GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

MASTER'S THESIS

Enhancing soil water infiltration through tree-enrichment planting within an oil-palm dominated landscape in Jambi, Indonesia

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Abstract

Monoculture oil-palm plantations in Indonesia are expanding faster than ever and pose a threat on biodiversity and ecosystem functioning. Two important consequences are water shortages during the dry seasons and frequent flooding events during the rainy seasons. This disruption of the water cycle affects the livelihood of local people and impairs plantation management. Increased water infiltration rates have the potential to restore the groundwater table and reduce the risks of floods. As particularly high water infiltration rates had been measured in forests, tree-planting within oil-palm plantations was hypothesised to have a positive effect on soil water restoration.

We tested this assumption in a biodiversity enrichment experiment (BEE) where trees had been planted grouped in tree islands of different sizes and with varying tree species diversity levels within a monoculture oil-palm plantation. We quantified field-saturated hydraulic conductivity with a dual-head pressure infiltrometer in 39 experimental plots while water infiltration rates were estimated with a double-ring infiltrometer in the remaining 17 plots. In three plots, we measured water infiltration with both devices to correct for differences between the two methods.

Four years after the establishment of the BEE we found that increasing tree species diversity is the most effective measure to elevate water infiltration rates. Tree island size, on the other hand, only has a minor effect on water infiltrability. Ground vegetation cover, canopy closure, stand structural complexity, and litter layer thickness further have an impact on water infiltration rates even though effects can be adverse depending on plot size and tree species diversity level. Among the planted tree species, *Durio zibethinus* (L. ex Murray) was particularly effective in restoring water infiltration rates.

We therefore conclude that tree enrichment is a suitable measure for a considerable enhancement of soil water infiltrability within a relatively short period of time, in order to restore ecosystem functioning and to promote the provision of ecosystem services.

Zusammenfassung

Verstärkung von Wasserinfiltrationraten durch Baumpflanzungen innerhalb einer Ölpalmplantage in Jambi, Indonesien

Ölpalm-Monokulturen breiten sich in Indonesien schneller aus denn je und bedrohen Biodiversität und die Funktionalität von Ökosystemen. Zwei akute Folgen sind Wasserknappheit während der Trockenzeiten und häufiger auftretende Überflutungen während der Regenzeiten. Dies hat Auswirkungen auf die Lebensgrundlage der lokalen Bevölkerung und das Management der Ölpalmplantagen. Erhöhte Wasserinfiltrationsraten des Bodens können dazu beitragen, das Grundwasser aufzufüllen und das Überschwemmungsrisiko zu reduzieren. Die vorliegende Studie untersucht die Hypothese, dass Baumpflanzungen zu einer erhöhten Wasserinfiltration in Ölpalmplantagen führen.

Wir testeten diese Vermutung im Rahmen eines Biodiverstätsanreicherungs-Experiments (BEE), in dem Bäume innerhalb einer Ölpalmplantage auf unterschiedlich großen Flächen mit verschiedenen Baumarten-Diversitätsstufen angepflanzt wurden. Die gesättigte hydraulische Leitfähigkeit des Bodens wurde auf 39 experimentellen Flächen mit Hilfe eines Zweifach-Druckhöhen-Infiltrometers und auf 17 Flächen mit einem Doppelring-Infiltrometer gemessen. Auf drei Flächen wurden Wasserinfiltrationsraten mit beiden Geräten bestimmt, um Unterschiede zwischen den beiden Methoden auszugleichen.

Vier Jahre nach Beginn des BEE stellten wir fest, dass eine Erhöhung der Baumdiversität zu einer besonders starken Steigerung der Wasserfiltration führt, während die Bauminselgröße nur eine geringe Auswirkung hat. Die Bodenvegetation, Baumkronen-Geschlossenheit, die Komplexität der Vegetation sowie die Laubschichtdicke beeinflussten die Wasserinfiltrationsraten, obwohl die Auswirkungen sich abhängig von Baumartendiversität und Bauminselgröße unterschieden. Unter den gepflanzten Baumarten stellte *D. zibethinus* sich als besonders geeignet für eine Steigerung der Wasserinfiltration heraus.

Wir kommen daher zu dem Schluss, dass das Pflanzen von Bäumen ein geeignetes Mittel zur Verstärkung der Wasserinfiltration innerhalb einer relativ kurzen Zeit ist, um die Funktionalität von Ökosystemen wiederherzustellen und die Bereitstellung von Ökosystemdienstleistungen zu fördern.

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1 Introduction

Tropical forests range among the most threatened ecosystems worldwide as they are subject to deforestation, mostly in favour of expanding agricultural land (Steffan-Dewenter et al., 2007). In Indonesia, oil palms (*Elaeis guineensis* Jacq.) are currently the most expansive crop, frequently replacing primary and secondary forests (Germer and Sauerborn, 2008; Sodhi et al., 2010). Between 1990 and 2005 at least 56% of the newly established oil palm plantations were located on formerly forested land (Koh and Wilcove, 2008). Since the early 1980s the worldwide production of palm oil increased more than 10-fold, amounting to more than 55 million tons in 2013 (FAOSTAT, 2017). Indonesia alone accounts for nearly half of the production and is therefore currently the largest producer of palm oil (FAOSTAT, 2017). Due to the growing world population demanding palm oil for food consumption and biofuel as well as its low production costs and required labour input, the production is expected to rise further (Corley and Tinker, 2016; Tan et al., 2009; UN, 2017).
This development created millions of jobs, improved the livelihood of many small-scale farmers and is a main driver of Indonesia's economy (Euler et al., 2017, USDA 2007). However, it also threatens unique biodiversity hotspots comprising large numbers of endemic species as forest conversion to oil palm results in a significant reduction of species richness (Clough et al., 2016; Krashevska et al., 2015; Sodhi et al., 2010). This loss of biodiversity impedes ecological functioning and reduces ecosystem resilience (Barnes et al., 2014; Sodhi et al., 2010). The latter is further enhanced by a drier and less stable micro-climate in monoculture oil palm plantations compared to forest ecosystems (Clough et al., 2016; Meijide et al., 2018).

Furthermore, land clearing, road construction, weeding, and harvesting activities alter soil physical properties as they cause topsoil compaction resulting in increased runoff rates and diminished groundwater supply (Comte et al., 2012; Moradi et al., 2015). Runoff on top of the soil surface mostly comprises excess flow when the soil is saturated but in heavy rainfall events runoff can also take place before field capacity is reached (Corley and Tinker, 2016). While runoff rates are negligible in forests (Ellison et al., 2017; Zhang et al., 2007), oil palm plantations in West Papua generated 20-49% runoff (Banabas et al., 2008). If rainfall intensities surpass the water holding capacities of the soil, eroded sediments and agrochemicals are washed into streams and rivers where they can cause eutrophication (Comte et al., 2012; Jose, 2009). This excess flow is mainly channelled through drainage systems. However, the water load during heavy rainfall events often exceeds the water carrying capacities of these channels and thus frequently leads to floods (Auxtero and Shamshuddin, 1991; Obidzinski et al., 2012). The latter not only result in reduced water quality but they also delay harvesting and restrict the growth of oil palm seedlings (Auxtero and Shamshuddin, 1991; Obidzinski et al., 2012). Even though mature oil palms are relatively tolerant to flooding, water-logging reduces their productivity as it impedes nutrient uptake and photosynthetic activities (Woittiez et al., 2017). Mitigating floods is therefore not only crucial for maintaining ecological integrity but it is also of an economically high relevance.

Increasing soil water infiltrability can be a measure to mitigate floods and runoff as the amount of above-ground water is reduced. Hereby, both water infiltration rates and hydraulic conductivity are crucial soil properties. Water infiltration describes the rate at which water is entering the soil and therefore determines how much water is removed from the above-ground system in a given period of time. Hydraulic conductivity, on the other hand, describes how easily water moves through the soil and is hence one of the main factors controlling water infiltration (Bagarello et al., 2004). Hydraulic conductivity is commonly determined in the field under water-saturated conditions and is thus referred to as field-saturated hydraulic conductivity, abbreviated as K_{fs} (Bagarello et al., 2004). In our study, parts of the data have been obtained from a pressure infiltrometer measuring field-saturated hydraulic conductivity while others were derived from a double-ring infiltrometer which estimates water infiltration rates. After the latter had been corrected for differences caused by the two measurement methods, the complete data set was analysed. As field-saturated hydraulic conductivity is a regulatory factor of water infiltration (Bagarello et al., 2013), the latter term is in the following used to describe both unless one or the other device is specifically referred to.

Forest clearing commonly leads to decreased soil water infiltrability. After rainforest conversion to pasture, Zimmermann et al. (2010) observed a significant reduction of water infiltration rates which remained low as long as grazing activities continued. Yimer et al. (2008) reported a 45% decrease of water infiltration rates after forest-to-pasture conversion and a reduction of even 70% following forest conversion to barley cultivations. Diminished saturated hydraulic conductivity, and hence also water infiltration rates, after forest clearing is often a result of soil compaction, a mixing of topsoil with subsoil, and water-repellency promoted by burning (Ziegler et al., 2006), and is most pronounced in the upper soil layers (Hassler et al., 2011).
In oil palm plantations, Banabas et al. (2008) measured relatively high water infiltration rates but as lateral flow was not accounted for and stable infiltration rates were not reached, the reported values are probably overestimated. On the contrary, frequent floods during heavy rainfall events (Lord and Clay, 2006; Merten et al., 2016)

and reduced dry season base flows (Merten et al., 2016) suggest that water infiltration below oil palms does not suffice to prevent excess flow and water scarcity. In forests, on the other hand, floods are rare (Bruijnzeel, 2004; Zhang et al., 2007) and the groundwater table was found to recharge considerably (Peck and Williamson, 1987; Eldridge and Freudenberger, 2005). Integrating trees into agricultural areas may thus help to increase water infiltration, thereby reducing floods and enhancing groundwater recharge.

In the humid tropics, trees are planted to obtain a wide range of benefits such as the conservation of biodiversity, carbon sequestration, soil protection from erosion as well as improvements in nutrient and water cycling (Cunningham et al., 2015). Ilstedt et al. (2007), for instance, reported that tree planting led to a two- to five-fold increase of water infiltration rates. This effect is often attributed to higher inputs of organic matter from litter degradation leading to an improved soil structure and increased soil micro-fauna activities (Comte et al., 2012). High tree species diversities can further enhance water regulation services (Maes et al., 2012). Planting a variety tree species promotes the formation of different root types with specific functions and often leads to a deeper and more completely developed structural rooting system than below tree monoculture plantations (Köstler et al., 1968; Reubens et al., 2007). As water mainly flows along root channels and macropores in the soil (Bargués Tobella et al., 2014; Comte et al., 2012), a more complex rooting system may facilitate water movement into deeper soil layers and groundwater pools. Furthermore, trees reduce the velocity of runoff, therefore supporting nutrient retention and water infiltration (Jose, 2009).

Tree planting influences factors which frequently have an impact on soil infiltrability, among them litter layer thickness, ground vegetation cover, canopy closure, and vegetation complexity. Litter layers not only conserve water in the topsoil but also enhance soil porosity due to an increased input of organic matter (Mumme et al., 2015). In oil palm plantations, empty fruit bunches and frond piles represent the most common form of mulching and are particularly effective in restoring water infiltration capacities (Moradi et al., 2015). A well-established understorey vegetation often reduces topsoil erosivity by fixing the soil with its comparatively shallow rooting system which also promotes water infiltration into the soil (Comte et al., 2012; Reubens et al., 2007). Trees, on the other hand, develop deeper roots and thus facilitate preferential flow into deeper soil layers (Comte et al., 2012). Their canopies can have a coalescing effect which enhances rain drop speed and erosive splash on the ground. A complex multi-layered vegetation, however, has a higher potential to mitigate this effect as the rain drop velocity is reduced (Reubens et al., 2007; Styczen and Morgan, 1995).

