Answers to the reviewers' comments:

Dear Mr. Fiener,

Thank you and all reviewers for your comments. In our revised version, we included more of the relevant literature, more details on the results and reshaped abstract, introduction, results and discussion. Additionally, we improved the English. We hope that we have been able to respond on all comments to your satisfaction. Please find below our detailed answers (line indication refers to revised manuscript):

Reviewer #1:

Dear reviewer,

Thank you very much for your comments and for highlighting further literature on soil erosion and ROP measurements. This is a great help to improve our manuscript.

Detailed comments:

1.) I found the paper of interest although some researchers will see this paper with a methodological problem due to the small plots. This is however NOT a problem as the number of measurements is large and contribute to understand the soil erosion processes and the impact of the plant canopy.

We fully agree that measurements with micro-scale ROPs raise certain constraints. Thus, we tried to point this out in chapter 4, where we discuss about advantages and disadvantages. Nevertheless, we also believe that micro-scale ROPs are appropriate to determine e.g. vegetational influences by interplot comparison. Furthermore, we think that the high number of measurements is a benefit to our statistical approach with lme models, as you already mentioned.

2.) See my minor comments to help the author attached. (Further literature)

Thank you for your suggestions of further literature on soil erosion and its mechanisms, such as vegetation cover and biota, which we added to the introduction. Moreover, we agree that policies applied in China led to remarkable changes concerning soil erosion. Nevertheless, the range of occurring soil erosion rates is still high in southern China as it has recently been shown by Guo et al. (2015).

3.) See my minor comments to help the author attached. (Change t to Mg / Figure 4)

We changed the units from *t* to *Mg* in the manuscript and figure 4 has been improved and font sizes changed.

Reviewer #2:

Dear reviewer,

Thank you very much for your comments and the positive valuation of our work. We tried to reorganize and reshape the introduction, the results and discussion part and our interpretation.

Detailed comments:

1. *Introduction: The introduction of the article introduces quite well into the problem and gives an overview on both, soil erosion processes and the problem of tree biodiversity or the functional traits. Nevertheless, the introduction seems for me a little bit too long and I would suggest to shorten it, especially at the very beginning. This would help to highlight the scientific problem described.*

Thank you very much for this comment. We shortened the introduction, especially the general overview on soil erosion at the beginning, to focus more on the scientific question (l. 35-40).

2. *P 706, lines 25ff is IMHO redundant to the very well and clear formulated hypotheses.*

This paragraph should briefly summarize the underlying mechanisms of our hypotheses. We agree that this is redundant and it has been taken out to further shorten the introduction.

3. *Methodology: The chapter of methodology includes a good description of the study site and the experimental design.*

Thank you very much for this assessment.

4. *P 708, l 10: please explain (or rephrase) the apparent contradiction between random selection of the plot placement and its installation on selected, representative places.*

Thank you for this indication. For the whole setup of the BEF China experiment, randomization played a major role. Not only the runoff plots but also the 25 m x 25 m study plots have been placed randomly in the study area during the installation of the experiment. Nevertheless, as the project comprises 13 subprojects with a large number of different experiments, the selection of Very Important study Plots (VIPs) and representative areas within them was necessary for practical reasons. Those selected representative places still comprise an area of more than 200 m^2 each. We rephrased this part in the manuscript to give a better explanation of the latter aspects (l. 144-147).

5. *The description of the statistical analysis lacks in my opinion of a table with a list and brief description of the parameters.*

The descriptive characteristics of the parameters (means, sd, ...) are presented in Table 5 and a brief description of all parameters and the corresponding measurement methods are given in the chapters 2.2 to 2.4, which have been slightly adapted.

To further address the reviewers recommendation, we added a short description of all parameters to the caption of Table 5 and presented the statistical outcomes of the mixed models (i.e. importance of the fixed effects analysed) in Table 2, which has now been moved from the appendix to chapter 3.

6. *P 708, l 20: do not understand the meaning of "nested in plot" here.*

This term was introduced due to our hierarchical design. As we have repeated measurements on one plot (5 ROP measurements and measurements during different rainfall events), we needed to account for this to avoid pseudoreplication considering the degrees of freedom in our hypotheses tests. That is why we introduced ROP nested in plot and rainfall event nested in plot as random factors in our model.

7. *Results: The results section is in general to short, and should be re-organised. Especially a first chapter describing the plots data should be placed at the beginning (emphasizing on common and differentiating data). This chapter should be followed by the description of the interrill erosion data and only afterwards the effects.*

Thank you for this indication. We agree that presenting the interrill erosion data first and adding further information on plot data is reasonable and thus the result section has been changed accordingly. We tried to answer our hypotheses "in line" (Chapter 3.1 and 4.1 are answering on hypothesis 1, 3.2 and 4.2 on hypothesis 2, etc.) and focusing on tree species effects. Thus, we believe that when regarding our hypotheses and the limitations of micro-scale ROP measurements, we should not spotlight the sediment discharge itself and we should not overemphasize the comparison to studies which are not focusing on the same vegetation impacts.

8. *Results: Also the tables included here in the appendix are in my opinion crucial for understanding the processes measured and should be included in the chapter.*

Tables A2 and A3 have been transferred from appendix to chapter 3.

9. *Discussion: The authors show here, as within the introduction, a good knowledge of the recent research. But the chapter should be reorganised similar to the results chapter.*

Thank you for this appraisal. Restructuring the discussion chapters has been done accordingly the "results" section.

10. *In addition, here the authors do not explain clearly the different effects they observed, especially concerning the different functional traits of the tree*

species. Some more information and discussion about the effects of the trees traits would make it also possible to expand the results to other regions, where the other species are present. This point of a missing in discussion in depth is especially evident when discussion the interrill erosion, as the authors mainly discuss the accuracy of their methodology.

We added further details and literature on the effects of crown cover, LAI and tree height (l. 327ff.). Furthermore, the discussion on the methodological accuracy has been shortened (l. 244f.).

As we mentioned in the conclusions a larger number of functional traits would be desirable and should be included in further studies. A comparison with other regions certainly is of great interest, but has not been in focus of this study. Moreover, further research on the effect of different tree functional traits on sediment discharge to compare with is scarce. We believe that this study should at first point on the effects of tree species richness and functional traits in our research area and the discussion of the interrill erosion rates themselves should not take a larger place than the discussion of tree effects.

