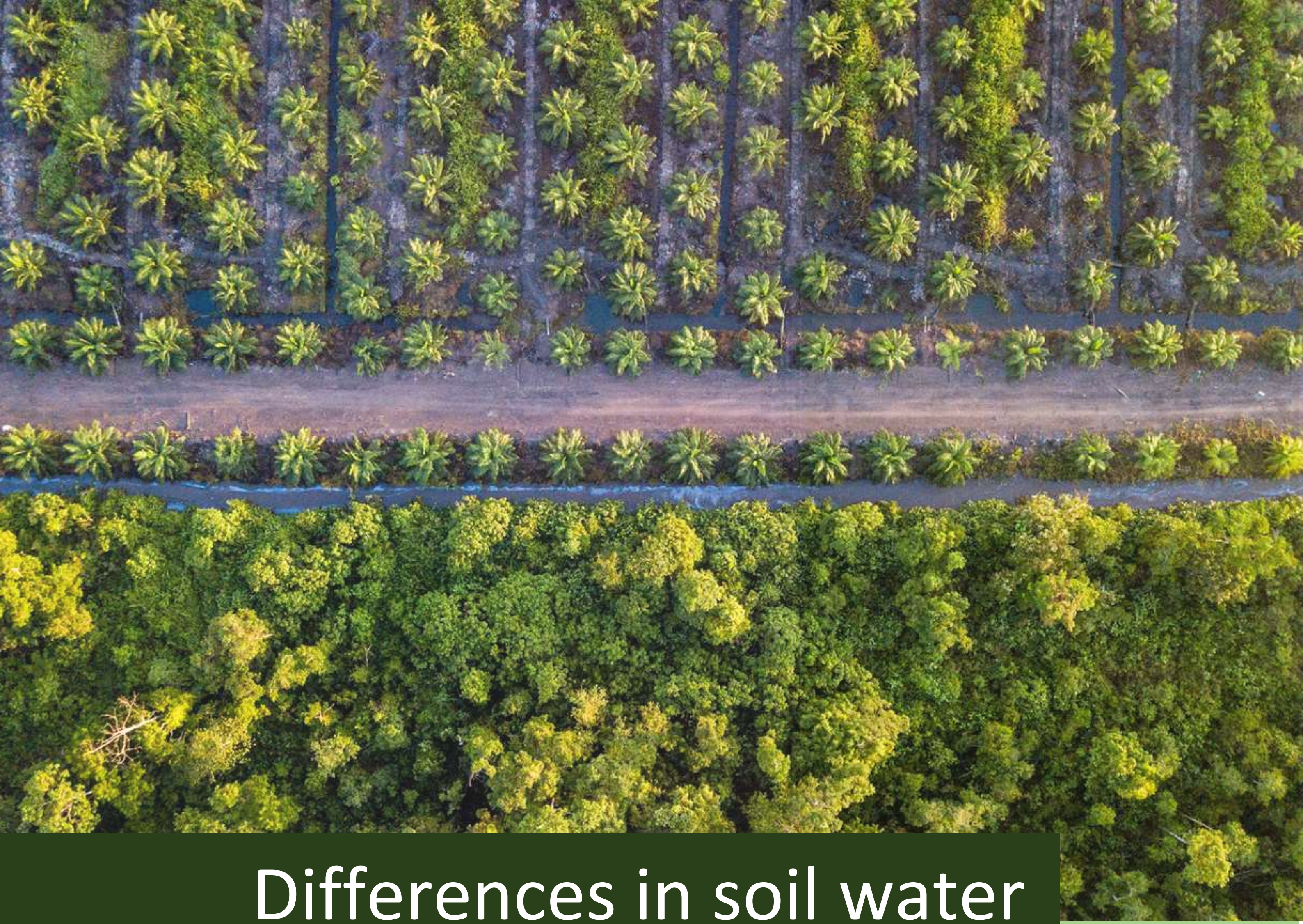

Source: https://ejfoundation.org/what-we-do/forests/ending-deforestation-for-palm-oil

Differences in soil water characteristics of monoculture oil palm plantations, agroforestry oil palm plantations and natural forest

Final
Bachelor thesis

21-08-2022

M. J. van Oosterhout

Preface

In front of you is my final report on the differences in soil-water characteristics of mono-culture oil palm plantations, agroforestry oil palm plantations and natural forest, which was written as part of my bachelor study Civil Engineering at the University of Twente. I did this research at University Gadjah Mada, Indonesia, as part of the 'Strategi Jangka Benah' team. In this thesis the soil water characteristics for different land use types have been investigated. I hope the outcomes of the result can be used to create more insight in the differences on soil water characteristics between different land use types and later their influence on vegetation and climate, so a more productive and sustainable way of food production can be implemented all over the world.

Looking back at the past three months, I can say I have learned a lot. Not only on the theoretical side of this research, but also on more practical sides: how to conduct field work, working in a lab, being part of a team, and experiencing a different culture.

Even though the research is an individual project, I could not have succeeded without the help of some people. Therefore, I would like to express my gratitude to these people. First, I want to thank Martijn Booij for helping me throughout my whole journey. I also would like to thank Hero Marhaento for giving me the opportunity to do my research as a part of the 'Strategi Jangka Benah' team. This is leading me to the next people I want to thank: the 'Strategi Jangka Benah' team. I especially want to thank Stevie Vista for giving me a warm welcome and showing me Indonesia, and Fanny Diah Nigrum for supporting me during the fieldwork. I would also like to thank Ellen van Oosterzee for supporting me regarding the difficult visa application.

Finally, I hope you will enjoy reading my thesis.

Madieke van Oosterhout

11 July 2022, Yogyakarta, Indonesia

Summary

Due to a growing population, more stress is put on food production all over the world. This causes the need for more agricultural land, and more productive agriculture. The first need can result into deforestation all over the world. While the second needs research into how more productive agriculture could be reached. Forest makes place for monoculture plantations, which have a negative impact on the climate and ecosystem of an area. Therefore, more sustainable options should be found for this problem. University Gadjah Mada (UGM) in Indonesia works together with the Kehati Foundation to transform monoculture oil palm plantations in Jambi province, Sumatra, into agroforestry plantations which are expected to have a better influence on the climate and ecosystem. However, this has not been proven yet. Therefore, this research focusses on soil water characteristics, namely water retention curves and infiltration rates, one of the important factors which can help provide more insight in the impact of the change of monoculture plantations to agroforestry plantations, but also the differences compared to natural forest. The impact of these different land uses on the soil-water characteristics can then be linked to the growth of vegetation.

To answer this question, first the research areas were investigated: natural forest, old agroforestry (more than 10 years), new agroforestry (around 2,5 years), and monoculture. Data was gathered on mostly visual features of the different areas like soil colour, vegetation density, organic material in the surface layer and the bulk density. This was done to make a fair comparison between the different land use types and explain the differences between them. From this research there was found that the vegetation density of the forest is the highest followed by the new agroforestry plot. The old agroforestry and monoculture both had a really low vegetation density. This corresponded with the thickness of the organic matter layer which was the largest for the natural forest. The average bulk density was 1,15 g/cm^3 for the natural forest and around 1,56 g/cm^3 for the other land use types. This difference can be explained by the compaction of plantation plots, while preparing or working on the plots.

Two different soil water characteristics were investigated. The first characteristic, water retention curves, was tried to be established by making use of the filter paper method. However, these results turned out to be not useable. This could have been caused by several reasons but based on literature research the unusable results were most likely caused by the use of wrong equipment. For the second characteristic the infiltration rates were determined for the different land use types by using a double infiltrometer. On the measured data an infiltration model was fitted, namely the Horton equation. It was found that there was a lot of variability within one land use type for all land use types, but this variability was hard to explain. The constant infiltration rate for the monoculture and old agroforestry was really low, with means of 0,38 cm/h and 0,56 cm/h respectively. The average constant infiltration rates for the forest and new agroforestry were higher with values of 10,37 cm/h and 5,76 cm/h respectively.

As the water retention curves could not be used, the porosities of the land use types were compared. This showed that both agroforestry plots had the lowest porosity (porosity new agroforestry = 0,28, porosity old agroforestry = 0,29). The monoculture plot had a similar porosity of 0,31, while the forest had a way higher porosity of 0,44. This could be partly explained by the bulk density found. The parameter values of the Horton equation on the infiltration rates, namely the k-value and constant infiltration rate, were compared. A lot of factors can influence the initial infiltration rate; therefore, this factor was not compared between different land use types. For the constant infiltration rate, it turned out there is a significant difference between the values of the forest and new agroforestry and the values of the old agroforestry and monoculture, despite the big variability within each individual land use type. Both the natural forest and new agroforestry have significantly

higher constant infiltration rates compared to the other two land use types. The differences between the old agroforestry and monoculture are not significant. This is the same for the new agroforestry and natural forest. The decay factor gained from the Horton equation was also compared between land use types. For this there was only a significant difference found between the new agroforestry plot and the other three land use types. The decay factor for the agroforestry is lower, which means in general it takes longer for the soil to reach a constant infiltration rate.