Enhancing the complexity of oil palm-based ecosystems is an essential step towards restoring ecosystem functioning and increasing intrinsic biodiversity (Foster et al., 2011). On the Indonesian island Sumatra, a biodiversity enrichment experiment (BEE) was initiated in 2013 in order to investigate effects of integrating trees into an oil palm-dominated landscape on biodiversity and ecosystem functioning. Tree islands of different sizes and species composition were established, and oil palms within these islands were thinned (Teuscher et al., 2016). Initial results of the BEE indicate that economic losses created by the removal of some oil palms could at least be compensated by increased yields of the remaining oil palms and those adjacent to the tree islands (Gérard et al., 2017). These findings suggest that ecological benefits are not necessarily accompanied by economic losses. However, most trees have not yet grown into the oil palm canopy (Zemp, unpublished data) and may thus still be too young to considerably compete with palms for nutrients and light. If long-term economically negative effects are expected, it is even more important to fully understand the underlying social, ecological, and environmental functions to be able to quantify and assess short- and long-term trade-offs. Soil water infiltrability plays a key role in ecosystem functioning, and its disruption affects people's livelihood who face decreasing groundwater levels and the pollution of rivers and streams. Furthermore, frequent flooding events may also result in economic losses as they increase road maintenance and harvesting costs (Corley and Tinker, 2016).

In our study, we measured field-saturated hydraulic conductivity (K_{fs}) and water infiltration rates in order to assess the effects of tree enrichment in oil palm plantations on soil hydrological functioning.
The overarching objective of our study was to assess the effects of tree enrichment planting among oil palms on soil water infiltration capacity. We hypothesized that water infiltration rates rise with increasing tree island size, species diversity of planted trees, litter layer thickness, ground vegetation cover, complexity of the vegetation, and canopy closure. Moreover, we expected a negative correlation between water infiltration rates and bulk density as well as higher water infiltration in areas where weeding and cattle grazing were banned.

2 Materials and Methods

2.1 Study area

The study was conducted in Jambi Province, Sumatra, Indonesia. In South-eastern Jambi Province, a tree enrichment planting experiment was established in Kebupaten Batanghari near Bungku village in a medium-sized oil palm plantation owned by PT. Humusindo Makmur Sejati (01.95° S and 103.25° E, 47 ± 11 m a.s.l) (Gérard et al., 2017; Teuscher et al., 2016, Figure 2.1). The region is dominated by tropical humid climate, with mean annual temperature of 26.7 ± 0.2° and a mean annual precipitation of 2235 ± 381 mm (Sulthan Taha Airport station, Jambi City, from 1991-2011; Drescher et al., 2016). The main natural vegetation type in the region is lowland dipterocarp rainforests, but over the past decades large forested areas have been converted to agricultural systems (Clough et al., 2016; Laumonier et al., 2010). The dominant soil type in this region are highly weathered loamy acrisols (Allen et al., 2015).

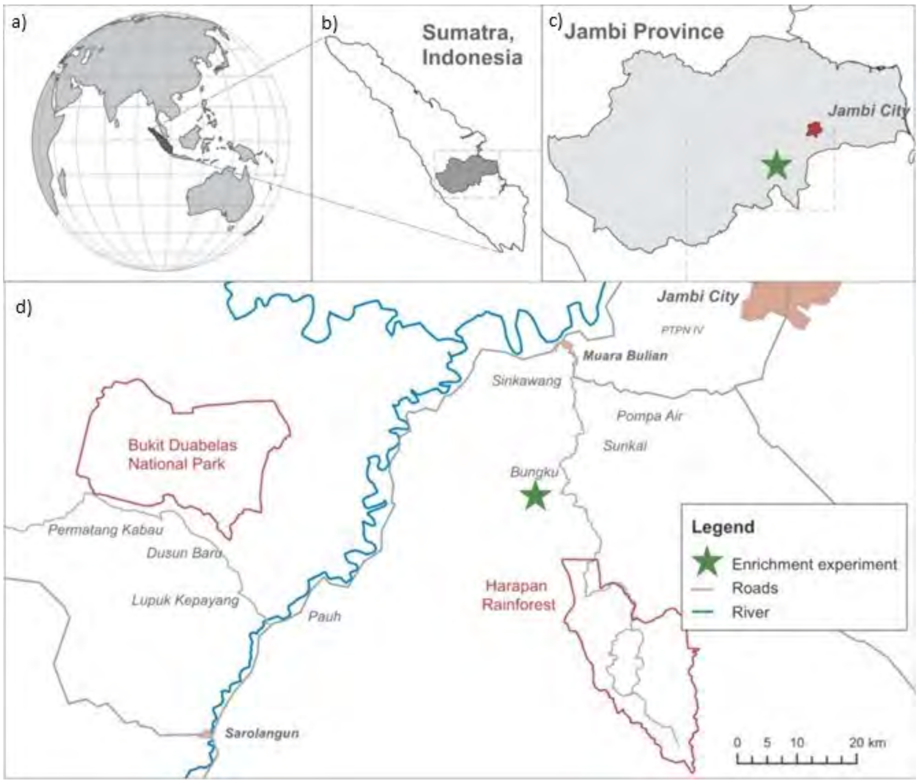

FIGURE 2.1: Study site in Jambi Province, Indonesia (Teuscher et al., 2016, modified from Drescher et al., 2016). The research location is marked with a green star.

2.2 Study design

Within a monoculture oil palm plantation in the lowlands of Jambi, a biodiversity enrichment experiment (BEE) has been established as part of the EFForTS Project (Drescher et al., 2016) which investigates ecological and socio-economic implications and trade-offs after rainforest conversion to agricultural land-use systems such as oil-palm plantations. The BEE comprises the planting of trees amidst oil palms as well as the abandonment of fertilizer use, cattle grazing and understorey weeding within the experimental plots (Teuscher et al., 2016). Plot sizes and tree species diversity levels vary across the plots, ranging from 25 m^2 (5 x 5 m), 100 m^2 (10 x 10 m), 400 m^2 (20 x 20 m) to 1600 m^2 (40 x 40 m) and from zero, one, two, three to six planted tree species per plot, respectively. Within each combination of size and diversity level, each species is represented once (Figure 2.2). Furthermore, there are four control plots on which no trees are planted and that are managed the same as the surrounding oil palm plantation. Consequently, the total number of plots amounts to 56. The tree species diversity levels and plot sizes were assigned to plot locations randomly, so that no intentional clusters according to plot size or diversity level were formed. The minimum distance between the plots was 85 m (Teuscher et al., 2016).

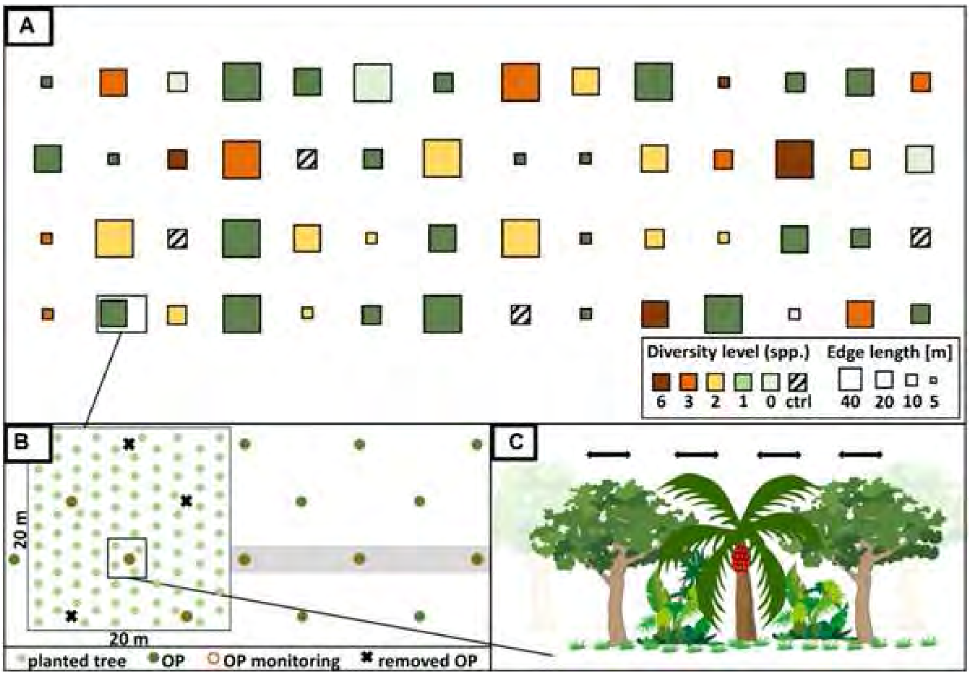

FIGURE 2.2: Experimental design of the biodiversity enrichment experiment (BEE). A: Plot sizes (5 x 5 m, 10 x 10 m, 20 x 20 m, and 40 x 40 m) and diversity levels (0, 1, 2, 3, 6 tree species); each tree species is represented once in each combination of plot size and diversity level. B: Some oil palms were removed and trees planted in regular rows. C: Interaction /competition between trees and oil palms (Teuscher et al., 2016).

In Humusindo, oil palms are arranged in a 9 x 9 m triangular grid, amounting to approximately 143 oil palms per hectare between the age of 12-17 years under the status quo (Teuscher et al., 2016). Within the BEE they reached a mean total height of 11.19 m (Lorenz, 2018). Apart from the 25 m² plots, selected oil palms were removed before tree planting to create room for the above-mentioned tree islands. In December 2013, trees were inter-planted in two-metre-rows, ranging from North to South. Individuals of one tree species were planted in a row, and rows with the same species were planted with the maximal possible distance between them.

For the enrichment planting, six multi-purpose tree species were chosen, comprising three species commonly grown for their fruits (*Parkia speciose* Hassk., Fabaceae; *Archidendron pauciflorum* (Benth.) I. C. Nielsen, Fabaceae; *Durio zibethinus* L. ex Murray, Malvaceae), two species grown for its timber (*Peronema canescens* Jack, Lamiaceae; *Shorea leprosula* Miq., Dipterocarapceae), and one species producing natural latex (*Dyera polyphylla* (Miq.) Steenis, Apocynaceae).

The plantation management system under the status quo included manual weeding of the understory vegetation, cattle grazing and the application of fertilizers (230 kg N (Urea), 196 kg P (Triple Superphosphate and rock phosphate), 142 kg K (KCl), 54 kg Mg (Kieserite and Dolomite), and 0.79 kg B (Borax), all in ha^{-1}, yr^{-1}, Teuscher et al., 2016). These activities were all stopped in the enrichment planting plots (Gérard et al., 2017).

2.3 Soil water infiltration

At all 56 study sites of EFForTS-BEE, we measured soil water infiltration as an important component of the hydrological cycle. We performed one measurement in each plot within a marked 5 x 5 m area, in the following referred to as 'subplot'. Each plot larger than 25 m² contained one subplot whose position within the plot had been chosen randomly provided that its edges were at least one meter away from the fence to avoid edge effects. Measurements in 39 plots were performed with a fully automated dual-head pressure infiltrometer (METER Group, 2017b), while the remaining 17 plots were sampled with a manual double-ring infiltrometer due to technical problems with the dual-head device. Three plots were sampled with both devices to allow a direct comparison of the methods and to potentially obtain a relationship for the extrapolation to a complete BEE dataset of 56 plots.

