % surface cover (sc)) and species D (Schima superba) the slowest decomposition and high surface cover (22 % rlm, 56 % sc). Species B (12 % rlm, 34 % sc) and G (11 % rlm, 27 % sc) had comparable values near to the overall mean (12 % rlm, 38 % sc). The four species mixtures showed a mean of 11 % remaining leaf litter mass and 31 % surface cover.

ROPs with fauna (11.2 %) lost 2 % more of their leaf coverage than plots without fauna (12.9 %). A slightly significant effect between fauna treatment and leaf mass loss was found ($P < 0.07$), but there is no clear directional pattern. Depending on the species and mixture, fauna shows very heterogeneous impacts on decomposition in both, positive and negative directions.

4. Discussion

Our results demonstrate that leaf litter cover protects soil from erosion by rainfall and this protection is removed as litter decomposes. However, this protective effect is not influenced by leaf litter species diversity, but by the presence or absence of soil meso- and macrofauna.

Effect of litter cover on initial soil erosion

An important difference was found between leaf-covered and bare plots. On the latter, sediment discharge was up to 1.8 times higher in timestep 1. Furthermore, erosion rates were considerably higher in September with reduced leaf litter coverage than in May. This finding emphasizes the importance of a protecting litter cover in forest ecosystems against soil erosion. A surface litter cover of nearly 100 % decreased soil loss by 82 % compared to bare ground. Benkobi et al. (1993) indicated that a 60 % surface litter cover can reduce soil loss by 62 %. Moreover, erosion rates did not differ significantly between plots with a litter cover of up to 38 % (in September) and bare ground plots. Runoff volume was significantly lower on leaf covered plots than on bare plots in timestep 1. Gerrits et al. (2007) illustrated that forest floor interception e.g. by short vegetation and litter can double the amount of intercepted rainfall in forest ecosystems and therefore, lead to lower surface runoff. Runoff volume has been 18 % higher during wet runs compared to dry runs due to higher initial soil water saturation. Nevertheless, sediment discharge has been 13 % lower during wet runs, which we ascribe to the wash-out of loose sediments during the first run.

Effect of leaf litter diversity on initial soil erosion

Leaf species diversity did not have an impact on initial soil erosion. Even if rising leaf litter diversity seems to lead to a slightly smaller sediment discharge, these effects were not statistically significant. Moreover, no change in the influence of leaf litter diversity could be detected from May (full leaf coverage) to September (reduced leaf coverage). Functional diversity of leaf traits did not influence erosion parameters. However, single leaf litter species differ in their influence on soil erosion as a result of their different sizes, shapes and decomposition rates. This may not be detectable in the functional diversity index, as different leaf traits are merged. The large range of litter cover percentages indicates important differences in the development of soil cover between single leaf species. Nevertheless, a positive effect of more diverse leaf mixtures cannot be confirmed nor is one species driving a diversity effect through the mixtures. The overlap and gap-filling within the leaf mixtures seems not to differ between the diversity levels. Different pos-

itive and negative feedbacks of leaf litter species are levelled within their mixtures and no directional pattern could be detected (c.f. Hättenschwiler et al., 2005). In addition to the latter, different decomposition rates of single leaf species resulted in a more heterogeneous influence on soil erosion in September. Sediment discharge from ROPs with *Liquidambar formosana* (A), *Machilus thunbergii* (B) and *Cyclobalanopsis glauca* (G) - each in monocultures - differed significantly from the mean sediment discharge. We found that species A (66.1 $g\ m^{-2}$) and B (68.0 $g\ m^{-2}$) showed significantly higher erosion rates, while ROPs with species G (7.9 $g\ m^{-2}$) had the lowest sediment discharge in September. Species A showed the fastest decomposition and low surface cover (2 % remaining leaf mass, 10 % surface cover), whereas species B (12 % rlm, 34 % sc) and G (11 % rlm, 27 % sc) had comparable values next to the overall mean. While the effect of species A and G on soil erosion can therefore be explained by altered soil protection caused by different decomposition rates, the effect of species B has to be interpreted by other processes.