11. *Conclusions: The conclusions can be shortened as they contain not only the overall results, but also some redundant information of the discussion.*

We agree on your comment and we have shortened the conclusions.

Marked up manuscript version:

Tree species identity and functional traits but not species richness affect interrill erosion processes in young subtropical forests

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Abstract

Soil erosion is seriously threatening ecosystem functioning in many parts of the world. In this context, it is assumed that tree species richness and functional diversity of tree communities

can play a critical role in improving ecosystem services such as erosion control. An experiment with 170 micro-scale runoff plots was conducted to investigate the influence of tree species richness and identity as well as tree functional traits on interrill erosion in a young forest ecosystem. An interrill erosion rate of 47.5 ~~t~~ Mg ha^{-1} a^{-1} was calculated. This study provided evidence that different tree species affect interrill erosion differently, ~~but higher~~while tree species richness did not ~~mitigate soil losses~~affect interrill erosion in young forest stands. Thus, different tree morphologies have to be considered, when assessing soil erosion under forest. High crown cover and leaf area index reduced ~~soil losses~~interrill erosion in the initial forest ecosystem~~s~~, whereas rising tree height increased ~~them~~it. Even if a leaf litter cover was not present, remaining soil surface cover by stones and biological soil crusts was the most important driver for soil erosion control. Furthermore, soil organic matter had a decreasing influence on interrill erosion. Long-term monitoring of soil erosion under closing tree canopies is necessary and a wide range of functional tree traits should be ~~taken into consideration~~considered in future research.

1 Introduction

Soil erosion is ~~seriously threatening natural and agricultural ecosystems in many parts of the world. Therefore, it is~~ considered as one of the most severe environmental challenges globally (Morgan, 2005). ~~Pimentel and Kounang (1998) stated that about 75 billion tons of soil are eroded at global scale every year and soil is lost 13 to 40 times faster than it can regenerate. Soil erosion~~It is also a serious challenge in the PR China, especially in the southern tropical and subtropical zone. Although important improvements in erosion control have been achieved in this area in the last decades (Zhao et al., 2013), ~~Within this region, the annual soil loss rate ranges between~~, the annual soil loss rates range between 0.28 ~~t~~Mg ha^{-1} and 113 Mg~~t~~ ha^{-1}, ~~depending on the annual precipitation, the landscape and the land use~~ (Guo et al., 2015).

~~Besides negative on-site effects like declining soil fertility, off-site effects triggered by the transport of sediment and included nutrients as well as pollutants cause high mitigation efforts and costs (Pimentel et al., 1995; Richter, 1998) and affect nutrient cycling and ecosystem functioning (Baumann et al., 2009; Zhao et al., 2009).~~ Thereby, soil erosion is negatively affecting e.g. soil fertility or nutrient cycling (Pimentel et al., 1995; Richter, 1998).

Moreover, soil erosion can negatively influence biodiversity (Pimentel and Kounang, 1998), but it is assumed that this relationship also acts vice versa (Körner and Spehn, 2002; Geißler et al., 2012b; Brevik et al., 2015). It has been shown that a change in biodiversity can have remarkable effects on ecosystem functions and stability (e.g. Hooper et al., 2005; Scherer-Lorenzen, 2005). In many cases, increasing biodiversity enhanced ecosystem productivity and stability (Loreau, 2001; Jacob et al., 2010). In particular, tree species richness as well as functional diversity of tree communities can play a critical role in improving ecosystem services such as water filtration~~,~~ or climate regulation ~~or erosion control~~ (Quijas et al., 2012; Chisholm et al., 2013; Scherer-Lorenzen, 2014). As forests are generally considered beneficial for erosion control, afforestation is a common measure of soil protection (Romero-Diaz et al., 2010; Jiao et al., 2012). This also applies to the south-eastern part of China, which is known as a hotspot of biodiversity and woody plants (Barthlott et al., 2005; Bruelheide et al., 2011). Guo et al. (2015) showed that forests in this area experienced the lowest soil loss rates of all land use types in China. Considering that studies on soil erosion under forest have mostly focused on deforestation (Blanco-Canqui and Lal, 2008) and counteracting measures like afforestation generally result in monoculture stands (Puettmann et al., 2009), it appears that the role of tree species richness for soil erosion has been largely disregarded. ~~Although positive effects of mixed-species tree stands like increasing productivity or reduced pest risks were demonstrated (e.g. Vilà et al., 2007; Bauhus and Schmerbeck, 2010), the effects on~~

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~~erosion control are still unclear.~~ Zhou et al. (2002) and Tsujimura et al. (2006) demonstrated that tree monocultures have only limited mitigation potential for soil losses, but further research is scarce. Nevertheless, there is growing evidence that higher species richness can reduce soil erosion (Körner and Spehn, 2002). Bautista et al. (2007) pointed out that an increase in functional diversity within a perennial vegetation cover decreased soil losses in a semiarid Mediterranean landscape. Pohl et al. (2009) showed that an increase in the diversity of root types led to higher soil stability on an alpine grassy hillslope and most recently Berendse et al. (2015) found that a loss of grass species diversity reduced erosion resistance on a dike slope.

Conceivable mechanisms underlying positive species richness effects on soil erosion are that vegetation covers with a high number of species include a high number of plant functional groups which complement one another. Thus, they are more effective in controlling erosion processes than vegetative covers with few species (Pohl et al., 2012). For example, a high tree species richness may result in an increased stratification of canopy layers (Lang et al., 2010). As a consequence, crown overlap, biomass density and total canopy cover often are higher in mixtures than in monocultures (Lang et al., 2012). In addition, a highly diverse structure within the leaf litter layer on the forest floor seems to improve its protecting effect (Martin et al., 2010). Recently, Seitz et al. (2015) pointed out that sediment discharge depends on the species identities in the leaf litter cover, whereas there was no effect of leaf species richness or functional diversity on soil erosion. Further research on the influence of tree species richness on erosion control seems to be necessary, but the complex system of interacting functional groups within the vegetation cover is also of great interest.