The portable single-ring pressure infiltrometer uses a modified two-ponding head method to estimate field-saturated hydraulic conductivity (Gonzales et al., 2018; Reynolds and Elrick, 1990). Instead of varying the depth of water columns as commonly practiced with manual pressure infiltrometers (Alagna et al., 2015; Reynolds et al., 2000), the automated infiltrometer establishes different air pressure heads to alter water infiltration conditions. While three complete pressure cycles are run to measure soil hydraulic conductivity, the water level remains constant. The control unit collects the data from which it then calculates saturated hydraulic conductivity in cm s^{-1} with an accuracy of ±5% (METER Group, 2017b).

Before the measurement in each plot, a ground area within the subplot was searched for which fulfilled the following set of criteria. Firstly, steep slopes were avoided as water infiltration rates have been shown to decrease on increasingly steep slopes and might thus hamper the comparison of measured values (Dunne et al., 1991; Huat et al., 2006; Janeau et al., 2003). Secondly, anthropogenically disturbed surfaces such as paths were excluded due to surface compaction on tracks (Ilstedt, 2002). To minimize destructive impacts on ground vegetation within the experimental subplots, spots with dense vegetation cover were avoided and areas near the edge of the subplot were given preference so that heavy equipment, such as water tanks and the electronic control unit, could be placed outside of the subplot. Among the spots fulfilling these criteria, the closest one to the plot centre was chosen.

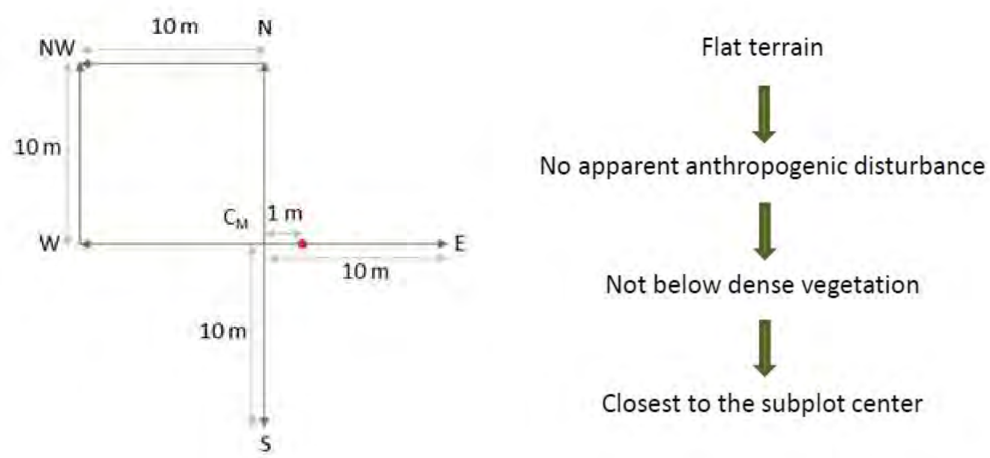

FIGURE 2.3: Systematic sampling designs. Left: Sampling design based on a systematic grid in Plot 23. The plot centre is indicated by the red dot; N: north; E: east; S: south; W: west; NW: northwest; CM: centre point moved 1 m to the west. Right: Subplot sampling design applied in all plots.

In addition to sampling the 56 plots (with one subplot each), six systematically distributed measurements were conducted in plot 23 to assess within-plot variability. Plot 23 combines the highest tree species diversity (six planted tree species) and largest plot size (1600 m^2). Measurements were taken with the dual-head infiltrometer one metre west of the plot centre as well as ten metres north, east, south, and west and northwest of it (Figure 2.3). Shifting the centre point was necessary because the exact plot centre was inaccessible due to climate sensors installed at this spot.

Wooden debris and leaf litter were removed to be able to install the measurement devices and to allow an unimpeded water flow. Installation and measurements procedures for the dual-head infiltrometer and the double-ring infiltrometer, respectively, are explained in the following:

2.4 Dual-head pressure infiltrometer

The insertion ring was driven into the soil, using a rubber hammer and a driving plate. If the terrain was slightly inclined, the ring was aligned perpendicularly to the slope with the two set screws on the left and right (METER Group, 2017b). Afterwards the pressure head was installed and connected to the pump which was in turn linked to two water tanks with a volume of 17 litres each (Figure 2.4).

FIGURE 2.4: Application of the dual-head pressure infiltrometer. Left: Set-up with control unit, water tanks and infiltrometer head. Right: Functionality with water and air inputs and the pressure sensor (METER Group, 2017b).

Following a set of exploratory field experiments, the 5-cm insertion ring was used for all measurements, thus the inserting depth was set at 5 cm using the touch pad in the control unit. A soak time of 10 minutes was chosen for most of the measurements as this period was observed to be sufficient for reaching the soil water saturation status needed to perform the test. This observation was based on live saturation curves visually displayed in the control unit. The soak time was followed by three pressure cycles for which – depending on soil conditions – one of two setting types was used. In soils with expected low infiltration rates (e.g. due to high soil compaction), the low pressure was set at 5 cm while the high pressure was 15 cm, in very rare cases even 20 cm. These settings are derived from suggestions for silty loam soils proposed by the manufacturer (METER Group, 2017b). In soils with expected high infiltration rates, on the other hand, (e.g. in apparently very porous soils), the low pressure was set at 3 cm and the high pressure at 10 cm, adapted from recommendations for loamy sand (METER Group, 2017b). The holding time usually amounted to 10 minutes for each pressure step, in rare cases (e.g. when in very porous soils the water infiltration rate did not stabilize within 10 minutes) a holding time of 15 minutes was applied.

2.5 Double-ring infiltrometer

First the inner ring (16 cm diameter) was driven 5 cm into the soil, using a piece of wood instead of a driver plate as well as a rubber hammer to minimize soil disturbance. Subsequently, the second ring (28 cm diameter) was inserted 5 cm into the soil. A ruler was inserted next to the inner wall of the inner ring to allow for water level surveillance (Figure 2.5). In case of inclined terrain, it was positioned on the left or right (medium slope). Water was filled to a level of 5 cm in both rings. As soon as the level was reached, a stopwatch was started. After two minutes, the sinking water level was restored to 5 cm. A manual water pump was used to refill water between the outer and the inner ring, while the inner ring was filled with water from a measuring cylinder (capacity of 500 mL, in 5 mL intervals) from which the amount of water needed for the refill was determined.

FIGURE 2.5: Application of the double-ring infiltrometer. Water was pumped from water gallons into the measuring cylinder (right) and from there poured into the inner ring (left) while the outer ring was filled directly with the pump.

Steady water flow from the measuring cylinder was approximated by applying a funnel lined with a piece of cloth and holding it close to the water surface to minimize pressure from falling water (Figure 2.5). In case of very high infiltration rates (often in the beginning of a measurement), the fennel was skipped as the low water flow could not keep up with the infiltration. The water refill was usually performed in 2-minute intervals but when water infiltration was too high, the water volume was already determined after one minute. Similarly, measurement intervals were extended when the infiltration rate was particularly low as the measurement cylinder was not suitable to precisely quantify very small volumes of water. This methodology aimed at maximizing the number of data points while ensuring the highest possible precision. Measurements were carried out until the infiltration rate stabilized, while allowing for smaller fluctuations.

Infiltration rates were calculated for one-minute intervals, then the mean value over the stabile period was determined ($\bar{y}$ in cm³ min^{-1}). Water infiltration rates were then transformed to centimetres per second, since these are the units of values produced by the Saturo infiltrometer, applying the following formula:

$$F\,(cm\,h^{-1}) = \frac{\bar{y}}{60\,\pi\,r^2}$$

Here, F is the water infiltration rate, $\bar{y}$ is the arithmetic mean of stable water infiltration rates over at least 10 minutes, and r is the radius of the inner ring (8 cm).

2.6 Merging both data sets

Three measurements obtained by the dual-head pressure infiltrometer with very low relative standard errors (from plots P02, P30, and P34) were repeated with the double ring infiltrometer to assess the comparability of the two data sets. For these repetitions, measurement locations within the respective subplots were chosen following the approach described in the preceding chapter. Results are displayed in Table 2.1.

TABLE 2.1: Data pairs used for the transformation regression. DH: Dual-head infiltrometer; DR: Double ring infiltrometer.

Plot ID	DH (in cm h^{-1})	DR (in cm h^{-1})	DH/DR
P02	36.792 ± 1.368	63.432 ± 0.540	0.58
P30	3.492 ± 0.144	1.044 ± 0.000	3.35
P34	7.776 ± 0.144	15.624 ± 0.252	0.50

Based on the preceding value pairs, a linear equation was formed (Figure 2.6), with the measurements derived from the double ring infiltrometer representing the dependent variable and the dual-head infiltrometer measurements representing the independent variable:

$$y = 0.5516x + 1.44$$

This equation was applied to all data points measured with the double ring infiltrometer to correct for differences between the two measurement techniques. As three data points are a relatively weak basis for the calculation of a regression, not only the combined data set was analyzed but also the data set comprising dual-head infiltrometer measurements only. As the double ring infiltrometer data set only consists of 17 measurements, it was not considered for separate two-way Anova analyses but only for simple linear models.

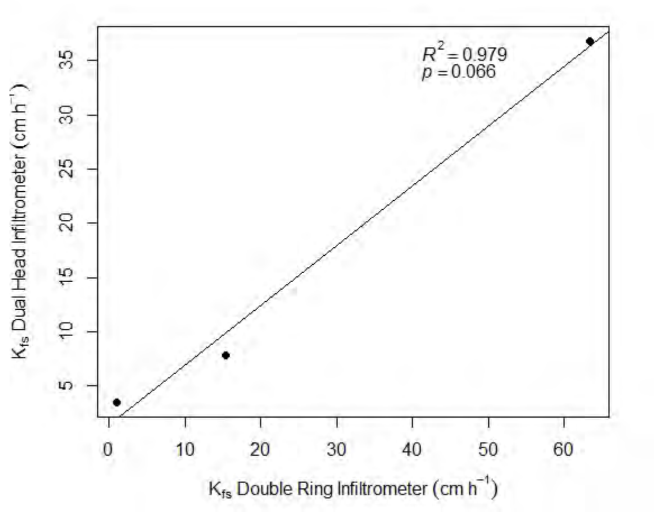

FIGURE 2.6: Regression line used to transform the double ring infiltrometer data to obtain a full data set of the 56 plots. Based on measurements displayed in Table 2.1. n = 3.

2.7 Complementary site and plot data

Complementary site data were kindly provided by Nina Hennings (bulk density), Dr. Delphine Clara Zemp (stand structural complexity), Hendrik Lorenz (gap fraction), and Lena Sachsenmaier (ground vegetation cover).

For the determination of bulk density, soil was extracted with a core cutter (100 cm^3 volume) and dried for up to 72 hours at 105°C (Hennings, unpublished). The bulk density was then calculated based on the following equation:

$$pbulk = \frac{M_{ds}}{V_s}$$

Here, *pbulk* is the bulk density (in g cm), M_{ds} is the measured dry weight of the sample (in g) and V_s is the volume of the sample (in cm^3).

In the computation of the stand structural complexity index, polygons derived from cross-section scan points were utilized (Ehbrecht et al., 2017). Next to the fractal dimensions of these polygons, the stand's vertical vegetation structure and the relative occupation of space by trees were included in the model.