Effects of soil fauna on initial erosion

The presence of soil fauna has a significant impulse on sediment discharge. If fauna was present in our plots, erosion rates were higher. Macropore-building soil fauna as well as bigger ground-living animals like mice were not present in the experimental setup. However, the activity of soil-dwelling and surface-active meso- and macrofaunal organisms may lead to the loosening and translocation of soil particles within the first centimetres of the soil surface. While springtails and mites were particularly abundant and might have contributed directly or indirectly to this process (by promoting the decomposition of the soil-protecting litter layer; Hättenschwiler et al., 2005), larger-sized and highly active ants and beetles can be assumed to have contributed significantly to the modification of the soil surface. Many species of these macrofauna groups influence soil processes in terrestrial ecosystems (Lavelle et al., 1997) and can show burrowing behavior when searching for food or when trying to evade short- or long-term unsuitable microclimatic conditions on the soil surface (Swift et al., 1979; Gabet et al., 2003; Dostál et al., 2005). When leaf cover declines by decomposition, soil meso- and macrofauna

attempt to protect themselves against transpirational water loss. This, in turn, can help to explain the fact that the impact of soil fauna slightly lost power in September. At this time, litter cover on the plots was reduced and microclimatic conditions were less optimal than earlier in the season, so the soil faunal activity was on the decline. Plots were not completely bare and thus, still offered resources for decomposers and associated predators. Exclusion of the soil fauna apparently removed significant faunal impacts on soil surface slackening and decomposition processes that favor soil particles to be detached and washed away during rainfall events. Longer-term changes in microclimatic conditions after litter is completely removed might lead to the disappearance of many soil organisms (e.g. Gill, 1969). Therefore, we assume that the erosion-supporting faunal effect disappears when ROPs get completely bare and do not provide habitats for decomposing animals over a longer period.

Our results further show that the soil meso- and macrofauna has an influence on litter decomposition and thus, on the reduction of the protecting litter cover. Several of the more abundant taxa found in our plots, such as Acari, Collembola and Oligochaeta, play an important role in litter fragmentation and decomposition (Swift et al., 1979; Hättenschwiler et al., 2005). Over all ROPs the presence of soil fauna led to a slight increase in mean leaf litter decomposition rate compared to no fauna treatments. Nevertheless, a general pattern did not appear and results are contrasting when single leaf litter mixtures come into account. This effect is based on positive and negative feedbacks of soil fauna on different food availability and habitat conditions (Hättenschwiler et al., 2005). In our experiment positive feedbacks were slightly dominant and, as discussed above, might have strengthened the faunal effects on soil erosion.

Design of experimental erosion research

No significant influence of slope could be found. This may be caused by the small size of the applied ROPs with a short slope line of 0.4 m and a small length-slope factor (c.f. Renard et al., 1987). Rilling processes due to low shear velocities of running water do not occur (c.f. Chaplot and Le Bissonnais, 2000). This result emphasizes the utility of small scale ROPs for experimental erosion measurements where single effects have to

be considered within a complicated system of parameters. Therefore, it is advisable to take out dominant parameters or to level them for every measurement. An example of this approach is the use of a portable rainfall simulator with constant rainfall intensity for every measurement.

5. Conclusions

We studied the influence of leaf litter cover and litter diversity as well as soil meso- and macrofauna on initial soil erosion processes in subtropical forest ecosystems. The general importance of leaf litter cover to protect soil against erosion can be underpinned by this study. Sediment discharge rates on bare ground plots exceeded tremendously the rates on covered plots, regardless of their diversity level. Leaf litter covers of more than about 40 % of the ground surface can prevent soil erosion effectively.