Vegetation covers are generally considered a key factor for the occurrence and dimension of soil erosion (Thornes, 1990; Hupp et al., 1995; Morgan, 2005). A leaf litter layer on the forest floor, for example, protects the soil from direct raindrop impact and modifies the water flow and storage capacities on the soil surface (Kim et al., 2014). Moreover, forests can provide a multi-storey canopy layer which largely influences rain throughfall patterns and leads to the capture of raindrops as well as the storage of water within the tree crown (Puigdefábregas, 2005). Nevertheless, large drops can be formed at leaf apexes of tall trees (Geißler et al., 2012a) and thus may increase the kinetic energy of throughfall in older forest stands up to a factor of 2.6 compared to open fields (Nanko et al., 2008; Nanko et al., 2015). This leads to considerable soil loss if the forest floor is unprotected, which may be the case if protecting layers diminish e.g. under shady conditions (Onda et al., 2010) or fast decomposition (Razafindrabe et al., 2010). Whereas the effects of soil surface covers on soil erosion is well studied (Thornes, 1990; Blanco-Canqui and Lal, 2008), much less is known about the influence of species-specific functional traits of the tree layer such as crown or stem characteristics (Lavorel and Garnier, 2002; Guerrero-Campo et al., 2008). Moreover, most research on the latter aspects was performed in old-grown forests (e.g. Zhou et al., 2002; Nanko et al., 2008; Geißler et al., 2012a), whereas forests in an early-successional stage are rarely mentioned. In those young forests, tree heights are lower than in later stages, but structural and spatial complexity is high and species-specific growth rates differ considerably (Swanson et al., 2011). It is assumed that these species-specific differences in structure and growth will influence soil erosion rates.

This research focused on the influence of tree species richness, tree species identity and species-specific functional traits on interrill erosion in young forests, when a leaf litter cover is not present. Testing for those effects on soil erosion requires a common garden situation, in which confounding factors such as different tree ages and sizes, inclination or soil conditions are closely controlled. These requirements were met in the forest biodiversity-ecosystem functioning experiment in subtropical China (BEF-China; cf. Bruelheide et al., 2014). Within this experiment, ~~a high number of~~170 micro-scale runoff plots ~~was~~ were established in a randomly dispersed and replicated design. Thereby, the following hypotheses were postulated:

1. Increasing tree species richness decreases ~~soil~~ interrill erosion rates.
2. Tree species differ in their impact on ~~soil~~ interrill erosion rates.
3. The effects of different tree species on ~~soil~~ interrill erosion rates can be explained by species-specific functional traits.

~~First, it is hypothesized that higher tree species richness leads to lower soil erosion rates. This is due to higher stratified and overlapping tree canopies, even when a leaf litter cover is not present. Second, it is presumed that soil erosion rates change in relation to different tree species due to species-specific functional traits. Third, it is hypothesized that tree height and canopy characteristics are good predictors for soil erosion rates.~~

2 Methodology

2.1 Study site and experimental design

The study was conducted in Xingangshan, Jiangxi Province, PR China (29°06.450′ N and 117°55.450′ E) at the experimental sites A and B of the BEF China project (Bruelheide et al., 2014). Together, both sites comprise an area of about 50 ha in a mountainous landscape with an elevation range from 100 m to 265 m a.s.l.. Slopes range from 15 ° to 41 °. The bedrock of the experimental site consists of non-calcareous slates with varying sand and silt contents and is intermittent by siliceous-rich joints. Prevailing soil types are Cambisols with Anthrosols in downslope positions and Gleysols in valleys (cf. IUSS, 2006) covering saprolites. Soil bulk density is low (0.98 g cm^{-3}) and soil reaction acidic (mean pH in KCl 3.68). Soil texture ranges from silt loam to silty clay loam. The climate in Xingangshan is humid and subtropical and ranked as Cwa after the Köppen-Geiger classification. It is characterized by an annual average temperature of 17.4 °C and a mean annual rainfall of 1635 mm (Goebes et al., 2015b).

The experimental area has been used as a commercial forest plantation (*Cunninghamia lancelota* and *Pinus massoniana*) until 2007. It was clear-cut and replanted in 2009-2010 following an experimental plot-based design with different extinction scenarios (Bruelheide et al., 2014). The experimental site represented an early successional stage with tree ages from four to five years at the time of measurements. In total, 566 experimental plots were established using a pool of 40 native tree species, as well as bare ground and free succession plots. Trees were planted randomly in seven species richness levels (div0, 1, 2, 4, 8, 16, 24) with a planting distance of 1.29 m, following a broken stick design (Bruelheide et al., 2014). This study focused on the Very Intensively studied Plots (VIPs) of which 34 were used in this study. The monocultures with tree heights lower than 1 m or crown covers less than 10 % were excluded from the analysis. The selected set comprised a bare ground feature (4 × div0) and four levels of tree species richness (20 × div1, 4 × div8, 4 × div16 and 2 × div24) with a total of 22 tree species, two of which only appeared in mixtures (Appendix Table A1).

2.2 Erosion measurements

To determine initial sediment discharge and surface runoff, micro-scale runoff plots (ROP, 0.4 m × 0.4 m) were used (cf. Seitz et al., 2015; without fauna treatment). Each ROP was connected to a 20 L reservoir and a rainfall gauge was placed next to it (Fig. 1). All 34 VIPs were equipped with five ROPs each, resulting in a total number of 170 ROPs. Within each VIP, ~~the ROPs were placed randomly in selected areas~~areas of 220 m^2 were sectioned for ROP measurements to avoid interferences with other BEF China experiments.~~,~~ ~~which~~ Those selected areas were representative for the range of surface properties in the ~~study area~~plot and~~.~~ the ROPs were placed randomly therein. All leaf litter was removed from the ROPs prior to measurements. The ROPs were operated in May and June 2013 during the rainy season.

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Runoff volume and rainfall amount were determined in situ and sediment was assessed after sampling by drying at 40 °C and weighing. The capacity of the reservoirs was not exceeded in any rainfall event.