The methods chosen and choices made during the project could have influenced the outcomes of the research. One of the points up for discussion is the available data. There was almost no data available on other factors which could influence the ground water characteristics investigated (for example on soil texture, amount of organic matter, etc.), which made it hard to explain the results. Besides, the precision of the double infiltrometer set up and measurements could have given slight deviations in the actual infiltration rates, due to human factors as well by factors caused by the procedure.

Generally, the conclusion can be made that the natural forest has the most optimal soil water characteristics, namely the highest constant infiltration rate and the highest porosity, followed by agroforestry (with new agroforestry having a way more positive effect than old agroforestry). Monoculture as a negative effect on the soil water characteristics investigated.

To further substantiate this conclusion more research into this subject is recommended. Even though the porosity might say something about the water retention curves, more research should be done in the actual water retention curves of the different land use types. Also, more data should be gathered on the different land use types and their features to explain the differences in soil water characteristics. Lastly more data on infiltration rates and water retention curves at other locations outside the research area of this report can be investigated to use the outcomes of the research in a broader scale.

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1 Introduction

1.1 Context

Due to a growing population, more stress is put on food production all over the world (Calicioglu et al., 2019). This causes the need for more agricultural land, and more productive agriculture. The first need can result into deforestation all over the world. While the second needs research into how more productive agriculture could be reached.
Next to non-agricultural factors like infrastructure or mining, agriculture has been the most significant cause of deforestation (Bennett, 2017). Deforestation can be seen in different climate zones but is most common in tropical areas (De Vis, 2006). Deforestation has negative impacts both at a global scale as well as at a more local scale. On a global scale deforestation can be seen as a cause for climate change due to its big emissions when deforesting areas, the smaller capacity of the replacing land use to hold carbon, and increase in temperatures (Longobardi et al., 2016). On a local scale deforestation also disrupts the water cycle as removal of the forest lead to differences in evaporation rates and water retaining properties, which can have direct effects on the deforested area and its surrounding areas. Deforestation also causes other ecological changes, like biodiversity loss and habitat loss (Chakravarty et al., 2012).
As mentioned before the stress put on the agricultural production is also demanding more productive ways of agriculture. Besides, more sustainable ways of agriculture should be implemented, to reduce environmental effects. An approach that is implemented at the moment may address both problems: a more productive agriculture and less environmental impacts caused by deforestation (Retnowati, 2003). This approach is called agroforestry. With this approach trees and other plants will be combined. In this way a more diverse biosystem is created.

Some areas in the world where a lot of deforestation takes place due to agriculture are Borneo and Sumatra, both located in Indonesia (Global Forest Watch, sd). The major cause for deforestation in Indonesia is agriculture with mainly oil palm plantations as driver (Austin et al., 2019). The agricultural sector plays a vital role in the economy (Bashir et al., 2019). This makes sustainable agriculture even more important in these areas. It is important to have the agricultural production as high as possible and keep the ground suitable for agriculture for a long time period.
In Indonesia mostly deforested areas are transformed into monocultural oil palm plantations, which have a bad impact mainly on local, but also on global scale as mentioned before. Strategi Jangka Benah (Corrective Term Strategy) is one of the means offered by the Faculty of Forestry, from the Gadjah Mada University, together with the Kehati Foundation to resolve the problem of monoculture oil palm plantations in forest areas. One of the goals is to transform the monocultural plantations to agroforestry plantations. These are oil palm plantations which are combined with the vegetation of the natural forest around the plantation (Jangkabenah, 2021).
Currently, research is being done by the Gadjah Mada University together with the Kehati Foundation on the differences between monocultural oil palm plantations, agroforestry oil palm plantations and natural forest. One of the research topics that have to be looked into are the soil-water characteristics of the different land uses. Research in this topic will provide more insight in the impact of the change of monocultural plantations to agroforestry plantations, but also the changes compared to natural forest, what it was before and into which it may be transformed later on (Jangkabenah, 2021). The impact of these different land uses on the soil-water characteristics can then be linked to the growth of vegetation. These results may have positive effects for environmental, as well as economical factors. Environmental factors can be positively affected in a way that the impacts or changes in soil-water characteristics caused by deforestation and monoculture in comparison to natural forest may be decreased by implementing agroforestry. This

can result in for example changes in water availability (Clarke, 2020). Economical factors can be positively affected as well when the results show agroforestry has a positive effect on vegetation growth based on the soil-water characteristics.

1.2 State of the art

1.2.1 Soil water characteristics and vegetation growth

As mentioned in section 1.1 there have to be looked into different soil-water characteristics regarding different land use types. As farmers are important stakeholders in this research, it is important to take their requirements into account as well. For farmers it is mainly important for their crops to have a good harvest. Therefore, it is especially important to look into soil-water characteristics that have an influence on vegetation growth.
Plant growth is affected by a lot of factors with water, temperature, light, and available nutrients as the most important ones (Poling, 2021). Water and nutrient availability are both related to soil characteristics. In previous research it has been found that adequate supply of water is one of the most important factors determining yield of oil palm (Henson et al., 2005). This indicates that soil-water characteristics like water retention and infiltration rate are important factors for oil palm yields. This is because most soil functions like regulation of water supplies, functioning as a medium for plant growth, or recycling raw materials, depend directly or indirectly on soil water retention following Rousseva et al. (2017). The soil water retention determines the water availability for plants. The infiltration rate is also an important factor for plant growth. Infiltration rate not only determines the amount of water that will enter a soil, but also the entrainment of nutrients and pollutants dissolved in it (Kirkham, 2014). The state of the art for both characteristics, and the characteristics regarding different land uses and more specifically for oil palm plantations in Indonesia will be described below.

1.2.2 Soil water retention

Soil water retention is a measure of how much water a particular type of soil can retain. Mostly the soil water retaining properties are shown by using a soil water retention curve. In these curves the relation between the water content and the soil water potential is given. The soil water potential is mostly described in units of pressure. This soil characteristic is of great importance for plant growth and therefore agriculture, because this characteristic is directly connected to the water availability for plants. Plant water availability is the amount of soil water that can be extracted by roots and used for growth (Chon, 2021). The water availability for plants is dependent on the permanent wilting point and the field capacity of the soil. Following from previous research this permanent wilting point is estimated usually around a pF of 4,2 but is dependent on the plant variety. The field capacity value is dependent on the type of soil. For sandy soils this value is mostly estimated around a pF of 2, while for clay soils this is 2,5 (Rai et al., 2017).

Soil water retention depends on a lot of different soil properties and other factors. A fundamental characteristic of soil water retention curves is the difference between fine and coarse textured soils. In Figure 1 the water retention curve for three different soil textures is shown, with the available moisture content for plants. In this figure it can be seen that the water retention depends on the soil texture. Sandy soils retain less water than loamy or clay soils at the same pressure.

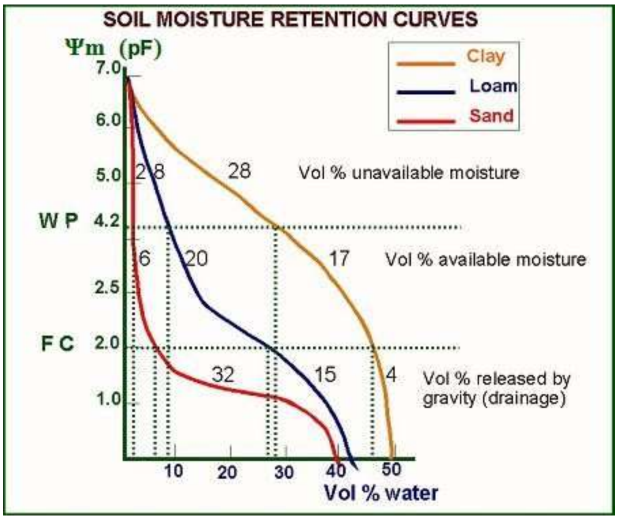

Figure 1: Soil water retention curves for different soil textures (Vittucci, 2015)

Another influence on soil water retention is the soil bulk density. In Figure 2 it can be seen that compacted soil will in most cases have a lower water content. However, for some matric potentials the compacted soil can have a higher water content. For example, in the figure can be seen that a soil with a bulk density of 1,05 g/cm^3 contains more water than a soil with a bulk density of 1,14 g/cm^3 at a low matric potential, while at a higher matric potential the difference is becoming really small and at some point the water content of the more compacted soil with the higher bulk density is even bigger than the soil with a smaller bulk density at the same matric potential (Oschsner, 2017).