Furthermore, the experimental investigation leads to the following conclusions:

I. This study provides evidence, that neither leaf litter species diversity nor functional diversity influence leaf litter cover, sediment discharge and thus, soil erosion. Hence, better overlap and gap-filling or different decomposition rates in highly diverse litter mixtures seem not to be considerable parameters for soil erosion control, although a non-significant negative trend is visible. Nevertheless, single leaf species show variable influences on sediment discharge if compared among each other. In our experiment, runoff plots with leaf litter from *Machilus thunbergii* showed the highest sediment discharge whereas plots with *Cyclobalanopsis glauca* showed the smallest rates. This can be related to variable leaf habitus, different decomposition rates and food preferences of litter decomposing fauna.

II. Our results show that the presence of soil meso- and macrofauna increases initial soil erosion. We assume that this faunal effect arises from arthropods slackening and processing the soil surface in subtropical forest ecosystems. Furthermore, soil meso- and macro fauna are a prominent factor in litter fragmentation and decomposition and thus, the reduction of protecting litter covers. Effects of this fauna group on sediment discharge have to be considered in soil erosion experiments.

Acknowledgements

Supplement

Table 1: Results of linear mixed effects modelling for sediment discharge with covariables and design effects (*** : $p < 0.001$, ** : $p < 0.01$, * : $p < 0.05$, n.s. : not significant, – : not tested).

	timestep 1 & 2	timestep 1	timestep 2
diversity level	n.s.	n.s.	n.s.
functional diversity	n.s.	n.s.	n.s.
monocultures vs. mixtures	n.s.	n.s.	n.s.
species identity vs. mixtures	n.s.	n.s.	n.s.
fauna treatment	***	*	***
fauna x diversity level	n.s.	n.s.	n.s.
covariables			
bulk density	n.s.	n.s.	*
litter cover	***	**	***
moisture	*	*	*
pH	n.s.	n.s.	n.s.
slope	n.s.	n.s.	n.s.
design effects			
block	***	*	***
run	***	**	***
species pool	***	*	***
timestep	***	–	–

Table 2: Mean sediment discharge and surface runoff volume in total and for timesteps, fauna treatment, rainfall runs and diversity levels.

	sediment discharge (g m⁻²/ 20min)	runoff volume (g m⁻²/ 20min)	by timesteps, first timestep 1, second timestep 2	sediment discharge (g m⁻²/ 20min)	runoff volume (g m⁻²/ 20min)
total	24.6	18.5	fauna tr.	23.3	21.0
timestep 1	18.9	19.7	no-fauna tr.	14.6	18.4
timestep 2	30.3	17.4	diversity 0	78.2	27.0
fauna	30.1	19.6	diversity 1	16.4	19.7
no fauna	19.1	17.4	diversity 2	11.6	18.4
1st run	26.3	17.0	diversity 4	14.1	20.4
2nd run	23.0	20.1	fauna tr.	36.9	18.3
diversity 0	57.0	23.5	no-fauna tr.	23.7	16.5
diversity 1	25.9	18.9	diversity 0	35.9	20.0
diversity 2	19.8	17.4	diversity 1	35.3	18.2
diversity 4	16.2	19.0	diversity 2	28.0	16.4
			diversity 4	18.2	17.6

Table 3: Basic soil parameters, soil texture and soil moisture characteristics.

	mean	minimum	maximum
bulk density ($g\ cm^{-3}$)	1.15	1.07	1.22
pH	3.7	3.6	3.8
soil organic carbon (%)	1.6	1.1	2.0
slope (°)	24	14	38
soil texture (%)			
sand	24	21.4	26.3
silt	50	49.1	50.9
clay	26	23.8	30.9
soil moisture (%)			
in May	45	31	60
in September	26	11	42
before dry run	31	11	49
before wet run	41	22	60

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Scientific publications and conference contributions

Scientific papers (peer-reviewed)

- Goebes, P., Seitz, S., Geißler, C., Lassu, T., Peters, P., Seeger, M., Nadrowski, K., Scholten, T. (2014): Momentum or kinetic energy - How do substrate properties influence the calculation of rainfall erosivity? Journal of Hydrology 517, 310-316. doi: `http://dx.doi.org/10.1016/j.jhydrol.2014.05.031`.