[Figure 1]

At each ROP (n=170), tree crown cover and leaf area index (LAI) were measured using a fish-eye camera system (Nikon D100 with Nikon AF G DX 180°) and the HemiView V.8 software (Delta-T devices, Cambridge, UK). Total tree height, stem diameter at 5 cm above ground (hereafter, stem diameter) and crown width for each tree individual were measured to represent the tree characteristics (Li et al., 2014). Soil surface cover was measured photogrammetrically (grid quadrat method with GIMP 2.8) and slope with an inclinometer at each ROP (n=170), respectively. Soil texture and soil organic matter (SOM) were identified for each VIP (5 cm depth, 9 replicates, n=34) using a SediGraph III 5120 (Micromeritics, Aachen, Germany) and a Vario EL III elemental analyser (Elementar, Hanau, Germany). ~~Furthermore, pH was measured in 1 M KCl using Sentix 81 electrodes.~~

2.3 Rainfall patterns

Weather conditions were recorded by an on-site climate station (ecoTech datalogger with Vaisala weather transmitter and ecoTech tipping bucket balance) in 5-min intervals. The total precipitation in the study area in 2013 was 1205 mm and lower than the mean of the preceding three years (1635 mm). Of this amount, a fraction of 957 mm (33 events) were strong enough to trigger soil erosion following Wischmeier and Smith (1978) who used an event threshold of 12.7 mm. This threshold was confirmed by Yin et al. (2007) to be valid for southeast China. In total, 10 rainfall events were captured at the study area in May and June. Four of those events (E1 - E4) can be considered erosive. The total rainfall amount from May to June was 185 mm, of which 135 mm fell during erosive rainfall events. The mean and peak

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intensities as well as the total rainfall amount (except for E4) increased from May to June (Table 1), reflecting a growing monsoon influence from beginning to mid-summer.

[Table 1]

2.4 Statistical analysis

Linear mixed effects models with restricted maximum likelihood were performed with R 3.0.2 (R Core Team, 2013) and “lmerTest” (Kuznetsova et al., 2014) to investigate the influences on sediment discharge. Models were fitted with crown cover, leaf area index, tree height, stem diameter, crown width, slope, surface cover, SOM, amount of precipitation and tree species richness as fixed effects. As random effects, precipitation event nested in plot, tree composition, site and ROP nested in plot were used. Tree and crown characteristics were fitted one after the other, because they were highly correlated. Contrasts of diversity levels (div0 to div1-24, div1 to div8-24) were introduced to quantify the effects of bare plots vs. tree ~~plantations~~ plots and tree monocultures vs. mixtures, respectively. The effect of individual tree species (div1) was tested separately against the mean sediment discharge using crown cover, slope, surface cover, SOM and amount of precipitation as fixed factors and site and ROP nested in plot as random factor (n=200). The maximum likelihood approach was used to obtain model simplification by step-wise backward selection, eliminating the least significant variable except for tree species richness. If multicolinearity was detected (spearman $\rho>0.7$), co-variables were omitted. All variables were continuous and scaled, so model estimates could be compared. The data was log-transformed and the residuals did not show any deviation from normality. Hypotheses were tested with an ANOVA type 3 with Satterthwaite approximation for degrees of freedom and p-values were obtained by likelihood ratio tests.

3 Results

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The results were based on 334 valid ROP measurements out of a total of 378 measurements. Sediment discharge over all VIPs and rainfall events ranged from 14 g m-2 to 920 g m-2 per ROP. Event-based mean sediment discharge increased with peak intensity from precipitation event 1 to event 4 with 42 g m^{-2} (E1), 85 g m^{-2} (E2), 120 g m^{-2} (E3) and 283 g m^{-2} (E4). The interrill soil erosion rate determined by micro-scale ROPs and extrapolated for all erosive precipitation events (>12.7 mm rainfall amount) in 2013 was estimated to be 47.5 Mg ha^{-1}.

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3.1 Species richness effects on interrill erosion processes

Tree species richness did not affect sediment discharge or runoff (Table 2 and Fig. 2~~ and Appendix Table A2~~). Sediment discharge tended to decrease from diversity level 0 to 8 and to increase to diversity level 24, while runoff volume tended to decrease from diversity level 0 to 16 and to increase to diversity level 24, but shifts were non-significant. Sediment discharge and runoff volume did not differ between bare plots (div0) and plots with trees (div1-div24), just as between monocultures (div1) and species mixtures (div8, div16, div24). The standard deviations of sediment discharge (g m^{-2}) and runoff volume (l m^{-2}) in relation to diversity levels were high (Fig. 2 and ~~Appendix ~~Table ~~A3~~3). Mean crown cover in mixed stands was 44 % and mean tree height was 2.30 m compared to monocultures with 22 % and 1.63 m. In this experiment tree height in mixed stands was not lower than 1.07 m and crown cover achieved at least 29 %.

[Table 2]

[Figure 2]

[Table 3]

3.2 Species identity effects on interrill erosion processes

Individual tree species in monocultures affected sediment discharge differently (Fig. 3) and sediment discharge rates ranged from 90 g m^{-2} (*L. formosana*) to 560 g m^{-2} (*Ch. axillaris*) per rainfall event.

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[Figure 3]

The mean sediment discharge is 199 g m^{-2} across all tree monocultures, among which *Ch. axillaris*, *C. glauca*, *R. chinensis* and *K. bipinnata* showed above average and *M. yuyuanensis*, *L. glaber*, *E. chinensis* and *L. formosana* below average sediment discharge. The growth characteristics of these tree species differed considerably between the species (Table ~~2~~4).

[Table ~~2~~4]

3.3 Effects of tree functional traits and site characteristics

Crown cover was highly correlated with LAI, tree height, stem diameter and crown width (r=0.82, 0.80, 0.75, 0.77, respectively). Crown cover ($p<0.01$) and LAI ($p<0.05$) negatively affected sediment discharge. Tree height marginally positively affected sediment discharge ($p<0.1$), whereas stem diameter and crown width had no influence (Fig. 4, ~~Appendix~~ Table ~~A2~~2). The soil surface cover consisted of stones and biological soil crusts and ~~canopied~~ covered on average one fifth of the ROP surfaces in May and June 2013. It affected sediment discharge negatively ($p<0.001$). Mean soil organic matter content in the top layer was high and reduced sediment discharge ($p<0.05$). An indication of hydrophobic surface coatings and a significant role of water repellency could not be found. The mean slope angle did not affect sediment discharge (Fig. 4, ~~Appendix~~ Table ~~A2~~2).