Gap fractions of the canopy were derived from hemispherical photos, taken with a Nikon D5100 SLR camera and Sigma 4.5 mm F2.8 EX DC circular fisheye lens (Lorenz, 2018). The camera was positioned in the subplot center and pictures were taken starting with high exposure values that were gradually reduced so that the picture with the highest exposure value and without a peak touching the very right end of the gray value histogram displayed on the camera could be selected. Pictures were taken in non-rainy morning and evening hours to avoid distortions by overexposed sky.

Ground vegetation cover was defined as the proportion of the soil surface not covered by leaf litter or wooden debris nor consisting of bare soil (Sachsenmaier, 2019).

2.8 Statistical analysis

Statistical tests were performed and plots created in R version 3.5.1 (R Development Core Team, 2018).

As two different methods were applied to determine water infiltration capacity, not only the full merged data set comprising 56 plots was analysed but also the two separate data sets with 39 (dual-head infiltrometer) and 17 plots (double-ring infiltrometer).
After the data obtained from the double-ring infiltrometer were transformed according to the above-mentioned regression, all data sets were tested for normality of residuals using the Shapiro-Wilk test. Since they were not normally distributed, the data points were square root-transformed (full data set, dual-head data) and natural log-transformed (double-ring data) to achieve a normal distribution which reduces the risk of committing a Type I or Type II error (Osborne, 2010). For the same reason, other variables included in the analysis were square root-transformed (litter layer thickness) and cubic root-transformed (gap fraction). The predictors bulk density, ground vegetation cover, and stand structural complexity exhibited normally distributed residuals and were thus not transformed.
According to Levene's test outputs, homoscedasticity of the data could be assumed for bulk density, gap fraction, and ground vegetation cover, but not for litter layer thickness and stand structural complexity. Thus, an analysis of variance (Anova) was performed using the former variables, while a Kruskal-Wallis test was applied on the latter.
Contrasts were included in a "Type III" two-way Anova to account for the unbalanced number of samples per group in the sampling design (e.g. 6 one-species plots per plot size but only 3 two-species plots per plot size) and to allow for the analysis of interactions between factors comprising litter layer thickness, gap fractions, ground vegetation cover, and stand structural complexity (Buckless and Ravenscroft, 1990).
The Games Howell-Post Hoc test was conducted to detect differences of water infiltration rates between plot sizes and tree species diversity levels. Simple linear models were applied on complementary site data (bulk density, gap fractions, ground vegetation cover, and stand structural complexity) to investigate direct effects of these factors on water infiltration.

The coefficient of determination (R^2) was further determined to assess the goodness of fit of the applied regression models (Cameron and Windmeijer, 1997).

3 Results

3.1 Comparison of dual-head and double-ring methodologies

After data transformation, water infiltration rates obtained by the double ring infiltrometer were lower in the experimental plots than those obtained by the dual-head infiltrometer ($p<0.05$, Figure A.3). When the four oil-palm control plots were included, no difference was detected between the data sets.

3.2 Tree planting and fencing

Within tree islands water infiltration rates were higher than in plots without trees, even though this effect was only observed in the data set obtained from the dual-head infiltrometer ($p<0.1$, Figure 3.1). Furthermore, the experimental plots exhibited higher water infiltration rates than the oil-palm control plots ($p<0.05$ in the merged data set and $p<0.05$ in the data obtained from the dual-head infiltrometer, Figure 3.1).

3.3 Tree island size with complementary plot characteristics

In the merged data set, water infiltration rates were considerably higher in the second largest plots (400 m^2) than in the smallest plots (25 m^2, $p<0.1$). Within the second largest plots, increasing gap fractions ($p<0.05$) and ground vegetation cover ($p<0.01$) were positively correlated with water infiltration rates. Similar trends were found in the second smallest plots (100 m^2) even though less pronounced ($p<0.1$ and $p<0.05$, respectively). In the smallest plots we detected a negative correlation with ground vegetation cover ($p<0.05$).

Within the dual-head infiltrometer data set, saturated hydraulic conductivity increased with higher litter layer thickness ($p<0.1$).

Significant p-values are summarized in Table 3.1.

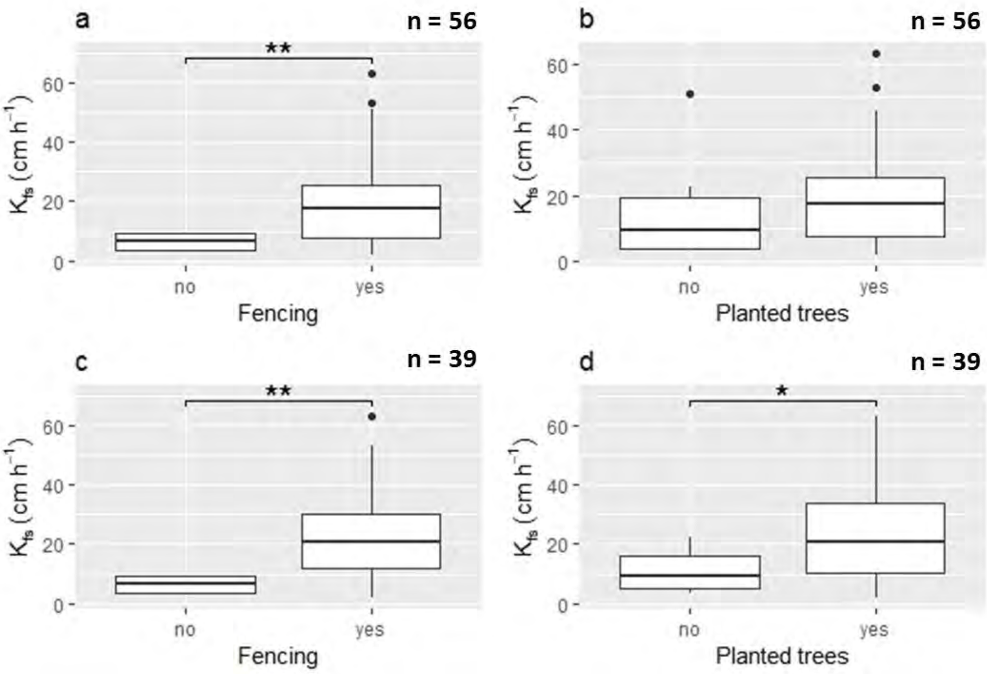

FIGURE 3.1: Water infiltration rates in open plots and plots surrounded by fences (a, c) as well as in plots with and without planted trees (b, d). a, b: Merged data set (dual-head and double ring infiltrometers, the latter transformed based on the regression in Figure 2.6;; c, d: Data produced by the dual-head infiltrometer only. In each boxplot, the median is shown (solid line) as well as the interquartile range represented by box enclosures (first and third quartile) and whiskers, representing the variability outside the upper and lower quartiles (maximal 1.5 times as long as the distance between the first and third quartile); * refers to p<0.1; ** refers to p<0.05.

TABLE 3.1: Water infiltration rates across different tree island sizes. DH: dual-head infiltrometer; LL: Litter layer; GF: Gap fraction; VC: Vegetation cover; SSC: Stand structural complexity; NSD: no significant difference. * from generalized linear model, e.g. glm(K_{fs}~Litter layer*tree island size)

	DH data set		Merged data set	
Predictor	Factor	*p*-value	Factor	*p*-value
Litter layer	LL	0.0864	-	NSD
Gap fraction	100 m²	0.08010		
	400 m²	0.01207		
			GF*100 m²	0.0846
	GF*400 m²	0.01470	GF*400 m²	0.0453
Vegetation cover	-	NSD	VC	0.02375
			100 m²	0.04174
			400 m²	0.00410
			VC*100 m²	0.03723
			VC*400 m²	0.00247
			VC*1600 m²	0.06830
SSC	-	NSD	-	NSD

3.4 Tree species diversity level with complementary plot characteristics

In the merged data set, water infiltration rates were higher in plots with three planted tree species than in the plots without any planted trees (p<0.1). Moreover, we found a negative correlation between water infiltration rates and stand structural complexity in plots without planted trees (p<0.05), whereas in plots where trees had been planted they remained stable (one or two planted tree species with p<0.05 each) or increased with higher vegetation complexity (three planted tree species, p<0.1). In experimental plots with six planted tree species, no statistically distinct trend was observed.

Significant p-values are compiled in Table 3.2.

TABLE 3.2: Water infiltration rates across different tree species diversity levels. DH: dual-head infiltrometer; SSC: Stand structural complexity; NSD: no significant difference. * from generalized linear model, e.g. glm(K_{fs}~Litter layer*tree species diversity level)

	DH data set		Merged data set	
Predictor	Factor	p-value	Factor	p-value
Litter layer	-	NSD	-	NSD
Gap fraction	-	NSD	-	NSD
Vegetation cover	-	NSD	-	NSD
SSC	-	NSD	SSC	0.03234
			1 species	0.04234
			2 species	0.04305
			SSC*1 species	0.04528
			SSC*2 species	0.03922
			SSC*3 species	0.07042

3.5 Complementary plot characteristics

Even though most of the complementary factors influenced water infiltration rates in certain tree island size classes and at different tree species diversity levels, they did not explain a lot of the variance of a simple linear model when plotted separately against water infiltration rates (Table 3.3).

TABLE 3.3: Coefficients of determination based on square root-transformed data. NSD: no significant difference.

Predictor	Merged		Dual-head	
	R^2	p-value	R^2	p-value
Bulk density	0.01	NSD	0.01	NSD
Gap fraction	0.03	NSD	0.03	NSD
Vegetation cover	0.02	NSD	0.05	NSD
Litter layer	0.05	NSD	0.03	NSD
Stand structural complexity	0.00	NSD	0.05	NSD

3.6 Sampling design

The within-plot variability was nearly as high as the variability of the entire dual-head infiltrometer data set (Figure 3.2). The relative standard errors varied considerably between the measurements, and high standard errors occurred across the entire range of water infiltration rates.

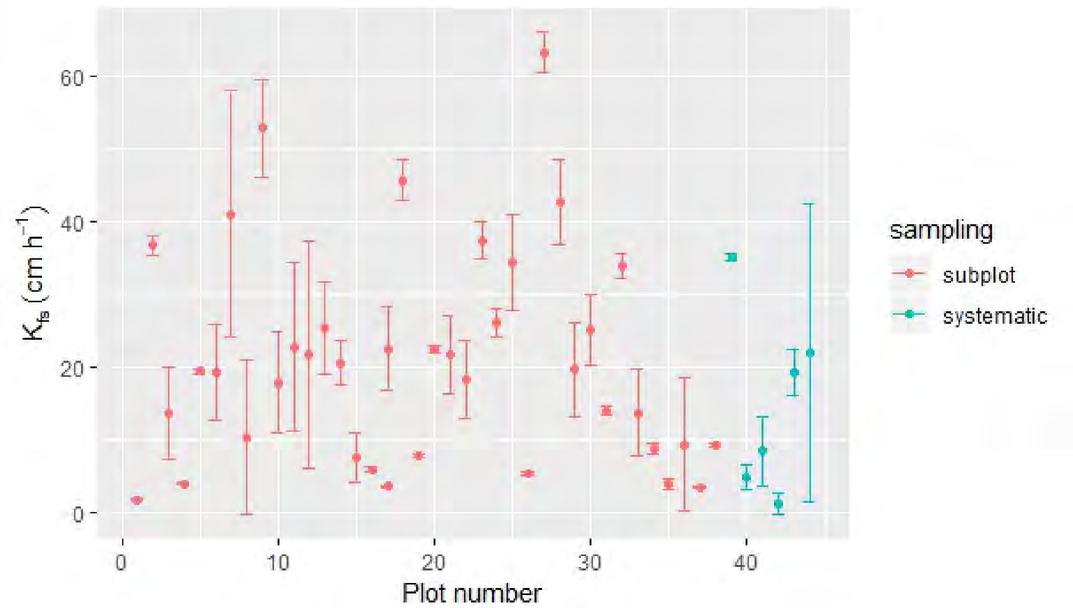

FIGURE 3.2: Subplot measurements ("subplot") vs. within plot variability ("systematic"). Only data produced by dual-head pressure infiltrometer, plots are continuously numerated based on the order of their respective plot IDs.