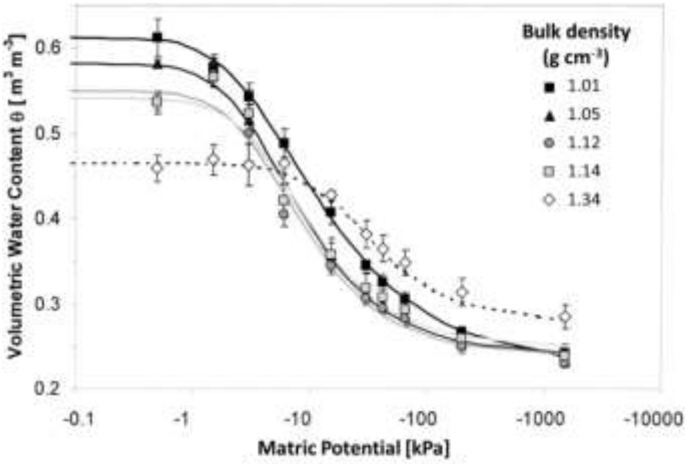

Figure 2: Soil water retention curves for different bulk densities (Ochsner, 2017)

Only little research has been done into the differences in soil water retention for different land uses. In Sollen et al. (2020) the focus is on agricultural practices mainly in Europe. This paper concludes that agroforestry improves the water-retaining properties of the soil in comparison to monoculture, because of the increase in organic material. Another research on the differences between agroforestry and monoculture performed by Wang (2017), also indicates that agroforestry results in an increased water retention capacity in the soil, compared to monoculture cropping.
In Bystřický et al. (2017) the soil water retention in mountain and foothill landscapes in Czech Republic was investigated. Bystřický et al. (2017) focussed on two different changes in land use. In the mountains there was a change in land use from forests to monoculture, while in the foothill areas the land use was changed from arable land to permanent grassland. Water retention in the

mountains was locally reduced due to monoculture, where the foothill areas showed an increase in retention capacity.

1.2.3 Infiltration rates

The soil infiltration rate refers to the ability of the soil to allow water to move into and through the soil. This characteristic indicates the amount of water that can enter the soil. The water flowing into the soil also carries nutrients which are needed for plants to grow. The infiltration rate of a soil can be influenced by different factors. Soil texture is one of those factors (Haghnazari et al., 2015). In general, it is stated the finer the soil, the lower the infiltration rate. For example, the constant infiltration rate, which is the rate at equilibrium state, of coarse sands is more than 2,03 cm/h, while for clay soils this constant infiltration rate is less than 0,51 cm/h (Cornell University, sd). Besides soil texture, other factors that may influence the infiltration rate are initial soil moisture content, soil depth, and soil surface roughness (Freie Universität Berlin, sd). But also, the type of vegetation cover, and human activities on the soil surface, which are both linked to land use, can influence the infiltration rate (Sen, 2015).

In Suprayogo et al. (2020) there is focused on agroforestry land uses in Indonesia. From Suprayogo et al. (2020) could be concluded that the conversion from forest to open field agriculture will lead to a decrease in soil hydrological functions related to infiltration, possibly caused by a decrease in soil macro porosity, organic matter content, and increased soil bulk density. A change from high-density forest to land uses with lower tree canopy resulted in a significant decrease in soil infiltration rates. Besides, a comparison between agroforestry and monoculture was made in Suprayogo et al. (2020), who concluded that agroforestry improves the soil infiltration rate compared to monoculture plantations. A study on soil characteristics in agroforestry in China of Wang et al. (2015) also confirmed this statement of agroforestry improving soil infiltration rates.

1.2.4 Soil-water characteristics specifically for oil palm plantations (in Indonesia)

For oil palm plantations (or even more specifically oil palm plantations located in Indonesia) less research has been done into the above-mentioned soil characteristics. Researched performed into this topic and their outcomes are shortly explained below.

Previous research has been done into the ecosystem functions of oil palm plantations compared to natural forest by Dislich et al. (2017). In Dislich et al. (2017) there is focussed on monoculture plantations, as this is the main land use for growing oil palms. The research is focussing on Southeast Asia, which is the same region as where the research described in this proposal will be executed. Therefore, results may be similar. In the research of Dislich et al. (2017) there is focused on a lot of different ecological aspects for both young and mature plantations. All data of the research was gained from literature research. The authors concluded that in comparison to the natural forest the functionality of a lot of factors that play a role in the water regulation and supply in plantation areas decreased for the monoculture oil palm plantations. Focussed on infiltration rates overall the oil palm plantations have a negative effect on this characteristic in comparison to the natural forest. However, this is strongly dependent on the location and soil type of the compared area.

Another research conducted into mitigation options for improving the ecosystem function of water flow regulation is Tarigan et al. (2016) which also focussed on oil palm plantations. In Tarigan et al. (2016) the soil infiltration rates were determined by using a double ring infiltrometer. Different land uses were compared for areas located in Jambi province, Indonesia. In this area the main soil type is Acrisols, which are clayey soils also known as Ultisols (Adams et al., 2019). Tarigan et al. (2016) found infiltration rates for oil palm monoculture of 3 cm/h and for forest much higher with a value of 47 cm/h.

1.3 Research gap, research objective, questions, and scope

Research gap

In section 1.1 the context and importance of the problem regarding deforestation, monoculture and the change to oil palm plantations are stated. In section 1.2 the current knowledge on the topic gained by research is given. In this section it is becoming clear that there is a lack in knowledge on the specific soil water characteristics water retention and infiltration rate of forest and oil palm plantations and its different forms: monoculture and agroforestry. In the research by Dislich et al. (2017) and Tarigan et al. (2016) on oil palm plantations there is only focused on one of the mentioned characteristics, namely infiltration rate. However, this is only studied for monocultural oil palm plantations and its differences with natural forest. This means research into agroforestry oil palm plantations and water retention curves for all three land uses still need to be done to fill this research gap.

Research objective

The objective of this research is to determine and explain the differences in soil-water characteristics between mono-cultural oil palm plantations, oil palm agroforestry, and natural forest in Indonesia.

The soil water characteristics that are selected are characteristics that are relevant for vegetation growth. The purpose of the Strategi Jangka Benah is to restore the ecosystem as much as possible. The selected characteristics may contribute to this significantly due to their relation with vegetation growth. Improving these specific characteristics may cause a quicker restoration of natural vegetation and with that a more natural ecosystem. Besides, a current problem with agroforestry land use for oil palm plantations is that plantation owners think that a switch from monoculture plantations to agroforestry will lead to less harvest (Spos Indonesia, 2019). The outcomes of this research can scientifically substantiate if this is the case, based on the soil-water characteristics investigated. The soil-water characteristics that will be considered are:

- The water retention curves of the soils and;
- The infiltration rates of the soils

Research questions

To meet the research objective the following research questions need to be answered. To answer the research questions the sub-research questions underneath the main research questions need to be answered. The research questions are:

1. ***What are the features of the different research locations that can influence the soil-water characteristics of that area?***

2. ***What are the soil-water characteristics of monoculture oil palm plantations, agroforestry oil palm plantations and natural forest in the research area?***
    2.1 What are the water-retention curves for monoculture oil palm plantations, agroforestry oil palm plantations and natural forest in the research area?
    2.2 What are the infiltration rates for monoculture oil palm plantations, agroforestry oil palm plantations and natural forest in the research area?

3. ***What are the differences in soil-water characteristics between monoculture oil palm plantations, agroforestry oil palm plantations and natural forest in the research area?***
    3.1 What are the differences in water-retention curves between monoculture oil palm plantations, agroforestry oil palm plantations and natural forest in the research area?

3.2 What are the differences in infiltration rates between monoculture oil palm plantations, agroforestry oil palm plantations and natural forest in the research area?

The research questions need to be answered in the order they are stated. The last question will provide the answer to the research objective.

Scope

The research needs to be executed in a limited time frame at a certain location. Due to this it is important that the scope of this research is being made clear. Therefore, there is only looked into the two soil-water characteristics related to vegetation growth mentioned before: water retention curves and infiltration. For example, the soil composition regarding organic matter or minerals available in the soil, which influence plant growth and the results of the above-mentioned characteristics, are not being investigated.

The number of samples that need to be taken and the number of measurements that need to be done in order to get representative and accurate results, which suits the purpose and answer to research question 1, can be really big. Due to a limited time frame the number of measurements is set to a fixed amount. This is also done for the sample depth, which is set to a fixed depth. The depth and number of samples are explained in sections 2.2 and 2.3.