[Figure 4]

Growth characteristics were highly variable between tree species, which was reflected by high standard deviations of the respective variables. In contrast, site characteristics of these plots showed a low variability (Table ~~3~~5).

[Table ~~3~~5]

~~3.4 Interrill erosion in young Chinese subtropical forests~~

~~Event-based mean sediment discharge increased with peak intensity from precipitation event 1 to event 4 with 42 g m^{-2} (E1), 85 g m^{-2} (E2), 120 g m^{-2} (E3) and 283 g m^{-2} (E4). The interrill soil erosion rate determined by micro-scale ROPs and extrapolated for erosive precipitation events (>12.7 mm rainfall amount) was estimated to be 47.5 t ha^{-1} in 2013.~~

4 Discussion

The soil loss rate determined by micro-scale ROPs (47.5 Mg ha^{-1} a^{-1}) for 2013 was considerably higher than the average rate Guo et al. (2015) recently calculated for South China (approx. 20 Mg ha^{-1} a^{-1}) in a study based on small-scale and field ROPs. Pimentel (1993) reported an average rate of 36 Mg ha^{-1} a^{-1} for the same area. Zheng et al. (2007) stated an average soil loss rate of 31 Mg ha^{-1} a^{-1} determined with ^{137}Cs/^{210}Pb tracing techniques in Sichuan Province, PR China. These different rates are due to different land use types and measurement techniques, but also due to the scale-dependent nature of soil erosion and runoff generation (cf. Boix-Fayos et al., 2006; Cantón et al., 2011). The micro-scale ROPs used in this study quantified interrill wash and sediment detachment by raindrop impact (cf. Agassi and Bradford, 1999). However, an important part of erosion appears in the rilling system and the influence of interrill processes on soil erosion varies greatly (Govers and Poesen, 1988). Sediment discharge and runoff change with ROP length (cf. Abrahams et al., 1995) and

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boundary effects increasingly influence the results with decreasing plot sizes (Mutchler et al., 1994). Nevertheless, Mutchler et al. (1994) stated that micro-scale ROPs are suitable to study basic aspects of soil erosion and furthermore, those measurements are particularly appropriate to define impacts of vegetation by interplot comparison (Wainwright et al., 2000).

4.1 Species richness effects on interrill erosion processes

Tree species richness did not affect sediment discharge or runoff volume and thus the first hypothesis has to be rejected. Nevertheless, a trend of decreasing sediment discharge and runoff from diversity level 0 to 8 was visible~~ from diversity level 0 to 8, where sediment discharge and runoff were decreasing~~. However, both parameters were nearly the same at diversity level 1 and 24 and standard deviations were high. Whereas tree growth patterns in monocultures were highly variable, mixed stands indicated a more balanced development (Kelty, 2006). All species mixtures in this experiment assured a higher level of tree height and ground coverage after four to five years of tree growth, whereas in monocultures the canopy cover was lower and highly tree species specific. Thus, several monoculture plots were excluded before measurements, because some species could not provide any considerable ground coverage. At the same time, sediment discharge in mixture stands was lower than in monocultures. Nevertheless, contrasts in the model could not show any statistical difference between monocultures and mixtures or bare and covered plots.

The absence of a species richness effect on soil erosion is likely attributable to the early successional stage of the forest experiment with low tree ages. Full canopy covers with high stratification and overlap have not yet been developed at the study site and the trees did by far not reach terminal height (Goebes et al., 2015b; Li et al., 2014). It is assumed that these vegetation characteristics will change with increasing tree age and tree species richness may become evident in adult stands. Young trees are functionally more equivalent than older trees (Barnes and Spurr, 1998) and specific crown traits may emerge more distinctly in later successional stages. Geißler et al. (2013) found that the erosion potential was higher in medium and old grown forests than in young forests. This effect is caused by raindrop transformation processes during the canopy passage, resulting in higher throughfall kinetic energy under forest than on fallow land (Geißler et al., 2010) and has only been proved for advanced successional forest stages (Nanko et al., 2008; Geißler et al., 2013). With ongoing time of the experiment and increasing tree height increasing throughfall kinetic energy is expected, which in turn increases the general soil erosion potential.

4.2 Species identity effects on interrill erosion processes

Trees in monocultures differed in their impact on soil erosion and thus hypothesis 2 can be confirmed. In a study on common European tree species, Augusto et al. (2002) showed that the tree species composition of forests has an impact on chemical, physical and biological soil properties. Several studies revealed that individual plants are important for erosion control in arid and semi-arid Mediterranean landscapes (e.g. Bochet et al., 2006; cf. Durán Zuazo and Rodríguez Pleguezuelo, 2008) and Xu et al. (2008) showed that different plant morphologies may control soil loss and improved soil properties in a dry river valley in China.

In this study, four tree species (*Ch. axillaris, C. glauca, R. chinensis, K. bipinnata*) seemed to foster soil erosion rates, whereas another four species (*M. yuyuanensis, L. glaber, E. chinensis, L. formosana*) showed a mitigating effect on soil erosion at this initial stage of the forest ecosystem. Thus, a species-specific effect on sediment discharge for this subtropical experimental area can be confirmed. Species-specific effects can result from different throughfall kinetic energy, which was recently shown by Goebes et al. (2015a) at the same study site in China. The effect of throughfall kinetic energy was ascribed to different tree architectural characteristics and leaf traits. The authors found three out of 11 tree species to have distinct differences in mean throughfall kinetic energy. *Ch. axillaris* and *S. saponaria* showed higher values, whereas *S. superba* was characterized by lower values of throughfall kinetic energy. At the experimental site, varying tree species revealed heterogeneous growth patterns, which were caused by species-specific growth variation and abiotic site conditions (Li et al., 2014). *Ch. axillaris* was the tallest tree species with a nearly closed canopy and caused the highest amount of sediment discharge in this study. Raindrops falling from leaves of this species nearly reached terminal velocity and hence throughfall kinetic energy was high (Morgan, 2005; Goebes et al., 2015a). This finding explained the high erosion rates below this fast-growing species. Further stands with significantly higher erosion rates and the four tree species with a mitigating effect on soil erosion showed lower tree heights and thus lower throughfall kinetic energy. Their effect on sediment discharge has to be explained by further functional traits.