4 Discussion

4.1 Dual-head infiltrometer versus double-ring infiltrometer

By the time technical defects occurred in the dual-head pressure infiltrometer, all plot size categories and tree species diversity levels had been sampled. However, the highest diversity level (six planted tree species) was sampled only once. Thus, data obtained from a double-ring infiltrometer were included in the analysis to allow for an investigation of the complete set of experimental plots. Generally, water infiltration rates obtained from the dual-head infiltrometer were significantly higher than those obtained from the double-ring infiltrometer when only the experimental plots were considered ($p<0.05$). When oil-palm control plots, all four of which were sampled with the dual-head infiltrometer and exhibited particularly low hydraulic conductivities, were included in the analysis, this difference was not statistically significant anymore ($p>0.1$). According to the manufacturer, the dual-head infiltrometer causes less soil disturbance than double-ring infiltrometers, particularly in porous soils (METER Group, 2017a) . This could explain the general lack of high water infiltration rates within the double-ring infiltrometer data set. On the other hand, the transformation regression, which was only based on very few pairs of values, nearly halved the originally measured values. A larger number of pairs might have changed the slope of the regression and could thus have had a substantial influence on the comparability of the data sets.

Standard errors of data produced by the double-ring infiltrometer were generally lower than those obtained by the dual-head infiltrometer (Figure A.4 in Appendix A), but this effect was expected since mean values were derived from stabilizing infiltration rates. Nevertheless, the extent of many standard errors calculated by the control unit of the dual-head infiltrometer is striking. Even though the settings were adjusted to the respective soil conditions, the pressure heads often failed to stabilize, which led to high standard errors and a low reliability of those particular data points. High infiltration rates sometimes exceeded the capacities of the electric pump, even though low pressure heads were used. Heavily compacted soil, on the other hand, also posed a challenge on the device as it struggled to detect low infiltration rates even though high pressure heads were applied. Thus, the dual-head infiltrometer appears suitable for determining infiltration rates in intermediate ranges but even then, it should be supervised continuously by observing the real-time pressure curve and restarted where necessary.

However, even stable pressure heads often produced highly variable data (Figures A.6 and A.7, Appendix A). Previous studies indicated that spatial heterogeneity in the soil, entrapment of air bubbles as well as variations of initial soil saturation and the conductivity gradient can lead to erroneous and invalid results with the dual-head pressure approach, especially in fine-textured soils and in soils with particularly low infiltration rates (Bagarello et al., 2013; Mertens et al., 2002). Next to a larger sampling size, the multiple-ponding depth (MPD) procedure might yield more accurate data (**bagarelloinpress**) and could thus be specifically considered for fine-textured or compact soils. However, the automated infiltrometer can only establish two different ponding depths per measurement run, therefore the MPD method can currently only be carried out manually.

As our results generated by a dual-head pressure infiltrometer and a double-ring infiltrometer generally correspond well with previously reported soil hydraulic conductivities in monoculture oil palm plantations (Tarigan et al., 2018), we considered their accuracies high enough for further analysis.

4.2 Tree planting

Within the dual-head data set, water infiltration rates were generally higher in the experimental plots with planted trees than in the surrounding oil-palm plantation or on experimental plots without planted treed (p<0.1).

Oil palms usually develop either horizontal or vertical roots from the stem with only few roots growing transversely (Corley and Tinker, 2016). The vertical roots mainly grow directly below the stem and develop relatively few secondary roots. Primary horizontal roots develop more secondary roots, of which some are growing vertically. However, there are only few connections between vertical roots (Corley and Tinker, 2016). As the xylem of roots often decays faster than the root bark, channels formed by growing roots can facilitate water movement through the soil even after the roots have died (Beven and Germann, 1982). However, preferential water flow also occurs along channels formed by living roots and soil fauna (Comte et al., 2012). In conventional oil palm plantations without empty fruit bunches left on the ground, soil fauna activities are generally low (Tao et al., 2016). Thus, water movement through the soil is probably mostly limited to channels along living or decaying roots (Beven and Germann, 1982). Due to the lack of connectivity between the roots, it may be difficult for air trapped below ponded water to escape when water is entering the soil (Beven and Germann, 1982). Hence, a continuous water flow within the soil is possibly impeded, especially during heavy rainfall events. Tropical trees, on the other hand, develop a complex multi-dimensional rooting system which is frequently associated with soil fungi and amounts to a root biomass that is much higher than below oil palms (Jenik, 2010; Pransiska et al., 2016; Sahner et al., 2015). Furthermore, high soil fauna activities lead to an increasing network of tubular channels in the soil, particularly near the soil surface (Beven and Germann, 1982; Wallace et al., 2005; Young, 1997).

Consequently, pore spaces along roots, fungal hyphae, and micro-fauna channels below trees are usually well connected and provide various pathways for air to escape, thereby enhancing a continuous water flow in the soil.

Moreover, we observed higher water infiltration rates in oil palm plantation plots surrounded by a fence (p<0.05 both in the dual-head infiltrometer data set and in the merged data set, Figure 3.1). Trees are not planted on either plot but in fenced plots weeding and cattle grazing activities are banned, therefore allowing for the natural establishment of trees and other plants. Grazing activities lead to a reduced vegetation cover and soil compaction, and thus also to lower water infiltration rates (Langlands and Bennett, 1973). The exclusion of cattle from the experimental plots prevents further soil compaction from grazing. Moreover, the omission of weeding activities allowed for the introduction of plants which may further contribute to soil restoration. These findings confirm our hypothesis that the exclusion of weeding and cattle grazing positively affects soil water infiltrability.

4.3 Tree island size

In the merged data set, water infiltration rates were higher in the second largest plots (400 m^2) than in the smallest plots (25 m^2, p<0.1). Furthermore, within these second largest plots, higher gap fractions (p<0.05) as well as increasing ground vegetation cover (p<0.01) were associated with higher water infiltration rates. In the second smallest plots (100 m^2), the same trends were observed even though less pronounced (p<0.1 and p<0.05, respectively).

As opposed to our hypothesis, no clear trend of increasing water infiltration rates with elevated plot size was observed. Thus, the elevated water infiltration rates in the second largest plots (400 m^2) as compared to the smallest plots (25 m^2) cannot be explained solely with the larger size of the plots. Thus, other factors (canopy closure, ground vegetation cover, stand structural complexity, and litter layer thickness) were included in the analysis. Even though none of these additional factors alone shows a considerable correlation with water infiltration rates (Table 3.3), they do exhibit distinct trends in different plot size classes and tree species diversity levels and therefore allow for a more differentiated discussion.

In experimental plots larger than 25 m^2, individual palms were removed during the experimental set-up. The resulting gaps in the oil palm canopy foster light penetration and create space for the planted trees to grow. However, as many of the planted trees have not yet reached the height of the palm canopy (Zemp, unpublished data), many of the artificial gaps in the canopy are still relatively open and thus show higher gap fractions than the small plots in which no palms had been removed. Next to light penetration, open gaps also enhance the amount of rain water falling onto the tree canopy and the ground since it is not intercepted by the palm canopy anymore. Direct throughfall hitting the ground has a lower kinetic energy than rain drops intercepted by a tree canopy before falling to the ground as the latter merge to larger drops with increased velocity (Geißler et al., 2010). Rain drops with a high kinetic energy can increase splash on the ground detaching small soil particles (Geißler et al., 2010; Larsen et al., 2009) which are then washed away by the water until they are deposited again. These deposited sediments can block entrances to macropores in the ground, hence impeding the penetration of water into the soil (Beven and Germann, 1982). Furthermore, the removal of loose soil particles exposes deeper, more compact and less porous soil layers which also reduces water infiltration and increases runoff (Banabas et al., 2008; Janeau et al., 2003; Pierson et al., 2008).

On the other hand, enhanced ground vegetation cover can reduce this canopy effect considerably (Khan et al., 1988; Simanton et al., 1991). Until the planted trees form a closed canopy, light and space is available for the establishment of an understorey vegetation. More available light supports a denser ground vegetation (Otsamo, 2000) which in turn protects the soil from rain drop splash and associated erosive effects. Since runoff leads to ponding, rainfall concentrates below the ground vegetation (Bromley et al., 1997). This ponding effect in combination with lower crusting leads to more rapid water infiltration (Bromley et al., 1997). The removal of palms further supports the creation of diverse micro-habitats, not only due to the different light conditions but also because of scattered palm stumps. Habitat heterogeneity promotes the establishment of both native and non-native plant species and can thus result in more diverse plant communities than in homogeneous habitats (Kumar et al., 2006). Due to more complex rooting systems below heterogeneous vegetation as well as increased soil fauna activities (Leroy and Marks, 2006), increasing micro-habitat diversity possibly has a positive effect on soil structure which in turn improves soil hydraulic properties (Maes et al., 2012). The generally well-established ground vegetation cover might also explain why litter layer thickness does not seem to play an important role in soil protection (Table 3.1) because there is not much bare soil left which needs additional soil conservation measures.

In the smallest plots (25 m^2), we did not only measure lower water infiltration rates than in the larger plots (400 m^2), but we also found a negative correlation with ground vegetation cover (p<0.05) in the merged data set. Within the dual-head infiltrometer data set, water infiltrability further increased with increasing litter layer thickness (p<0.1).

The treatment in the smallest plots differed from the larger ones in two main aspects. Firstly, no palms were removed, so no artificial gaps in the canopy were created. Secondly, the subplot borders are identical with the plot borders while in larger plots, the distance between the subplots borders and the plot border (i.e. the fence) amounted to at least one metre. Camargo and Kapos (1995) reported that even though the effects of edges on soil hydraulic properties occur up to 100 m inside of the forest, the immediate edge is most affected due to the direct exposure to outer influences such as wind and solar radiation. In our experiment, the effects of wind and sun on vegetation patterns inside the plots can probably be neglected, but other outside-plot factors such as the prevalence of invasive species like *Clidemia hirta* ((L.) D. Don) may affect vegetation dynamics upon plot establishment. After demarcation and clearing of the experimental plots, invasive species thriving in the surrounding oil palm plantation probably quickly spread into the small plots because most growth conditions, such as light and nutrient availability, were initially similar to those in the plantation. Thus, the introduction of plant species adapted to different habitats such as light-tolerant species, which likely established themselves in parts of the larger plots where gaps were created, was probably much lower than in other experimental plots. Invasive plants such as *C. hirta* usually allocate less biomass to roots than to above-ground biomass (DeWalt et al., 2004). Consequently, a high vegetation cover might not necessarily lead to improvements in soil structure and hydraulic properties. On the contrary, a prevalence of invasive species that are well-adapted to the prevalent environment could result in the repression of other plants, hence creating a relatively homogeneous vegetation structure. Since the rooting system below a homogeneous vegetation is usually not well developed (Kumar et al., 2006), it may not contribute very much to soil structural improvement. A lower ground coverage, however, could then leave more space for more complex tree roots to develop in between the already existing oil palm roots, thus forming deeper channels along which water can penetrate the soil.