As already mentioned in the state of the art (section 1.2), a lot of factors can influence the results on the water retention curves and infiltration rates. However, on these factors, like soil texture, amount of organic matter and so on, almost no information is available for the research area. There cannot be assumed that these features are completely the same for all land use types. Therefore, these characteristics were investigated by looking into literature and the visual characteristics of the soil in the field, which results are given in chapter 3. Due to time limitation and some other unexpected circumstances during the research, this could only be done visually and no qualitative data was gathered on this. This means these factors cannot (completely) be used to explain the results.

The research will be performed on different land use types in Jambi province, located on Sumatra, Indonesia. This indicates that the results of the research may present suitable outcomes for this area and possibly for areas with similar characteristics (similar soil types, climate, etc.). Due to a limited time frame, other areas are not considered in this research.

The water retention curve is dependent on the wetting and drying conditions of the soil (Dohnal et al., 2006). For this research the results are limited to only giving the water retention curves for the drying soil.

2 Methodology

In this chapter the methods for answering the research questions mentioned in section 1.3 are stated. Per research question a step-by-step approach is described and the choices made are described.

2.1 Features of the different research locations

In section 1.2 a lot of factors are described, which can influence the infiltration rate and soil-water retention curve of a soil. In this study the focus is on the influence of different land use types on the soil water characteristics. This means other factors not related to land use type should be kept constant or as similar as possible at all locations to make a fair comparison between the different land use types. According to Vittucci (2015) and Haghnazari et al. (2015) both the water retention curve and infiltration rate are dependent on soil texture. Schwyter & Vaughan (2021) also indicate that the slope of an area may influence the soil-water characteristics investigated. Sen (2015) mentions vegetation type and human activity also have an influence on the infiltration rate. Therefore, there was also looked into those characteristics of the research areas.

The exact research areas were determined while doing the fieldwork. During the field work data was collected on the land use, vegetation, slope, and soil of the areas. This information is mostly visual information. Data collected on the land use was mostly gathered by interviewing plantation owners and using the already collected data from other projects: SJB (2021). For the vegetation there was visually looked at the vegetation density and diversity. Data on the slope was collected from Topographic-map (https://en-gb.topographic-map.com). Data on the soil was divided into different categories: soil colour, organic layer, and bulk density. The colour of the soil was visually found during the field work. For the organic layer there was mainly focussed on the organic material on the soil surface. The depth of this material was measured with a measuring rod. The bulk density of the soils was determined by oven drying the soil samples which were collected for determining the water retention curve. The depth and measurements for collecting these samples will be described in section 2.2. The samples were dried at a temperature of 80°C for 24 hours (O'Kelly, 2005). This temperature was chosen to prevent burning of the organic matter in the samples. The height and diameter of the cylindrical rings in which the samples were taken, were measured in advance and were used for determining the volume of the soil. After that the mass of the oven dry samples was determined. Equation 1 was used for determining the bulk density of the soil (Brown & Wherrett, sd):

$$D = \frac{M_{s\,(od)}}{V_s} \qquad \text{Equation 1}$$

In which:

- D is bulk density (g/cm^3)
- $M_{s\,(od)}$ is mass of the oven dried soil (g)
- V_s is the volume of the soil (cm^3)

2.2 Soil water retention curve for different land use types

For determination of the soil-water retention curves the filter paper method was used. This method has a lot of advantages because of its simplicity and its ability to measure a wide range of suctions (Leong et al., 2002).

The filter paper method makes use of filter paper of which suction characteristics are known. This paper is placed on top of soil samples with a specific water content till an equilibrium between the filter paper and soil samples is reached. By measuring the amount of water, the filter paper has absorbed and by making use of the calibration curve for translating the water content of the filter paper into suction, the water retention curve can be established.

The steps for answering this sub-question are:

1. Collecting samples
2. Determine the water content
3. Execute filter paper method
4. Curve fitting

1. Collecting samples

First the samples were collected for all different land use types. In order to get accurate results, enough measurements should be done on the water retaining properties of the soil of a specific research area. Because of the limited time frame, the measures were executed on different samples, this means for each water content needed to establish the water retention curve a different soil sample was used. This can give a deviation in the results of the water retention curves, as there can be spatial differences between the different samples. This can result in a higher or lower suction in comparison to the actual suction value for different samples. The number of measurements that has been done was mostly dependent on the available resources and the time limit of the research. Both Almeida et al. (2015) and Gevaert et al. (2014) indicate that 15 samples should be enough to get adequate results, while the research of Robert et al. (2011) only uses 6 samples to determine the full water retention curve. However, in Pereira et al. (2010) more samples, namely 18, are used to establish the water retention curve. Based on this literature and the available time and resources the number of samples was set to 15 samples per land use type.

The depth at which the samples are taken also plays a very important role in the determination of the water retention curve. This is because it is possible that the soil composition differs per soil depth, meaning the amount of soil organic matter, clay, silt, and sand as well as the presence of minerals at a certain soil layer. According to Sollen et al. (2020) the water retention curve can vary because of differences in organic material. That means the soil-water characteristics can differ per soil depth. Therefore, a fixed depth was chosen to take the samples. Because of a limited time frame, only one soil depth was investigated for determining the soil-water retention curve. Water retention curves gives an indication on the water available for plants. This is the water stored in a soil at a certain depth which can be used by plants. One of the main stakeholders in transformation of monoculture oil palm plantations to agroforestry, are the farmers that own the plantations. The main objective of those stakeholders is a high oil palm production. Therefore, the oil palms need to have sufficient water. That is why there is chosen to determine the water retention curves at the depth of oil palm roots.

Oil palms have a big root system, which shape is dependent on the available water, soil characteristics and the stage of the crops (Safitri et al., 2018). Intara et al. (2018) focusses on the root growth of oil palms in Indonesia. In the research of Intara et al. (2018) there was found that the root system of oil palms could horizontally grow more than 6 meters, and vertically about 1,5 to 5 meters, depending on the soil as also mentioned by Safitri et al. (2018). Most of the roots of the oil palms are located between 0 – 40 cm depth. At this location the roots will subtract a lot of water and nutrients from the soil. Therefore, this is the most interesting as well as feasible depth to take the samples. In Figure 3 an illustration of the root system of oil palms is shown.

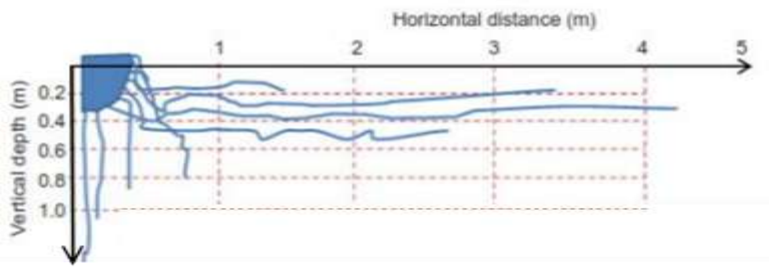

Figure 3: Root system of oil palms (Intara et al., 2018)

Plants that will be placed in between the oil palms to create the agroforestry system are mostly woody plants, like Durian, Sengon, Meranti and Mahoni (SJB, 2021). The root depth of most of these plant species also corresponds with the 0-40 cm depth. To take these root depths into account the soil depth at which the samples were taken is set at a depth between 20 and 30 cm.

The samples were collected using metal cylindrical rings of 5,4 cm heigh and a diameter of 4,9 cm. The cylinders were forced into the ground from a depth of 20 cm representing the soil between 20 and 30 cm. In this way the soil samples remain as undisturbed as possible. However, during the fieldwork there was noticed that forcing the cylindrical rings into the ground may have caused some disturbance in the samples. The samples were collected at different locations in the field which are described in section 3.1. From the field the samples were completely sealed and vertically transported to the lab to prevent any disturbance of the samples.

2. Determine the water content

The next step of this method is performed in the lab. For determining the water retention curves by using the filter paper method, the soil samples need different water contents. As the samples per land use type were all taken at the same location within a short time period of 1 to 2 days, the soils most likely do not differ a lot in water content, therefore the different water contents of the soil samples were adjusted in the lab. For this the formula for determining the volumetric water content was used (Gardner et al., 2000). This formula can be found in Appendix A.

For determining the amount of water that should be added, first the bulk density was determined for all samples (see section 2.1).