- Seitz, S., Goebes, P., Zumstein, P., Assmann, T., Kühn, P., Niklaus, P.A., Schuldt, A., Scholten, T. (2015): The influence of leaf litter diversity and soil fauna on initial soil erosion in subtropical forests. Earth Surface Processes and Landforms, accepted. doi: `http://dx.doi.org/10.1002/esp.3726`.

- Goebes, P., Seitz, S., Kühn, P., Li, Y., Niklaus, P., von Oheimb, G., Scholten, T. (2015): Kinetic energy of throughfall in subtropical forest ecosystems as a function of tree species richness and spatial variability. Agricultural and Forest Meteorology, under review.

- Goebes, P., Bruelheide, H., Härdtle, W., Kröber, W., Kühn, P., Li, Y., Seitz, S., von Oheimb, G., Scholten, T. (2015): Species-specific effects on throughfall kinetic energy in subtropical forest plantations are related to leaf traits and tree architecture. PLoS ONE, under review.

- Seitz, S., Goebes, P., Bruelheide, H., Kühn, P., Song, Z., Scholten, T. (2015): How do tree species richness and identity affect initial soil erosion processes in early subtropical forest planatations? Soil, submitted.

Conference contributions

- Goebes, P., Seitz, S., Kühn, P., Kröber, W., Bruelheide, H., Li, Y., von Oheimb, G., Scholten, T.(2015): Species-specific effects on throughfall kinetic energy below 12 subtropical tree species are related to leaf traits and tree architecture. European Geosciences Union (EGU) General Assembly 2015, Vienna, Austria. [Poster]

- Goebes, P., Seitz, S., Kühn, P., Scholten, T. (2014): How does litter cover, litter diversity and fauna affect sediment discharge and runoff?. International Union of Soil Sciences (IUSS) 20th World Congress of Soil Science 2014, Jeju, Korea. [Poster]

- Goebes, P., Seitz, S., Kühn, P., Scholten, T. (2014): Kinetic energy and spatial variability of throughfall in forest ecosystems as a function of biodiversity. European Geosciences Union (EGU) General Assembly 2014, Vienna, Austria. [Talk]

- Goebes, P., Seitz, S., Geißler, C., Lassu, T., Peters, P., Seeger, M., Nadrowski, K., Scholten, T. (2014): Kinetic energy or momentum - how do substrate properties influence the calculation of rainfall erosivity? European Geosciences Union (EGU) General Assembly 2014, Vienna, Austria. [Poster]

- Scholten, T., Geißler, C., Goebes, P., Seitz, S. (2013): Verändert die Zugabe von Biokohle die Erodibilität von Böden? Jahrestagung der DBG 2013, Rostock. [Poster]

- Goebes, P., Seitz, S., Kühn, P., Scholten, T. (2013): Wie beeinflussen Streubedeckung, Streudiversität und Fauna den Sedimentabtrag und den Oberflächenabfluss bei Erosionsprozessen. Jahrestagung der DBG 2013, Rostock. [Talk]

- Goebes, P., Seitz, S.,Kühn, P., Scholten, T. (2013): Carbon and nitrogen loss during initial erosion processes under litter cover. European Geosciences Union (EGU) General Assembly 2013, Vienna, Austria. [Talk]

Other publications

- Scholten, T., Seitz, S., Goebes, P., Geißler, C., Schmidt, K., Bruelheide, H., Kühn, P. (2013): Soils and Geomorphology of the Main Experiment - with additional Information on Climate, Topography and Plot Design. Sino-Swiss-German Research Unit BEF China. University of Tübingen, Germany.

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