4.3 Effects of tree functional traits and site characteristics

Tree species differed widely in canopy characteristics and sediment discharge was significantly related to crown cover~~ and~~, LAI and tree height. Therefore, the species-specific effects of soil erosion can be partially contributed to species-specific functional traits, which confirms hypothesis 3. The falling velocities of throughfall drops are highly variable under different tree species due to the species-specific growth pattern and crown characteristics (Goebes et al., 2015a). Frasson and Krajewski (2011) showed that the mechanisms of interception are manifold even within a single canopy and varying canopy levels create different drop size distributions.

Increasing crown cover and LAI were mitigating ~~soil~~ interrill erosion in this early ecosystem stage. ~~The magnitude of canopy cover determines the proportion of raindrops intercepted (Blanco-Canqui and Lal, 2008).~~ The magnitude of canopy cover determines the proportion of raindrops intercepted (Blanco-Canqui and Lal, 2008) and it has been shown that drop size distributions differ between different canopy species (Nanko et al., 2006). High crown cover and leaf area increase the interception of rain drops and the storage capacity of water in the canopy (Aston, 1979; Geißler et al., 2012a), which can lead to higher stemflow and thus decreasing throughfall (Herwitz, 1987). Nevertheless, Herwitz (1987) equally showed that canopy drainage can lead to larger throughfall drops and thus to increasing throughfall kinetic energy depending on the leaf species (Hall and Calder, 1993; Geißler et al., 2012a; Goebes et al., 2015). Anyhow, LAI showed a weaker significance than crown cover, probably because many trees had not yet developed a multi-layered canopy structure.

It has been shown that tree height is an import factor for sediment detachment under forest (Geißler et al., 2013), mostly due to increasing drop falling heights (Gunn and Kinzer, 1949). As trees did not yet reach adult height (mean height <2 m) in this study, the kinetic energy of raindrops formed at leaf tips was lower than in grown up tree stands and drops did not reach terminal velocities (Morgan, 2005; Geißler et al., 2013; Goebes et al., 2015a). Therefore, tree height had a weak effect on sediment discharge ($p<0.1$) in this study and sediment discharge rates under trees were not exceeding those on bare ground. Nevertheless, high sediment discharge under *Ch. axillaris*, by far the fastest growing tree in this experiment, showed the potential of high trees to increase soil erosion on uncovered forest floors.

Stem diameter and crown width did not seem to influence erosion processes in early stage forest ecosystems. Several other tree-related functional traits (Pérez-Harguindeguy et al., 2013) could be used to explain sediment discharge such as branching architecture, specific leaf area and root system morphology. Especially studies on leaf traits (Nanko et al., 2013) as well as belowground stratification (Gyssels et al., 2005; Stokes et al., 2009) showed the potential to influence soil loss and pointed out the complexity of factors mitigating soil erosion in forest ecosystems.

Results showed that soil surface cover and soil organic matter ~~also~~ affect interrill erosion. Even though a leaf litter cover was not present in this experiment, the remaining soil surface cover by stones and biological soil crusts was the most important driver to reduce sediment discharge. This finding underlines the general importance of covered soil surfaces for erosion control (cf. Thornes, 1990; Morgan, 2005) and shows that the protecting effect of leaf litter could not only be replaced by soil skeleton but also by topsoil microbial communities in young forest stands. The mitigating effect of leaf litter on soil losses has not been in the focus of this experimental approach, but it is presumed that the fall of leaves even in young aged forests reduces soil erosion considerably compared to bare land (Blanco-Canqui and Lal, 2008; Seitz et al., 2015). Furthermore, soil organic matter effectively prevented soil erosion by binding primary particles into aggregates (Blanco-Canqui and Lal, 2008). If soil organic matter increases with increasing species richness, as it was recently demonstrated in a grassland study by Cong et al. (2014), an indirect effect of biodiversity on soil erosion can be presumed. At last, slope angle was not affecting soil erosion due to the short plot length that limits runoff velocities (cf. Seitz et al., 2015).

~~4.4 Interrill erosion in young Chinese subtropical forests~~

~~The soil loss rate determined by micro-scale ROPs (47.5 t ha^{-1} a^{-1}) for 2013 was considerably higher than the average rate Guo et al. (2015) recently calculated for South China (approx. 20 t ha^{-1} a^{-1}) in a study based on small-scale and field ROPs. Pimentel (1993) reported an average rate of 36 t ha^{-1} a^{-1} for the same area. Zheng et al. (2007) stated an average soil loss rate of 31 t ha^{-1} a^{-1} determined with ^{137}Cs/^{210}Pb tracing techniques in Sichuan Province, PR China. These different rates are due to different land use types and measurement techniques, but also to the scale-dependent nature of soil erosion and runoff generation (cf. Boix-Fayos et al., 2006; Cantón et al., 2011). In an event-based approach, Zhu and Zhu (2014) pointed out that ROPs with short slope length yield higher sediment discharge than those with longer slope length and Bagarello and Ferro (2004) showed that increasing the size of ROPs from 0.04 m^2 to 0.16 m^2 decreased runoff and sediment discharge by a factor of 2.6. The micro-scale ROPs used in this study (0.16 m^2) quantified interrill wash and sediment detachment by raindrop impact (cf.~~

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~~Agassi and Bradford, 1999). However, an important part of erosion appears in the rilling system and the influence of interrill processes on soil erosion varies greatly (Govers and Poesen, 1988). Sediment discharge and runoff change with ROP length (cf. Abrahams et al., 1995) and boundary effects increasingly influence the results with decreasing plot sizes (Mutchler et al., 1994). Nevertheless, Mutchler et al. (1994) stated that micro-scale ROPs are suitable to study basic aspects of soil erosion and further, those measurements are particularly appropriate to define impacts of vegetation by interplot comparison (Wainwright et al., 2000). A major advantage of micro-scale ROPs is the possibility to implement a high number of replications to tackle measurement variability (Wendt et al., 1986). A high number of ROPs in turn requires great efforts in maintenance and control, which are easier to ensure with plots of small scale and small-sized reservoirs (Boix-Fayos et al., 2006).~~

5 Synthesis and conclusions

An experiment with 170 micro-scale runoff plots was conducted to investigate the influence of tree species richness and identity as well as tree functional traits on soil erosion processes in a young forest ecosystem. The results led to the following conclusions:

1. Tree species richness did not affect sediment discharge and runoff~~.~~, ~~A~~although a negative trend was visible from level 1 to 8 and mixed stands showed a more balanced and homogenous vegetation development than monocultures~~, higher tree species richness was not mitigating soil erosion~~. This effect was ascribed to the young successional stage of the forest experiment. Future research should concentrate on how erosion rates change with increasing stand age. Therefore, long-term monitoring of soil erosion under closing tree canopies is necessary.