To calculate the range of the volumetric water content of the samples, the porosity of one sample was determined. For all land use types one sample was used for this. The sample that was used was the sample with the bulk-density closest to the average and a soil colour similar to the soil colour of the majority of the samples at that location. The porosity can be calculated by using Equation 2:

$$\varphi = \left(1 - \frac{\rho_s}{\rho_p}\right) = \frac{V_p}{V_t}$$ *Equation 2*

In which:

- φ is the porosity (-)
- ρ_s is the particle density of the soil (kg m^3)
- ρ_b is the bulk density of the soil (kg m^3)
- V_p is the pore volume (m^3)
- V_t is the total volume (m^3)

The pore volume was calculated by using the mass of the completely saturated soil. To create a completely saturated soil water was added to the samples and the samples were put into a water bath for 24 hours to let them absorb the water (groundwatergovernance, 2022). After 24 hours it was noticed the soil looked like it was not completely saturated yet, therefore the soil was left into the water for another 24 hours, after which the porosity was determined.

The porosity was used as the maximum water content. Then different volumetric water content values between 0 and the maximum water content value were determined, by dividing the maximum water content by the number of samples. By rewriting formulas stated in Appendix A, Equation 3 was obtained. This equation can be used to determine the amount of water that needs to be added to the soil samples to get a specific water content.

$$V_w = \frac{\theta * M_{s\,(od)}}{\rho_b} \qquad \text{Equation 3}$$

In which:
- V_w is the volume of water that needs to be added (m^3)
- θ is the volumetric water content
- M_s is the mass of the dry soil (kg)
- ρ_b is the dry bulk density of the soil ($kg\ m^{-3}$)

This amount of water was added to the soil samples. As the oven dried samples not all directly absorbed the water, they were set aside for 12 hours to let them absorb the water. For this the samples were wrapped in plastic film. For a few samples it was noticed that there was a small hole in the plastic film due to small roots sticking out the sample or the sharp edge of the sample ring. Therefore, the samples were weighed again after 12 hours to see if the right volumetric water content was created for the samples. This was the case for almost all samples. For the few samples with small holes in the plastic film it was noticed that some water had escaped the sample, therefore a little more water was added to these samples to create the right volumetric water content. This was taken into account when wrapping the samples in the next step to make sure no holes were made in the plastic film.

3. Execute filter paper method

The filter paper method has been applied to the prepared samples. For this the following materials were used:
- Soil samples with different water contents
- Whatman filter paper No. 42
- Plastic film
- Aluminium foil
- Analytical balance (precision of 0,0001 gram)
- Styrofoam box

The procedure for the filter paper method from Almeida et al. (2015) is used but will be explained step by step. First all the mass of all air-dried filter paper sheets was determined. Then a portion of air-dried filter paper was placed directly on the soil with an area equal to the sample. On top of this another portion of filter paper was placed. This is done as the paper in direct contact with the soil serves as protection against impregnation by soil particles to avoid errors of measurement. Immediately after placing the filter paper, the soil was wrapped in plastic film and aluminium foil and was stored in a Styrofoam box to keep the temperature of the samples stable. The samples were set aside for seven days to reach an equilibrium between the moisture content of the filter paper and the soil sample. After seven days the aluminium foil and plastic were removed from the sample. When this was done the upper filter paper was removed from the sample with tweezers to prevent contamination with other substances and was weighted as fast as possible (preferably within 3 to 5 seconds). This process needs to be done within this short time frame to minimize moisture loss or

gain by the filter paper due to exposure to the air. For all samples the weight of the filter paper was also weight after 10, 15 and 20 seconds. This was done to see the decrease in mass of the filter paper over time. This was used to estimate the actual weight of the filter paper when the first measurement could not be executed within the indicated 3 to 5 seconds. This was only the case for 3 samples at which the upper filter paper stuck to the lower one and was not easily removable with the tweezers.
When the wet weight of the filter paper was determined the filter paper was dried in an oven at a temperature of 105°C till the paper was completely dry. After this the paper was weight again to determine the dry weight. This weight was compared to the air-dried weight to see if there was any big difference due to contamination by for example the soil. This was not the case and therefore this mass was used for determining the water content of the filter paper. This was done by using Equation 4.

$$wc_{fp} = \frac{M_{fp,wet} - M_{fp,dry}}{M_{fp,dry}} \quad \text{Equation 4}$$

In which:

- wc_{fp} is water content of the filter paper (-)
- $M_{fp,wet}$ is the mass of the wet filter paper (g)
- $M_{fp,dry}$ is the mass of the dry filter paper (g)

The data gained in this phase was analysed during the next phase.
The porosity value indicates the matric potential with a pF-value of minus infinity.

4. Curve fitting
The gathered data on the water content of the filter paper from phase 3 was first transferred to the corresponding soil suction making use of the equations corresponding to the calibrated Whatman number 42 filter paper given in Equation 5 and Equation 6 (Kim, Prezzi, & Salgado, 2016).

$$For\ wc_{fp} > 45{,}26\% \qquad \log_{10} S = 5{,}327 - 0{,}0779\ (\mathrm{wc_{fp}}) \quad \text{Equation 5}$$

$$For\ wc_{fp} \leq 45{,}26\% \qquad \log_{10} S = 2{,}412 - 0{,}0135\ (\mathrm{wc_{fp}}) \quad \text{Equation 6}$$

In which:

- S is the suction (kPa)

The data points were plotted in a graph against the water content of the corresponding soil sample. The aim was to fit the van Genuchten curve to the data, this was however not possible due to the results of the filter paper method, which will be further elaborated in section 3.2.1.

2.3 Soil water infiltration rates for different land use types

For determining the infiltration rates for the different land use types, a ring infiltrometer was used. For this procedure the following equipment was necessary:

- Double infiltrometer
- Wooden piece
- Hammer
- Stopwatch
- Ruler (and clip)
- Water
- Plastic

For determining the infiltration rates both a double ring as well as a single ring infiltrometer can be used. The procedure of using these different infiltrometers is almost the same. The difference is that the double ring ensures the vertical movement of the water from the inner ring, while with the single ring this water may also partly move horizontally (Lili et al., 2008). Therefore, there was chosen to use a double ring infiltrometer to obtain the results on the infiltration rates for the different land use types.

Infiltration rates are highly variable. To obtain data as closely as possible to the real values, several infiltration measurements were conducted at each location. Burgy & Luthin (1956) concluded that six measurements were needed to be within 30 % of the true mean. Therefore, at least six measurements were conducted at each land use type, which was feasible within the given timeframe and availability of the equipment.

For the research there is only looked into the infiltration rate of the soil. Therefore, the organic material and plants on the surface layer of the soil were removed before placing the double infiltrometer. When the plants and layer of organic matter was removed, first the inner ring was forced into the soil to a depth of around 20 cm by using a piece of wood and a hammer (or big piece of wood to function as hammer). This depth was chosen to be as large as possible as a greater installation depth decreases lateral flow, according to Youngs (1991). After that the outer ring was placed and also forced into the soil. This ring had a smaller height and therefore only could be forced into the ground to a depth of around 10 cm. The hammering of the rings into the soil can still have caused a little disturbance of the soil within the ring. The ruler was attached to the inner ring with a clip to prevent it from moving during the measurement. Then water should be added to the ring(s). First a plastic was added to the inner ring to prevent disturbance of the soil when pouring the water in. After that the water was added to the outer ring and the plastic from the inner ring was removed. At the moment the plastic was removed, the stopwatch was started, and the measurement began.

The method that was used for this research looks at the water infiltrating in the soil during fixed time steps. For these steps the amount of water infiltrated in the soil needs to be noted. The size of the time steps was first set to 30 seconds as in most cases the water infiltrated really fast into the ground during the first time steps. By processing the data, the infiltrated water during the smaller time steps was converted into bigger time steps of 10 minutes to get more accurate results. This was done as later in the process the infiltration rate became really low. A ruler accurate to 0,1 cm was used to measure the infiltration, this meant a decrease in water level in the inner ring less than 0,1 cm could not be measured. This means the calculated infiltration for one step could be equal to zero while it actually is not but is a combination in the decrease of water level of this time step and the next. For each individual measurement there was looked at which time step gave the most accurate results. This was for most cases a time step of 10 minutes. Only for one measurement a time step of 20 minutes was used (C9: Old agroforestry), as the infiltration rate was really low.
More water was added to the inner ring after reading the water level at a certain time step. When the outer ring was getting dry, also more water was added to this ring, this could be done at any time as the water in the outer ring was not measured. After a certain time period, when the soil is (almost) fully saturated the infiltration rate will no longer change. This value for the infiltration rate is called the constant infiltration rate or equilibrium (Gebrekiros, 2015; Eijkelkamp, 2012). When the infiltration rate kept constant for at least 30 minutes, the measurement was stopped.