The observation that the smallest plots, as opposed to subplots in the larger plots, rarely surpass a ground vegetation cover of 70% (Figure A.5, Appendix A), might explain why litter layer thickness plays a more important role in these plots. A well-established litter cover on the ground reduces the erosive effect of rain drop splash and enhances soil water conservation (Khan et al., 1988; Simanton et al., 1991), particularly when ground vegetation is scarce (Zhongming et al., 2010). Organic litter further provides a source of nutrition for soil fauna communities creating subsurface pore channels which contribute to water flow in the soil (Douglas and Guyot, 2005). However, litter layer thickness does generally not seem to be a decisive factor for soil water infiltrability here. Nevertheless, one should keep in mind that the depth of litter layers is usually highly variable (Vorobeichik, 1995) and thus requires large sampling sizes to obtain reliable data. In our experiment, especially deep litter layers showed large variations among measurements (Table B.1, Appendix B), hence four samples per site may not have been a sufficient number to derive accurate values.

In the largest experimental plots (1600 m^2), we detected no significant differences in water infiltration rates compared to other plot sizes, not even to the smallest plots. Since the numbers of oil palms removed during the establishment of the experiment differed among the plots, particularly among the large ones (Gérard et al., 2017), the sizes of the resulting canopy gaps probably varied as well. Hence, the variability among and within the large plots might be too high to allow for the detection of distinct trends valid for the whole group. Furthermore, one should keep in mind that the subplot locations within the plots were determined randomly. As a result, some subplots were located close to the plot edge, even in large plots, and might thus be exposed to similar conditions like the smaller plots. For assessing whether larger-sized plots affect soil hydraulic conductivities, consistent measurements in the plot centre might therefore be more revealing.

4.4 Tree species diversity level

In the merged data set, our results show higher water infiltration rates in plots with three planted tree species than in the plots where no trees had been planted ($p<0.1$) and a general trend of increasing water infiltration with a larger number of planted trees is visible as we hypothesized (Figure A.1. Furthermore, we detected a negative correlation between water infiltration rates and stand structural complexity in plots without planted trees ($p<0.05$), while at higher diversity levels they remained stable (one or two planted tree species with $p<0.05$ each) or increased (three planted tree species, $p<0.1$). Within the most species-rich category of six planted tree species, no statistically distinct trend was observed.

Stand structural complexity was developed as an indicator for vertical diversity based on the number of vegetation layers and their respective fractal dimensions (Ehbrecht et al., 2017). Where no trees were planted, individual palms were still removed in larger plots during the experimental set-up. The newly available space and light not occupied by palms or planted trees could be occupied by other plants. Such gap-occupying pioneer species are often shrubs and light-tolerant tree seedlings (Otsamo, 2000). As pioneer species usually invest more energy in above-ground material than in below-ground biomass, particularly when there is a lot of competition with other plants (DeWalt et al., 2004), a high complexity of a pioneer-dominated vegetation might lead to an even more pronounced allocation of biomass to above-ground biomass in order to be able to secure access to sunlight. Such dynamics may result in a relatively poorly developed rooting system providing less sub-surface pathways for water moving through the soil than below a more homogeneous ground vegetation where access to sunlight could be achieved with less effort, leaving capacities for the development of roots.

In three-species plots, on the other hand, the opposite trend was observed. Here, increasing vegetation complexities had a positive effect on water infiltrability. All planted tree species are light-tolerant to different degrees (Teuscher et al., 2016) but they are not necessarily pioneer species as well. With each tree species adapted to a different ecological niche, they are more likely to complement each other instead of competing for available light (Kohyama, 1993). An increasing number and complexity of canopy layers could thus suggest more diverse habitat requirements of the assembled tree species, e.g. one species tolerant to direct sun exposure, one species preferring lower exposure, and one species tolerating shaded conditions relatively well. In case of reduced above-ground competition, below-ground competition for nutrients and water are possibly more pronounced, encouraging the development of complex rooting systems which facilitate water movement through the soil. Nevertheless, planting a combination of three tree species already increased soil water infiltration as compared to experimental plots without trees, and this trend was independent of the above-ground vegetation structure. Four years after the tree planting, the rooting system below combinations of this specific selection of tree species thus seems to be sufficiently complex to improve the soil structure and noticeably increase its water infiltrability.

Moreover, an increased tree species diversity supports the establishment of a higher diversity of invertebrate species feeding on residual organic matter. Litter heterogeneity supports the creation of many different micro-habitats and leads to balanced nutrient availabilities both of which are crucial for the establishment of diverse consumer communities and the enhancement of microbial activities. Leroy and Marks (2006), for instance, reported that leaf mixtures from different tree species lead to higher litter decomposition rates than in litter originating from one tree species only. High soil fauna activities in turn result in a higher input of organic material to the soil which promotes soil porosity and water infiltrability (Bonell, 1998; Wallace et al., 2005).

Interestingly, our results further suggest that durian trees (*Durio zibethinus* L. ex Murray) are particularly effective in restoring soil hydraulic properties. In those experimental plots in which only durian was planted water infiltration rates were significantly higher than in plots enriched with monocultures of other tree species ($p<0.05$ in the dual-head infiltrometer data set and $p<0.1$ in the merged set, Figure A.2 in Appendix A). Masri et al. (1998) reported that already in early growth stages, durian develops an extensive rooting network with both a longer taproot and a larger number of lateral roots than other tropical fruit trees. As most broadleaf tree species, especially in wet climates, initially grow a deep taproot to enhance the tree's stability and ensure access to the groundwater before developing a complex rooting system (**weber2005roots**; Köstler et al., 1968; Schenk and Jackson, 2002), the early and extensive development of lateral roots in durian likely plays a more important restorative role. Lateral roots may not only enhance the connectivity and complexity of below-ground water pathways but also protect the soil by reducing topsoil erosivity. Since in the tropics, the root : shoot ratio of trees is usually relatively low (Schenk and Jackson, 2002), the allocation of more resources to the below-ground biomass could have a strong effect on the establishment of an improved soil structure.

Generally, however, planting only one or two tree species does not seem to be enough to measurably improve soil hydraulic properties within four years. In one- or two-species plots, a higher density of each respective species was planted. Since all individuals of one species strive towards niches particularly suitable for this species' growth, there might be more competition among individual trees of the same species than among individual trees of different species. Furthermore, each tree species develops its rooting system differently in time and space (Masri et al., 1998). A less species-diverse vegetation might therefore lead to less complex roots below-ground as well as to lower micro-fauna activities (Leroy and Marks, 2006), both resulting in reduced soil porosity and water infiltrability.

The highest tree species diversity level (i.e. six species), however, did not show significant differences in water infiltration rates from the oil-palm plots (Figure A.1, Appendix A) nor is there a correlation between stand structural complexity and water infiltration rates. In fact, measured infiltration rates in these plots are considerably lower than in plots in which one, two or three tree species had been planted (Figure A.1, Appendix A). Six planted tree species possibly create dynamics too complex or fluctuating to derive noticeable trends after only a few years. It should also be kept in mind that there are altogether only four experimental plots for this diversity level, and it is therefore difficult to derive reliable and representative results from them. The latter is particularly challenging in our case because one out of these four plots was sampled with the dual-head infiltrometer and the remaining three with the double-ring infiltrometer, hence creating further potential sources of error.

4.5 Bulk density

Low bulk densities result from a high abundance of pore spaces in the soil which facilitate the penetration of water. Therefore, we expected a strong negative correlation between bulk density and water infiltration rates. However, we did not detect any statistically significant relationship between these two factors and thus rejected our hypothesis. Bulk density values for each subplot were averaged based on five measurements spread on a systematic grid across the subplot (Henning, unpublished data) while water infiltration rates were determined only in one spot per subplot. Our results therefore suggest that there is a high spatial variability of soil physical characteristics even within the relatively small subplots. This interpretation corresponds with our observation of six measurements in plot P23 which were systematically distributed on a grid and cover almost the entire range of measured water infiltration rates (Figure 3.2).

Due to the high frequency of research activities conducted in the subplots, paths are established, the vegetation is disturbed, and various additional micro-habitats, e.g. below litter traps, are formed which are more densely distributed in the subplots than in the remaining plot areas. Thus, samples from sites arranged in a systematic grid within the subplots are likely more suitable to capture the variability inside of the subplots as they may fall onto paths or spots below litter traps. However, capturing the latter might also make the detection of tree enrichment effects on soil porosity difficult as compacted soil on paths will increase the mean subplot bulk density while measurements from relatively protected soils below litter traps might reduce the overall average. Our sampling design that targeted least disturbed soils within the subplots did not account for these variabilities. Apparently, these differences in the sampling designs had such a pronounced effect on the respective results that no correlation could be found whatsoever.

4.6 Complementary plot characteristics

Even though most of the complementary site characteristics seemed to have an impact on water infiltration in certain plot size and tree species diversity levels, none of them alone explained much of the variability within the data (Table 3.3). Some site factors, such as canopy closure, may even have adverse effects depending on other plot characteristics. Thus, we reject the hypotheses that litter layer thickness, ground vegetation cover, stand structural complexity, and canopy closure generally have a positive effect on water infiltration rates.

4.7 Time-scaling

After forest conversion to pasture or cultivated land, the recovery of soil water infiltrability requires the abandonment of grazing and agricultural activities for at least one decade (Hassler et al., 2011; Zimmermann and Elsenbeer, 2009; Zimmermann et al., 2010). Even though water infiltration rates in our study have not yet achieved the pre-disturbance level of forested land, the soil below oil palms enriched with three planted tree species approached dimensions reported from rubber-based agroforestry systems in the same region (Tarigan et al., 2018) already four years after planting. This effect occurred despite of continuing management activities, such as harvesting, in the plots. These results suggest that planting combinations of at least three native tree species within oil palm monocultures has the potential to considerably speed up soil restoration processes, specifically in regard to hydrological functioning.

4.8 Conclusions

Our results show that tree enrichment can be an effective measure to restore soil hydraulic properties in intensively cultivated agricultural systems such as oil palm plantations already after a relatively short period of time. Both planting trees and banning grazing and weeding activities strongly contribute to soil restoration. Hereby, combinations of at least three different tree species appear most effective. Among the tree species tested in our experiment, *D. zibethinus* showed particularly high water infiltration rates. Furthermore, light conditions and available space in tree islands of 400 m^2 size seem to suffice for the establishment of a vegetation cover which enhances water infiltration.
Based on these findings I conclude that tree enrichment can be an effective measure to restore hydrological functioning in oil palm plantations. If a valuation of associated ecosystem services, such as less severe flooding events and increased groundwater recharge, was included in the overall economic assessment of tree enrichment effects, losses from reduced oil palm yields might hence be compensated. Based on such evaluations, recommendations for a sustainable management of oil palm plantations through enhanced biodiversity could be developed and backed up with both ecologically and economically sound arguments.

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A Figures

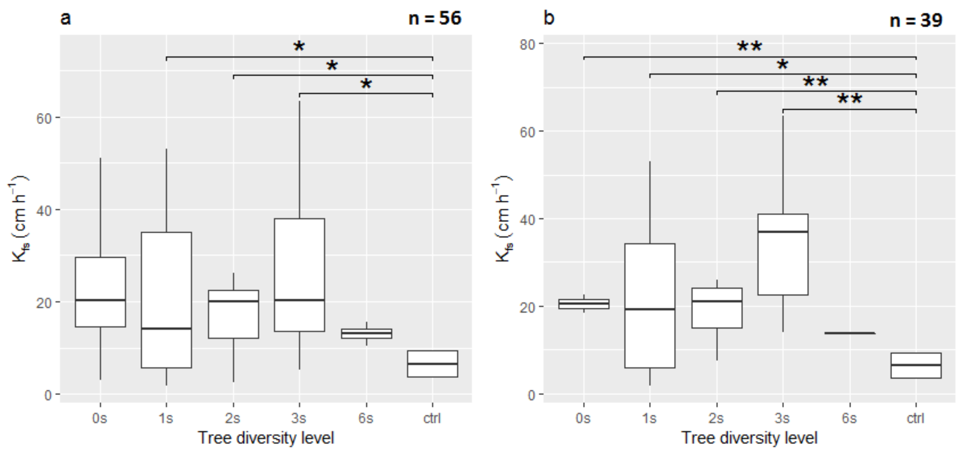

FIGURE A.1: Soil hydraulic conductivity across the different tree species diversity levels in the merged data set (a) and the dual-head infiltrometer data set only (b). ctrl: oil-palm control plots. * refers to p<0.1; ** refers to p<0.05.