2. This study provided evidence that different tree species affect interrill erosion processes. Different tree morphologies have to be considered, when regarding erosion in young forest ecosystems. The appropriate choice of tree species for afforestation against soil erosion becomes already important in an early successional stage. ~~*Chorespondeas axillaris*, *Cyclobalanopsis glauca*, *Rhus chinensis* and *Koelreuteria bipinnata* were related to increasing soil erosion rates, whereas *Magnolia yuyuanensis*, *Lithocarpus glaber*, *Elaeocarpus chinensis* and *Liquidambar formosana* mitigated soil erosion in young forest stands.~~

3. Species-specific functional traits and site characteristics affected soil erosion rates. High crown cover and leaf area index reduced soil erosion, whereas it was slightly increased by increasing tree height. Thus, low tree stands with high canopy cover were effectively counteracting soil loss in initial forest ecosystem. In further studies, a wider range of functional tree traits like leaf habitus or belowground stratification should be taken into consideration. ~~Even if a leaf litter cover was not present in this experiment, the remaining soil surface cover by stones and biological soil crusts was the most important driver for soil erosion control.~~ ~~Furthermore~~Moreover, ~~soil organic matter had a decreasing influence on sediment discharge. I~~investigations on the influence of biological soil crusts, topsoil microbial communities and their impact on organic matter accumulation will open the way to new insights on soil erosion processes.

Appendices

[Table A1]

~~[Table A2]~~

~~[Table A3]~~

Author contribution

Thomas Scholten, Peter Kühn and Steffen Seitz designed the experiment and Steffen Seitz carried it out. Steffen Seitz, Philipp Goebes and Helge Bruelheide developed the model code and performed the statistics. Ying Li and Werner Härdtle provided data on tree growth and species-specific functional traits. Steffen Seitz prepared the manuscript with contributions from all co-authors.

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Table 1: Characteristics of rainfall events considered erosive (threshold 12.7 mm) in Xingangshan, Jiangxi Province, PR China in May and June 2013.

Event	Mean intensity (mm h^{-1})	Peak intensity (mm h^{-1})	Total rainfall amount (mm)
E 1	1.38	11.4	20.29
E 2	2.34	23.04	25.74
E 3	3.19	45.24	54.42
E 4	14.60	83.04	34.01

Table ~~A2~~2: Results of the basic linear mixed effect model for sediment discharge (* : p<0.001, ** : p<0.01, * : p<0.05, . : p<0.1, n.s. : not significant; n=334). Crown cover was highly correlated with the four other vegetation characteristics and therefore, they have been exchanged and fitted in separate models.**

		denDF	F	Pr	estimates
Fixed effects	Surface runoff	204	49.0	<0.001 ***	(-) 0.33
	Crown cover	120	7.25	0.008 **	(-) 0.18
	Slope	141	1.33	0.250 n.s.	(-) 0.05
	Surface cover	140	56.1	<0.001 ***	(-) 0.46
	Soil organic matter	42	5.61	0.022 *	(-) 0.07
	Precipitation	70	0.12	0.733 n.s.	(-) 0.01
	Tree species richness	25	0.30	0.589 n.s.	(-) 0.05
		sd	variance		
Random effects	Precipitation event : plot	0.204	0.042		
	Tree composition	0.332	0.110		
	Site	0.577	0.333		
	Plot : rop	0.503	0.253		
Vegetation characteristics fitted in exchange to crown cover					
	Leaf area index	95	5.16	0.026 *	(-) 0.17
	Tree height	31	3.58	0.069 .	(-) 0.10
	Tree stem diameter	30	0.20	0.661 n.s.	(-) 0.04
	Tree crown width	31	0.79	0.383 n.s.	(-) 0.08

Table ~~A3~~3: Mean sediment discharge in g m^{-2} and surface runoff volume in L m^{-2} (standard deviation in brackets, n=334) for tree species richness in May and June 2013.

	Diversity 0-24	Diversity 0	Diversity 1-24	Diversity 1	Diversity 8	Diversity 16	Diversity 24
Sediment discharge	199 (106)	361 (187)	188 (90)	202 (105)	103 (57)	135 (123)	204 (107)
Runoff volume	32.6 (21.4)	47.8 (32.1)	29.8 (18.5)	31.9 (20.9)	27.5 (14.5)	22.5 (15.7)	30.2 (19.7)

Table ~~2~~4: Discharge rates and growth characteristics (means) of tree species with significant differences in sediment discharge at the experimental site in Xingangshan, Jiangxi Province, PR China.

	Sediment discharge ($g\ m^{-2}$)	Crown cover (%)	Leaf area index	Tree height (m)	Stem diameter (m)	Crown width (m)
Mean	199	32	0.75	1.84	0.03	0.94
Monocultures	202	22	0.63	1.63	0.02	0.78
Tree mixtures	135	44	1.18	2.30	0.04	1.26
Ch. axillaris	566	90	2.27	7.40	0.07	2.21
C. glauca	556	51	0.93	1.25	0.02	0.65
R. chinensis	502	47	0.85	1.82	0.03	1.62
K. bipinnata	378	19	0.30	1.97	0.03	1.15
M. yuyuanensis	64	11	0.14	1.62	0.04	0.95
L. glaber	114	20	0.28	2.32	0.03	1.09
E. chinensis	66	64	1.02	2.19	0.05	0.97
L. formosana	91	15	0.19	2.28	0.04	1.64

Table ~~3~~5: Growth characteristics of the 20 tree species analysed and associated plot characteristics in Xingangshan, Jiangxi Province, PR China (mean, standard deviation (sd), maximum (max) and minimum (min)).