The data gained from the measurements was plotted in a graph. On this data an infiltration model from the literature was fitted. Following from Návar & Synnott (2000), Horton's infiltration model was proven to give a better correlation compared to other models like Green and Ampt, modified Kostiakov, and Philip. Therefore, the Horton model was chosen. The formula for the Horton equation is given in Equation 7 (Gebrekiros, 2015). The Horton equation is only applicable when the water application is bigger than the constant infiltration rate (Ochsner, 2019). The method that was used to collect the data makes use of this as there was always water present in the double ring infiltrometer while measuring.

$$f_p = f_c + (f_0 - f_c)e^{-kt}$$ *Equation 7*

In which:

- f_p is infiltration capacity (cm/h at any time t)
- f_0 is the initial infiltration capacity (cm/h)
- f_c is the final constant infiltration capacity at saturation (cm/h)
- *k* is soil specific decay constant depending on soil and vegetation (h^{-1})
- t is the time (h)

To check if the Horton curve is representative for the measured data, the correlation between the measured data and the fitted Horton equation is calculated for all measurements.

2.4 Differences in soil water characteristics between different land use types

In research question 2 the soil water retention curves and infiltration rates per land use type were determined. For research question 3 the results are compared to each other and the differences were analysed. This consists out of two parts: comparing the soil water retention curves and comparing the infiltration rates. The method for both parts is explained below.
Unfortunately, the results on the water retention curves were not representative for the actual water retention curves of the soil. However, the porosity of the different land use types is more likely to be representative, even though only one test has been performed on the porosity of the soil. Therefore, only the porosity will be compared between the different land use types. Because only one measurement per land use type has been done on the porosity, no statistical tests were performed to determine if the difference between land use types is significant.
For the infiltration rate the constant infiltration rates and soil specific decay constant (k) are compared per land use type taken the uncertainties and variability into account by using a boxplot, which shows the minimum, maximum, average and 25-75% percentages. Besides the boxplot which visually shows the results, an independent sample t-test has been performed. In this way there was concluded whether the differences between the different land use types are significant. For this Equation 8 was used (Glen, sd).

$$t = \frac{\mu_A - \mu_B}{\sqrt{\frac{\left(\sum A^2 - \frac{(\sum A)^2}{n_A}\right) + \left(\sum B^2 - \frac{(\sum B)^2}{n_B}\right)}{n_A + n_B - 2} * [\frac{1}{n_A} + \frac{1}{n_B}]}}$$ *Equation 8*

In which:

- A represents sample A
- B represents sample B
- μ is the mean of the samples
- n is the number of samples

By comparing the outcome of this formula with the value for the t-distribution corresponding with the degrees of freedom of this experiment, there can be concluded if the difference is significant.

The results of research question 1 are used to explain the differences in soil water characteristics between the land use types.

3 Results

In this chapter the outcomes for each research question are presented and discussed.

3.1 Features of the different research locations

3.1.1 Illustration, location, soil type, bulk density and soil colour of all land use types

The study will focus on the different land use types in Jambi province, a province in Sumatra, Indonesia. In this province three different land use types will be investigated: Monoculture palm-oil plantations, natural forest, and agroforestry palm oil plantations, in which a distinction will be made between new agroforestry plantations (around 2,5 years old) and old agroforestry plantations (more than 10 years old). A picture of all different land use types is given in Figure 4 to illustrate the differences between the land use types. A more detailed description of the different land use types will be given in sections 3.1.2, 3.1.3, 3.1.4, and 3.1.5.

Figure 4: Different land use types

Because of the availability of the locations and the documents required in Indonesia to do research in a certain area, the locations were determined by the university and people from the researched areas (plantation owners and forest maintainers from UGM), based on which locations they thought were most suitable and available for research. All locations are shown in Figure 5.

Figure 5: Research locations Sumatra, Indonesia (Google Maps)

Soil texture data is hardly available. Therefore, the Harmonized World Soil Database (HWSD version 1.2) was used. However, this database is very general and shows only the soil type at a low spatial resolution, while in practice the soil type can differ locally within the bigger selected areas by the data base. In Figure 6 the soil types provided by the data base and the research areas are given.

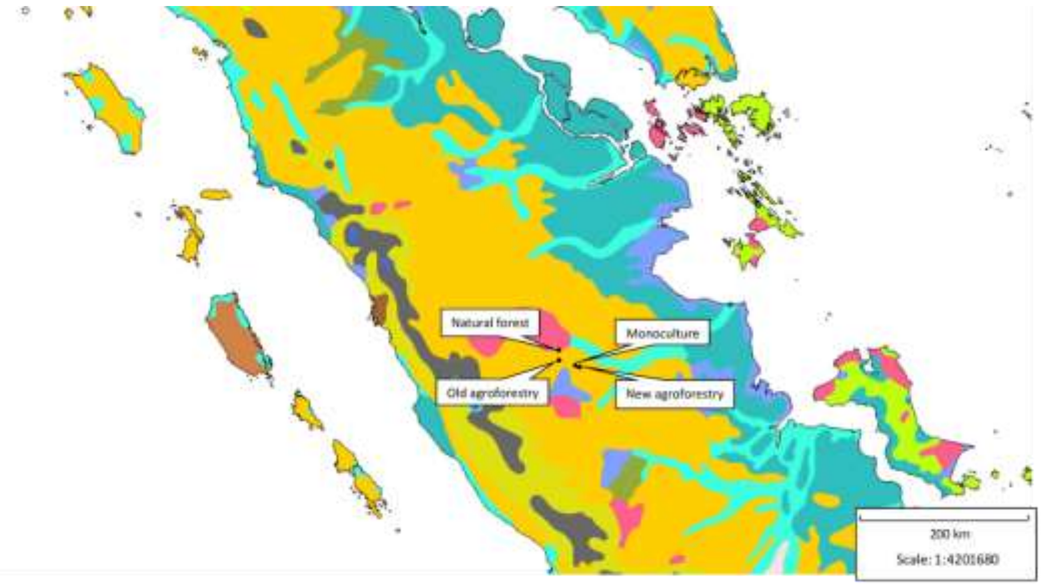

Figure 6: Soil types at the research areas (HWSD version 1.2)

This figure shows that the areas in which the monoculture, new agroforestry, and the old agroforestry plots are located have been characterised as Acrisol (yellow colour in Figure 6), also known as Ultisols. The natural forest is located at a border of this soil type and the soil type Ferralsol (pink colour in Figure 6), also known as Oxisols. In Hansell (1981) the area of the natural forest

consists of a combination of Ferralsols and Acrisols. This indicates the uncertainty of the soil types in the research area.
Even though the soil types are known, the soil texture (percentages of clay, sand, and silt) is not available. The soil types gained from HWSD can give an indication of the soil composition, but within a soil type the composition of sand, clay and silt can still differ (Guitet, et al., 2016). As this factor can influences the results of the water retention curves and infiltration rate for each land use type a lot, the soil should be analysed on the soil texture. However, this is not done for this research and the assumption will be made that the soils are equal for all locations. However, the dry soil bulk density of the different locations was investigated. The minimum, maximum, average, 25th percentile, and 75th percentile of the bulk density per land use type are given in Figure 7.

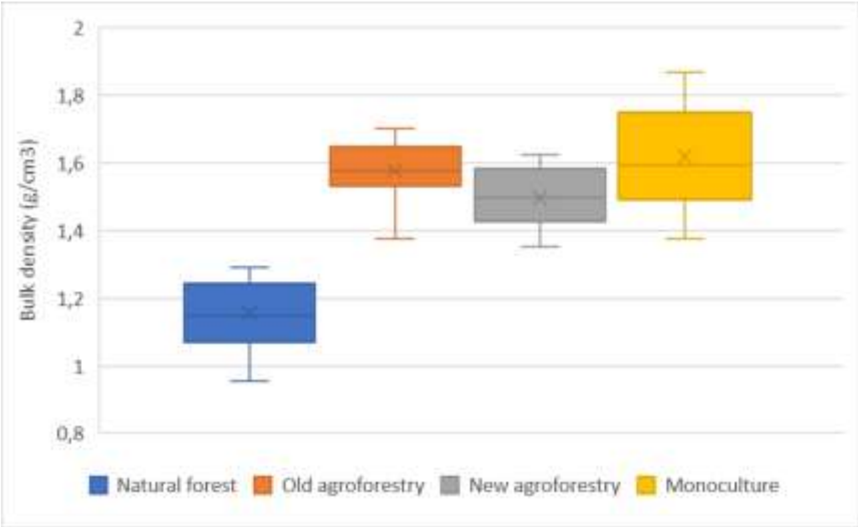

Figure 7: Dry bulk density for the different land use types

In this figure there can be seen that the bulk densities for all plantation plots (old agroforestry, new agroforestry, and the monoculture plot) are similar, while the bulk density of the natural forest is lower. The performed sample t-test (using a significance level of 0,05) also indicates that there is a significant difference between the bulk density of the forest and the other land use types. This difference can be caused by several factors. One of the factors that may have caused the difference is the compaction of the soil. The more compact the soil, the higher the bulk density. This compaction can be caused by soil depth or use of the land. As the samples were all taken at the same depth, the soil depth will not play a significant role in the differences in bulk density. However, the use of the land is different for the forest and plantation plots. The plantations are more frequently used by people and machinery which can compact the soil.
Next to compaction, Chaudhari et al. (2013) indicates the soil bulk density is also influenced by organic matter and soil texture. Chaudhari et al. (2013) concluded that clayey soils tend to have a lower bulk density than sandy soils. The difference in the bulk densities may indicate a difference in soil texture between the different plots. However, this is not investigated and therefore cannot be concluded as a lot of different other factors also play a role in the value for the bulk density of a soil. Chaudhari et al. (2013) also mentioned that an increase in organic matter gives a decrease in the soil bulk density. As it is expected that the forest has a higher organic matter content, this can explain the difference in bulk density. However, the old agroforestry plot and new agroforestry plot are also expected to have a higher organic matter content than the monoculture plot. Though in the figure there is no clear difference between the bulk density of those land use types. Besides bulk density, the organic matter can also influence the water retention curves according to Sollen et al. (2020).
The soil colour is an indication of the minerals and organic material present in the soil (NRCS