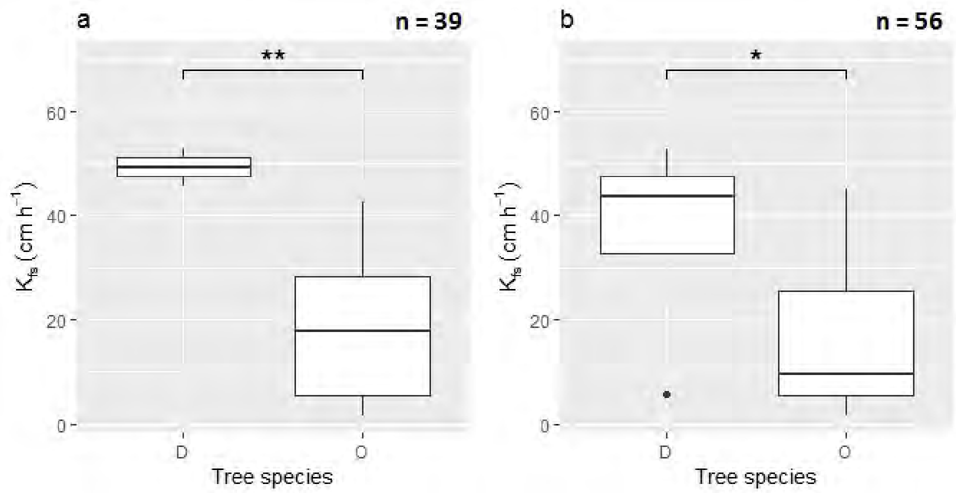

FIGURE A.2: Soil saturated hydraulic conductivity in mono-species-plots with planted *D. zibethinus* (D) and other tree species (O). a: dual-head pressure infiltrometer data set only; b: merged data set. In each boxplot, the median is shown (solid line) as well as the interquartile range represented by box enclosures (first and third quartile) and whiskers, representing the variability outside the upper and lower quartiles (maximal 1.5 times as long as the distance between the first and third quartile); * refers to p<0.1; ** refers to p<0.05.

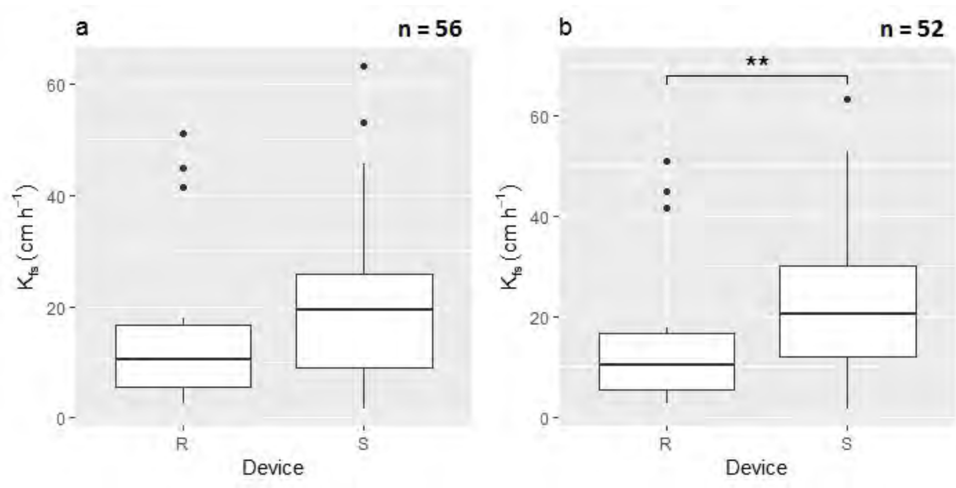

FIGURE A.3: Water infiltration rates measured with the double-ring infiltrometer (R) and dual-head pressure infiltrometer (S). a: including oil palm plots; b: only experimental plots. In each boxplot, the median is shown (solid line) as well as the interquartile range represented by box enclosures (first and third quartile) and whiskers, representing the variability outside the upper and lower quartiles (maximal 1.5 times as long as the distance between the first and third quartile); ** refers to $p<0.05$.

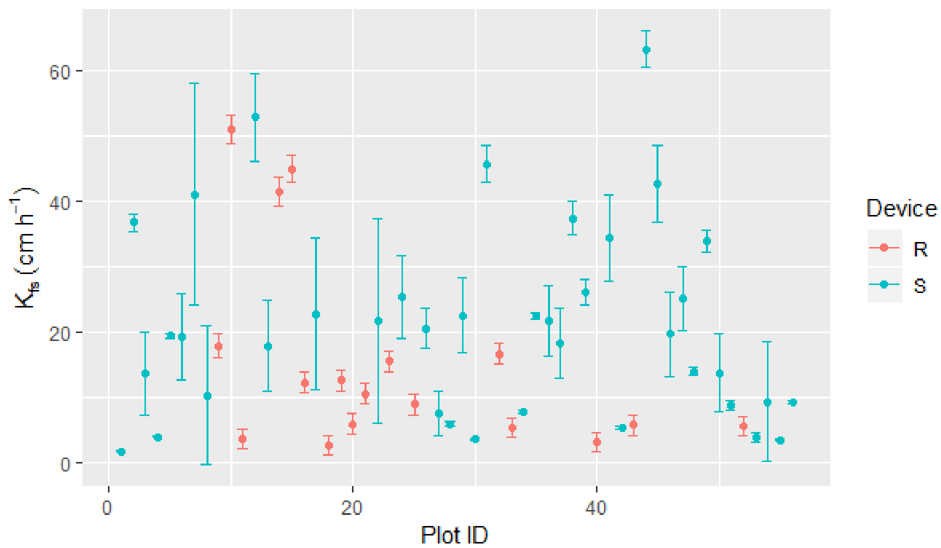

FIGURE A.4: Water infiltration rates estimated with a dual-head pressure infiltrometer (S) and a double-ring infiltrometer (R) with their respective standard errors.

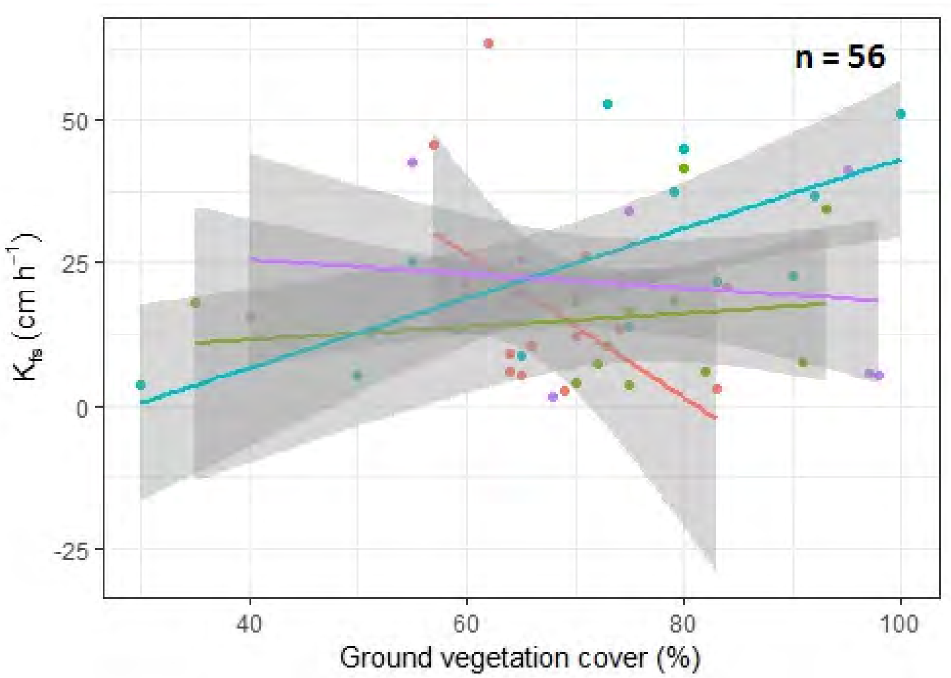

FIGURE A.5: Ground vegetation cover (in %) with regression lines grouped by plot size. Red: 25 m^2; green: 100 m^2, blue: 400 m^2; purple: 1600 m^2.

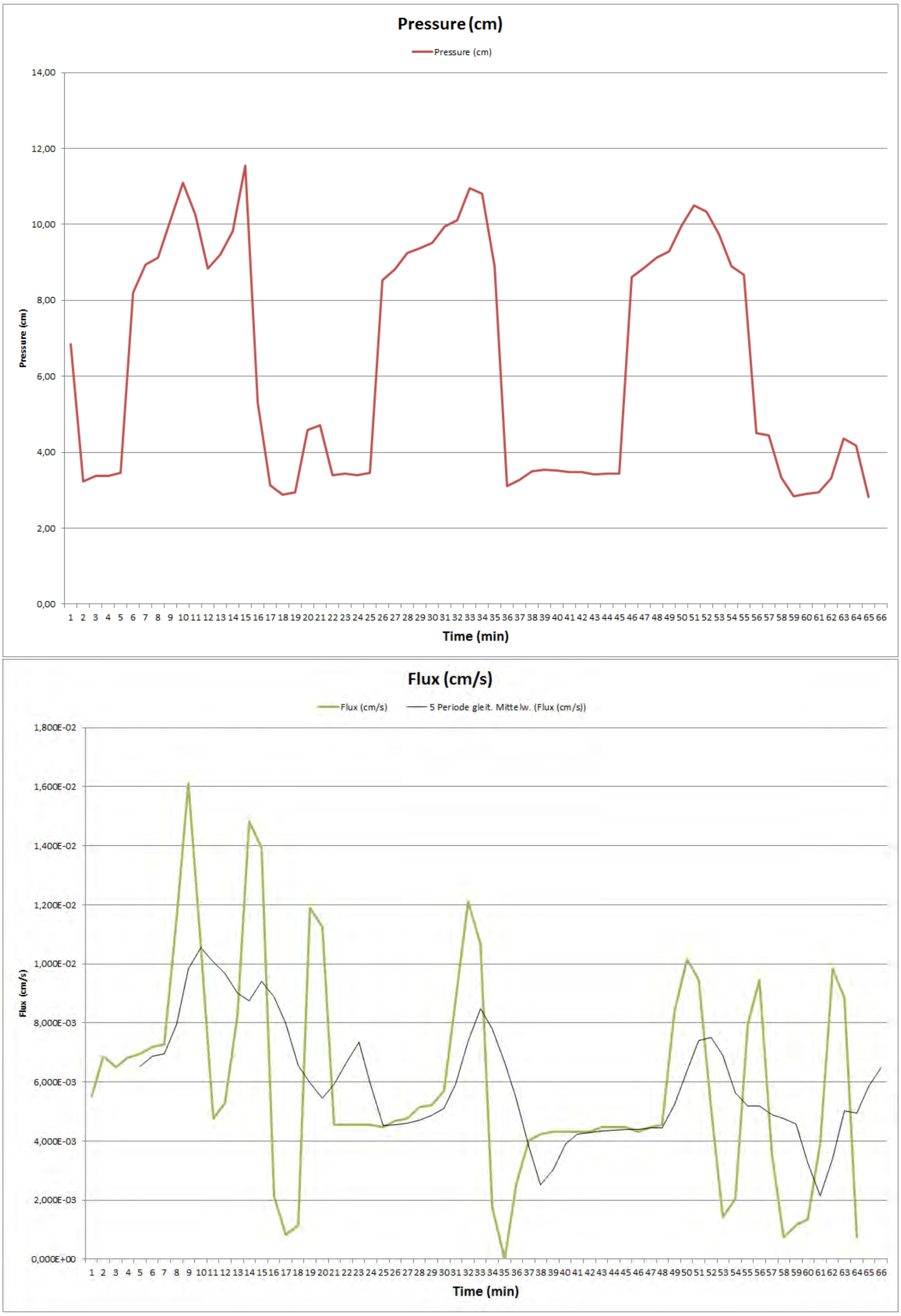

FIGURE A.6: Exemplary diagram showing highly variable water infiltration rates despite relatively stable pressure heads. Obtained from Plot 08. Above: Pressure heads (in cm) over time. Below: Water flux rates (green line, in cm s^{-1}) and the respective rolling means (black line, min cms^{-1})