	Mean	Sd	Max	Min
Vegetation				
Crown cover (%)	37	31	93	1
Leaf area index (LAI)	0.88	1.08	4.20	0.03
Tree height (m)	2.55	1.64	7.40	1.16
Stem diameter (m)	0.04	0.02	0.07	0.02
Crown width (m)	1.25	0.61	3.00	0.40
Site				
Soil surface cover (%)	16	14	55	1
~~Bulk soil density (g cm^{-3})~~	~~0.99~~	~~0.05~~	~~1.12~~	~~0.91~~
Soil organic matter (%)	6.4	1.4	9.4	4.3
~~pH~~	~~3.68~~	~~0.24~~	~~4.39~~	~~3.25~~
Slope (°)	27	5	35	19

Crown cover: proportion of soil surface area covered by crowns of live trees (%), leaf area index: one-sided green leaf area per unit soil surface area (dimensionless), tree height: distance from stem base to apical meristem (m), stem diameter: cross-section dimension of the tree stem at 5 cm above ground (m), crown width: length of longest spread from edge to edge across the crown (m), soil surface cover: proportion of soil surface area covered by stones, biocrusts and litter (%), soil organic matter: fraction of organic carbon containing substances in the soil (%), slope: inclination (°).

Table A1: 22 selected tree species used in the experiment according to the Flora of China (http://www.efloras.org). Asterisks (*) mark species which only appear in mixtures.

Feldfunktion geändert

Species name and author	
Ailanthus altissima (Miller) Swingle	*Koelreuteria bipinnata* Franch.
Alniphyllum fortunei (Hemsl.) Makino	*Liquidambar formosana* Hance
Betula luminifera H. Winkl.	*Lithocarpus glaber* (Thunb.) Nakai
Castanea henryi (Skan) Rehd. et Wils.	*Magnolia yuyuanensis* Hu
Castanopsis fargesii Franch.	*Nyssa sinensis* Oliver *
Castanopsis sclerophylla (Lindl.) Schott.	*Rhus chinensis* Mill.
Choerospondias axillaris (Roxb.) Burtt et Hill.	*Sapindus saponaria* Gaertn.
Cyclobalanopsis glauca (Thunb.) Oerst.	*Schima superba* Gardn. et Champ.
Elaeocarpus chinensis Gardn. et Chanp.	*Triadica sebifera* (L.) Roxb.
Elaeocarpus glabripetalus Merr.	*Quercus fabri* Hance
Elaeocarpus japonicus Sieb. et Zucc.	*Quercus phillyreoides* A. Gray *

~~**Table A2: Results of the basic linear mixed effect model for sediment discharge (*** : p<0.001, ** : p<0.01, * : p<0.05, . : p<0.1, n.s. : not significant; n=334). Crown cover was highly correlated with the four other vegetation characteristics and therefore, they have been exchanged and fitted in separate models.**~~

		~~denDF~~	~~F~~	~~Pr~~	~~estimates~~
~~Fixed effects~~	~~Surface runoff~~	~~204~~	~~49.0~~	~~<0.001 ***~~	~~(+) 0.33~~
	~~Crown cover~~	~~120~~	~~7.25~~	~~0.008 **~~	~~(-) 0.18~~
	~~Slope~~	~~141~~	~~1.33~~	~~0.250 n.s.~~	~~(-) 0.05~~
	~~Surface cover~~	~~140~~	~~56.1~~	~~<0.001 ***~~	~~(-) 0.46~~
	~~Soil organic matter~~	~~42~~	~~5.61~~	~~0.022 *~~	~~(-) 0.07~~
	~~Precipitation~~	~~70~~	~~0.12~~	~~0.733 n.s.~~	~~(-) 0.01~~
	~~Tree species richness~~	~~25~~	~~0.30~~	~~0.589 n.s.~~	~~(-) 0.05~~
		~~sd~~	~~variance~~		
~~Random effects~~	~~Precipitation event : plot~~	~~0.204~~	~~0.042~~		
	~~Tree composition~~	~~0.332~~	~~0.110~~		
	~~Site~~	~~0.577~~	~~0.333~~		
	~~Plot : rop~~	~~0.503~~	~~0.253~~		
~~Vegetation characteristics fitted in exchange to crown cover~~					
	~~Leaf area index~~	~~95~~	~~5.16~~	~~0.026 *~~	~~(-) 0.17~~
	~~Tree height~~	~~31~~	~~3.58~~	~~0.069 .~~	~~(-) 0.10~~
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~~**Table A3: Mean sediment discharge in g m^{-2} and surface runoff volume in L m^{-2} (standard deviation in brackets, n=334) for tree species richness in May and June 2013.**~~

	~~Diversity 0-24~~	~~Diversity 0~~	~~Diversity 1-24~~	~~Diversity 1~~	~~Diversity 8~~	~~Diversity 16~~	~~Diversity 24~~
~~Sediment discharge~~	~~199 (106)~~	~~361 (187)~~	~~188 (90)~~	~~202 (105)~~	~~103 (57)~~	~~135 (123)~~	~~204 (107)~~
~~Runoff volume~~	~~32.6 (21.4)~~	~~47.8 (32.1)~~	~~29.8 (18.5)~~	~~31.9 (20.9)~~	~~27.5 (14.5)~~	~~22.5 (15.7)~~	~~30.2 (19.7)~~

Figure 1: Measurement setup showing a runoff plot (ROP, 0.4 m × 0.4 m) with reservoir and rainfall gauge on the experimental site in Xingangshan, Jiangxi Province, PR China.

Figure 2: Sediment discharge and runoff volume at five diversity levels based on four rainfall events in May and June 2013 in Xingangshan, Jiangxi Province, PR China (n.s.: not significant, n=334). Horizontal line within boxplot represents median and diamond represents mean.

Figure 3: Sediment discharge under 20 tree species in monocultures based on four rainfall events in May and June 2013 in Xingangshan, Jiangxi Province, PR China. Dashed line indicates mean sediment discharge of all 20 species. Horizontal lines within boxplot represent median and diamonds represent mean values found for a respective species.

Figure 4: Effects of tree functional traits and site characteristics on sediment discharge. Analyses were based on four rainfall events in May and June 2013 in Xingangshan, Jiangxi Province, PR China. Black lines symbolize linear trends.