Wisconsin, sd). This can be influenced by the land use (Schroeder, 1995). In Table 1 the different soil colours per land use type are given.

Table 1: Soil colour per land use type

Land use type	**Natural forest**	**Old agroforestry**	**New agroforestry**	**Monoculture**
Soil colour at 20 cm depth	Dark brown (some locations have a slight deviation to a more red-brown or lighter brown colour)	Yellow brown	Light brown (some locations have a slight deviation to a more red-brown or more yellow colour)	Light brown ((some locations have a slight deviation to a red-brown or darker brown colour)

Most locations had only one soil colour from the surface until a depth of 20 cm, with some locations with a slightly different soil colour. The old agroforestry plot, however, could be clearly divided in two different layers the upper layer of the soil with a depth from the surface to 8 - 17 cm depending on the measurement location, could be described as a dark brown soil, while the layer underneath has more of a yellow-brownish colour.

Underneath a more detailed description for each land use location is given. A description of the natural forest, old agroforestry plot, new agroforestry plot and monoculture plantation will be given in the sub-sections below. All sections firstly focus on the geographical location of the area including the elevation, second a short description of the vegetation in the area and organic material on the surface layer will be given.

3.1.2 Detailed description of location and vegetation Natural forest

Geographical location

This location is located close to the city of Muaratebo, in Tebo regency and is called Wanagama (see Figure 5). The exact research area and measurement and sample locations can be seen in Figure , in Appendix B. The total area of the natural forest plot covers around 6 hectares. The larger area of the natural forest plot also allows the plot to have more diversity in elevation (see Figure B2 in Appendix B). The height within the plot can vary between 52 m to 58 m above sea level. This was also noticed while doing the fieldwork. The measurement locations (shown in Figure) have been chosen to have (almost) no slope.

Vegetation

Wanagama forest is owned and maintained by the Gadjah Mada University. The natural forest has a lot of diversity in vegetation and the density of the vegetation is very high (see Figure 4a). A combination of young as well as older plants are found in the area. No oil palms can be found in this area. The great diversity and high density of the forest also results in a thick layer of organic material on the soil surface. At each measurement location the depth of this organic material was measured. For the forest this organic material mostly consists of a dense root system of small roots, and plant and animal residues. The depth of this organic material for the natural forest is between 4 and 5 cm.

3.1.3 Detailed description of location and vegetation Old agroforestry

Geographical location

The old agroforestry plot used for the research is located in the village Lembah Kuamang. The plot is located behind some of the houses of the people who own the plantation. As the location is located between several houses the plot sometimes is also used as a way through and therefore the soil can be more compacted by the people frequently walking on the plot. The research area and the exact locations where the samples were taken can be found in Figure in Appendix B. The plot covers about 0,3 hectares. Within this area the elevation height differs from 67 meters above sea-level to 66 meters above sea-level (see FigureB5, Appendix B). This small difference in elevation was not noticeable during the fieldwork.

Vegetation
The old agroforestry plot that was used has been an oil palm plantation for around 15 years. Before the oil palms were planted, the plantation only consisted of Meranti trees. Because the Meranti was already growing on the plot the oil palms were planted in between the Meranti trees, later new Meranti was planted to replace some of the old trees. This however resulted in a not easily to be described plantation pattern. In some areas of the plot most of the vegetation is Meranti and in other parts the oil palm is dominant. Mostly in the north-western part of the plot, Meranti is dominant. On the other parts of the plot more oil palms can be found with some Meranti in between. Overall, the distance between Meranti is 6 by 7 meters, while the space between oil palms mostly is 8 by 7 meters. The space between Meranti and oil palms mostly is also between 6 and 7 meters. On the plot a combination of young and older trees can be found, both oil palms as well as Meranti. This can also be seen in Figure 4b. The organic material on the soil surface of this area mostly consists of dead leaves. This layer of organic material is really thin in comparison to the natural forest. The layer of plant residue that was found in the old agroforestry plot was less than 0,5 cm for all measurement locations.

3.1.4 Detailed description of location and vegetation New agroforestry

Geographical location
The new agroforestry plot is located close to Sungai Jernih in a deforested area with a lot of oil palm plantations. The plot and exact measurement locations can be found in Figure in Appendix B. The total area of the plantation is 2,2 hectares. The elevation of this area 58 to 63 meters above sea-level (see FigureB7 in Appendix B). This difference in height was however not noticeable in the field.

Vegetation
The new agroforestry plantation was started in 2011 as a monoculture palm-oil plantation and was transformed to an agroforestry plantation in 2020. The monoculture plantation started by planting oil palms at a distance of 8 by 9 meters. In 2021 different other trees like Mahoni, Meranti and Sengon were placed in between with a distance of 3 by 3 meters. An example of the plantation lay-out can be seen in Figure in Appendix B. In between the planted trees and oil palms there is a lot of other vegetation. These are mostly small plants that are growing to a maximum of 0,5 meters above the ground. The diversity of these plants is not really big, but there is a high vegetation density in the area, see Figure 4c. The organic material on the surface level of the soil consists of small roots from the plants growing above the soil and some plant residue. The roots of the plants growing on top do not reach very deep and there are not much dead leaves, etc. on the soil surface, so the depth of the organic material (not taking the heights of the plants into account) for the new agroforestry plot is only less than 1 cm.

3.1.5 Detailed description of location and vegetation Monoculture

Geographical location
The monocultural plantation is located in the village of Sungai Jernih, see Figure 5. The total area of the monoculture plot is around 1,5 hectares. The measurement locations are spread over the plot and can be found in Figure B9 in Appendix B. In the area there is almost no slope as the elevation in the field is 38 to 39 meter above sea-level (see Figure B1117B11 in Appendix B).

Vegetation
At the monoculture plantation the vegetation diversity and density are really low. Oil palms are planted in a pattern of 8 by 9 meters. In between the palms grass is growing, but no more vegetation

is present in the area (see Figure 4d). The organic material on the soil surface is therefore also not much, only grass and its small roots. This is at all measurement locations less than 0,5 cm (not taking the height of the grass into account). No more organic material can be found in this location on the soil surface.

3.2 Soil-water characteristics of different land use types

3.2.1 Water retention curves

In this section the results of sub-question 2.1 are given, which is: "*What are the water retention curves for monoculture oil palm plantations, agroforestry oil palm plantations and natural forest in the research area?".* For answering this question, the method explained in section 2.2 was used. However, the results turned out not as expected. Figure 8 shows an example of the graph in which the suction measured by the filter paper is plotted against the corresponding soil water content. In this graph there can be clearly seen that the filter paper only measured around 2 suction values: 5,32 pF and 2,37 pF. This was the case for all land use types. Due to these results, no conclusion can be made on the water retention curves of the different land use types. The graphs for the other land use types are given in Appendix C.