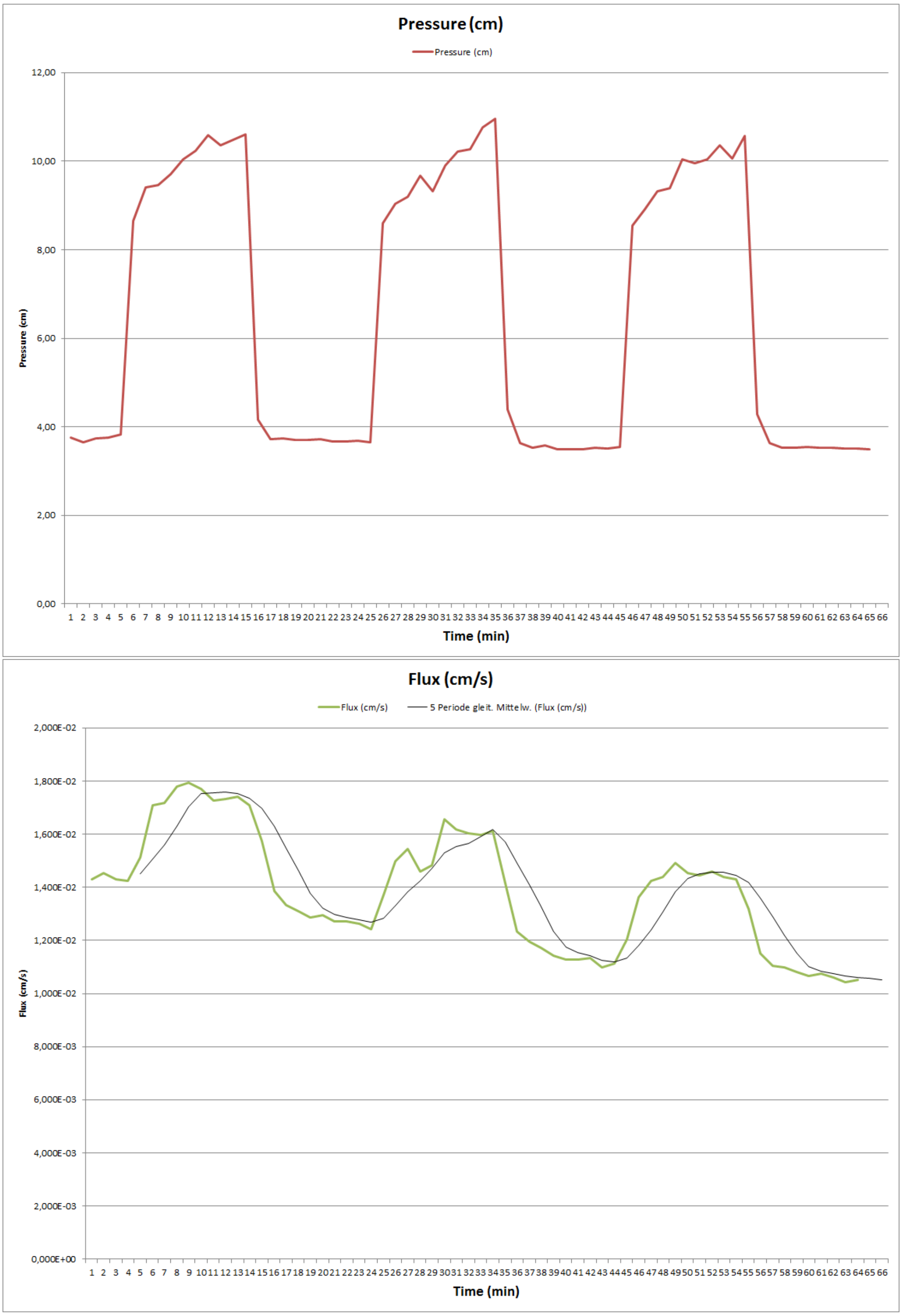

FIGURE A.7: Exemplary diagram showing stable water infiltration rates following the varying pressure heads. Obtained from Plot 05. Above: Pressure heads (in cm) over time. Below: Water flux rates (green line, in cm s^{-1}) and the respective rolling means (black line, in cm s^{-1})

B Data

TABLE B.1: Litter layer thickness (in cm) with four measurements per plot and the respective mean values.

Plot ID	1	2	3	4	Mean	Plot ID	1	2	3	4	Mean
01	1.0	3.0	3.0	4.0	2.75	29	2.0	6.0	3.0	1.0	3.00
02	3.0	5.0	8.0	7.0	5.75	30	0.0	1.0	1.0	2.0	1.00
03	11.0	7.0	6.0	12.0	9.00	31	3.0	8.0	8.0	4.0	5.75
04	4.0	5.0	2.0	1.0	3.00	32	6.0	5.0	3.0	1.0	3.75
05	3.0	4.0	3.0	6.0	4.00	33	3.0	4.0	5.0	0.0	3.00
06	2.0	6.0	4.0	0.0	3.00	34	4.0	10.0	14.0	0.0	7.00
07	9.0	5.0	11.0	7.0	8.00	35	1.0	1.5	0.5	1.0	1.00
08	1.0	0.0	0.0	1.0	0.50	36	1.0	2.0	2.0	1.0	1.50
09	7.0	5.0	3.0	2.0	4.25	37	4.0	3.0	5.0	5.0	4.25
10	2.0	6.0	4.0	4.0	4.00	38	3.5	2.5	2.5	1.0	2.38
11	5.0	3.0	2.0	2.0	3.00	39	1.0	2.0	0.0	2.0	1.25
12	3.0	1.0	0.0	6.0	2.50	40	4.0	2.0	0.0	2.0	2,00
13	4.0	12.0	3.0	4.0	5.75	41	3.5	1.0	3.0	3.0	2.63
14	7.0	7.0	5.0	6.0	6.25	42	1.0	0.0	0.0	2.0	0.75
15	2.0	3.0	4.0	7.0	4.00	43	1.0	3.0	2.0	3.0	2.25
16	2.0	5.0	4.0	0.0	2.75	44	1.0	2.0	3.0	3.0	2.25
17	8.0	5.0	7.0	8.0	7.00	45	3.0	2.0	4.0	3.0	3.00
18	4.0	2.0	0.0	4.0	2.50	46	6.0	5.0	0.0	4.0	3.75
19	7.0	9.0	6.0	6.0	7.00	47	7.0	2.0	3.0	0.0	3.00
20	2.0	1.0	5.0	2.0	2.50	48	4.0	6.0	3.0	7.0	5.00
21	6.0	7.0	5.0	8.0	6.50	49	1.5	2.0	1.5	2.0	1.75
22	3.0	2.0	2.0	0.0	1.75	50	1.0	2.0	3.0	7.0	3.25
23	5.0	4.0	5.0	8.0	5.50	51	2.0	2.0	1.0	1.0	1.50
24	5.0	12.0	7.0	10.0	8.50	52	6.0	3.0	4.0	4.0	4.25
25	4.0	3.0	2.0	2.0	2.75	53	3.0	1.0	4.0	5.0	3.25
26	2.0	1.5	3.0	1.5	2.00	54	4.0	0.0	1.0	2.0	1.75
27	7.0	11.0	5.0	4.0	6.75	55	4.0	8.0	0	0.0	3.00
28	0.0	2.0	2.0	1.0	1.25	56	4.0	2.0	5.0	2.0	3.25

TABLE B.2: Water infiltration rates with standard errors, measured with a dual-head pressure infiltrometer and a double-ring infiltrometer. raw: non-transformed data.

Dual-head infiltrometer		Double-ring infiltrometer		
Plot ID	K_{fs} (in cm h^{-1})	Plot ID	K_{fs} (in cm h^{-1})	K_{fs} (raw) (in cm h^{-1})
01	1.7 ± 0.1	09	17.8 ± 0.6	29.7 ± 1.8
02	36.8 ± 1.4	10	51.0 ± 1.4	89.9 ± 2.2
03	13.6 ± 6.3	11	3.5 ± 0.1	2.5 ± 1.5
04	3.9 ± 0.1	14	41.5 ± 1.2	72.7 ± 2.1
05	19.4 ± 0.3	15	45.0 ± 1.2	77.3 ± 2.1
06	19.2 ± 6.6	16	12.2 ± 0.2	19.5 ± 1.6
07	41.1 ± 16.9	18	2.6 ± 0.0	2.1 ± 1.4
08	10.3 ± 10.7	19	12.6 ± 0.2	19.9 ± 1.6
12	52.9 ± 6.7	20	5.9 ± 0.2	8.1 ± 1.6
13	17.9 ± 6.9	21	10.5 ± 0.3	16.4 ± 1.6
17	22.8 ± 11.7	23	15.5 ± 0.3	25.5 ± 1.6
22	21.8 ± 15.7	25	8.9 ± 0.2	13.6 ± 1.5
24	25.4 ± 6.4	32	16.6 ± 0.3	27.5 ± 1.6
26	20.6 ± 3.0	33	5.2 ± 0.1	6.9 ± 1.5
27	7.5 ± 3.4	40	3.1 ± 0.0	1.5 ± 1.5
28	5.9 ± 0.4	43	5.7 ± 0.1	7.8 ± 1.5
29	22.5 ± 5.7	52	5.5 ± 0.1	7.3 ± 1.5
30	3.5 ± 0.1			
31	45.6 ± 2.8			
34	7.8 ± 0.1			
35	22.5 ± 0.4			
36	21.7 ± 5.4			
37	18.3 ± 5.3			
38	37.4 ± 2.5			
39	26.1 ± 2.0			
41	34.4 ± 6.5			
42	5.2 ± 0.2			
44	63.3 ± 2.8			
45	42.7 ± 5.9			
46	19.6 ± 6.5			
47	25.1 ± 5.0			
48	13.9 ± 0.6			
49	34.0 ± 1.7			
50	13.7 ± 6,0			
51	8.8 ± 0,6			
53	3.8 ± 0,7			
54	9.3 ± 9,2			
55	3.4 ± 0,2			
56	9.3 ± 0,3			

Eigenständigkeitserklärung

Hiermit versichere ich gemäß § 7 Abs. 5 der Master-Prüfungsordnung vom 23.09.2010, dass ich die vorliegende Arbeit selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

Göttingen, den . . . .

Unterschrift