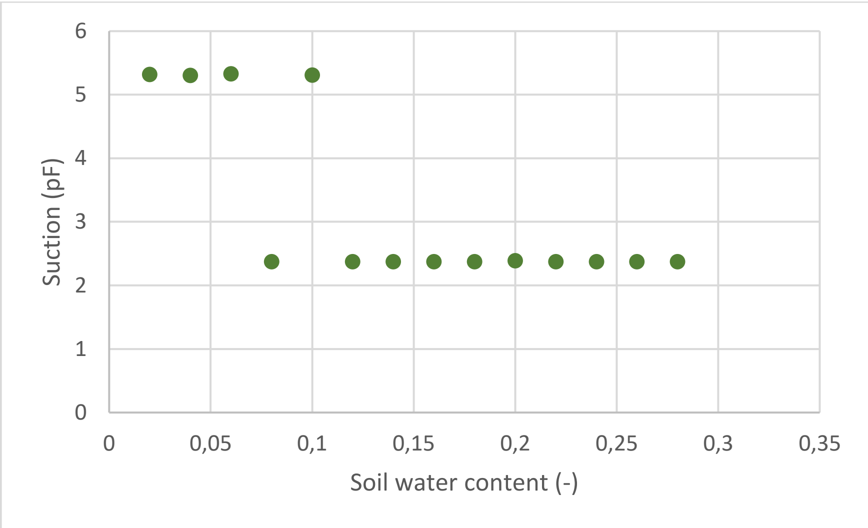

Figure 8: Soil water retention curve Monoculture

Possible explanations for these strange results were investigated by doing literature research and evaluating the procedure executed. An option which in this case looks like it may explain the results best, is the use of equipment. The main equipment used for this research is the Whatman filter paper no. 42. When a wrong/not certificated version of this filter paper was used, the results would most likely be different from results using the certificated paper. However, this cannot be concluded for certain, as it cannot be checked if the used filter paper is the real Whatman no. 42 filter paper. For this the time, equipment and knowledge are not available. Another less likely option is a wrong equilibrium time. Following Suits et al. (2008) the equilibrium time is a factor that can influence the outcomes of the filter paper test. The samples were set aside for 7 days, which was prescribed by the ASTM D-5298-93 standard (Almeida, et al., 2015). Following from Al-Khafaf (1972), an equilibrium is in most cases reached way sooner (certainly after 5 days). This indicates that the equilibrium time most likely did not cause the strange results. The calibration curve of Whatman No. 42 filter paper was determined at 10°C, 25°C, and 50°C (Haghighi, et al., 2012). The temperature of the samples while setting an equilibrium was set to be almost constant by using a styrofoam box, but was not exactly set to 10°C, 25°C, and 50°C. Al-Khafaf (1972) concluded that differences in the temperature (within a range of 15°C to 24°C) do not give significant differences in the results of the water retention curve. The temperature of the samples was also around this value. Therefore, this also most likely not caused the strange results for the water retention curves. Another factor that can influence the results of the water retention curves is the contact of the filter paper with the soil. In this research the matric suction is determined, for this the equilibrium is established because of liquid flow (Bicalho, et al., 2007). The filter paper was directly placed on top of the soil. Even though during the preparation of the samples, attention was paid to placing the filter paper in such a way that there was good contact between the soil and the filter paper, it is possible that there was no full contact between the soil and filter paper. This can have caused the results to become a combination of the matric and total suction, which is measured by an equilibrium created by vapor flow (Bicalho, et al., 2007). The results for total suction would give deviating results from the matric suction for the water retention curve, but this would not explain the results gained in this test which only give two different values for the suction. Human errors while measuring the weight of the filter paper could explain small differences in results, but do not explain the results shown in Figure 8. Lastly the soil samples itself also could have influenced the factors. The soil samples were dried at a temperature of 80°C. Following from the literature this would not affect the samples. However, after the samples were removed from the oven, it was noticed that some samples were completely clumped together. This could have been caused by a high percentage of clay within the samples or a not well functioning oven (for example if water could not escape from the oven and the samples were steamed). When adding water, the samples would not easily absorb it anymore. Therefore, the samples were set aside for 24 hours to absorb the water. Most samples did after 24 hours, but some samples did not, which could indicate a change in the soil samples due to drying.

3.2.2 Infiltration rates

In this section the results of sub-question 2.2 are given, which is: “*What are the infiltration rates for monoculture oil palm plantations, agroforestry oil palm plantations and natural forest in the research area?”.* For answering this question, the method explained in section 2.3 was used. For all measurement locations the correlation between the measured data and the fitted Horton equation was determined. 22 out of 26 measurements have a correlation coefficient higher than 0,77 (see Appendix D), which indicates there is a strong correlation between the fitted curve and the measured points (van Heijst, 2021). From these 22 locations more than half of the locations have a correlation coefficient of 0,96 or higher. The four locations with a lower correlation coefficient have a correlation coefficient between 0,65 and 0,70, which indicates there still is a correlation between the measurements and fitted Horton curve, but the correlation is less strong. Figure 9 gives an example of a good fit of the Horton curve (at location S3: New agroforestry) and Figure 10 illustrates an example of a less good fit (location C2: Old agroforestry). In Figure 9 there can clearly be seen that the initial infiltration rate in the measured data is higher compared to the Horton curve. This was the case for all executed measurements. Collis-George (1977) found that Horton’s model does not describe the initial and early infiltration rates well, which can explain the higher initial infiltration rates. All four locations which have a smaller correlation coefficient, reached the constant infiltration rate very quickly. This can be an explanation for the smaller correlation coefficients of these measurements.

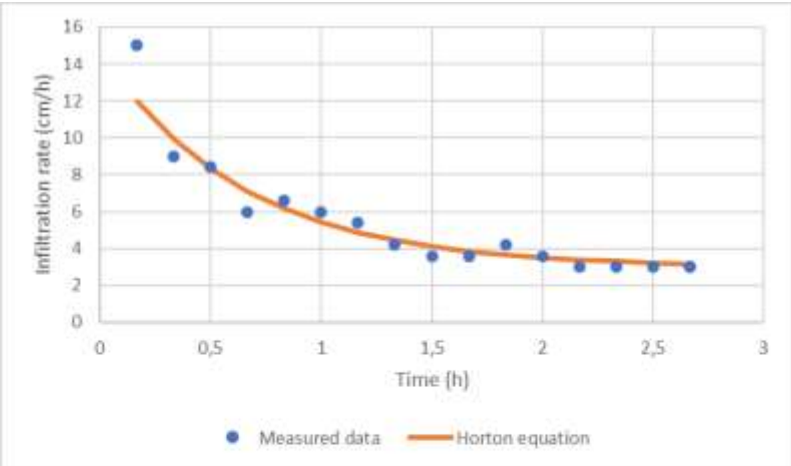

Figure 9: Example of a good Horton curve fit (location S3: New agroforestry) Correlation = 0,97

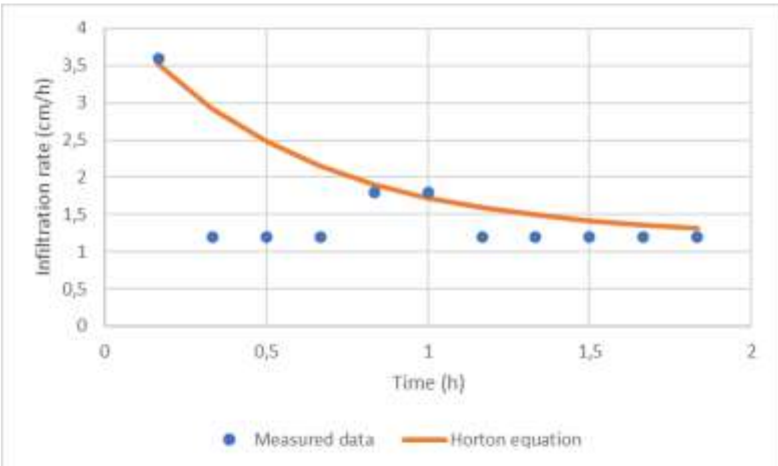

Figure 10: Example of a less good Horton curve fit (location C2: Old agroforestry) Correlation = 0,66

Underneath the results on the infiltration rates per land use type are given with the parameters found of the Horton equation. For all locations a big deviation in initial infiltration rates was found. The variability for the initial infiltration rate can be explained by different factors: difference in saturation of the ground before measuring, the removal of the organic matter at the soil surface was not completely done, spatial variability of the area in vegetation or soil compaction, different vegetation composition causing different porosity with the roots, etc. The Horton parameter values for all measurement locations are given in Appendix D per land use type.

3.2.2.1 Natural forest

Figure 11 shows the Horton curves for all different measurements within the natural forest location. In Table 2 the range of parameter values are given. A lot of variability can be seen within this land use type. The variability of the k value and initial infiltration rate is influenced by a lot of different factors and therefore the large range is not completely unexpected. However, the differences in constant infiltration rate are a little harder to explain and more unexpected. In Figure 11 it can be seen that 4 locations (F1, F2, F7, F14) have a similar constant infiltration rate around 1,35 cm/h, while the constant infiltration rate of locations F3, F5 and F12, is much higher (39,6 cm/h, 21 cm/h and 6,6 cm/h respectively). The locations of the measurements with a higher infiltration rate were more to the west of the plot (F3 and F12) or more to the east (F5), while the measurement locations with a lower constant infiltration rate were mostly located in the middle part of the plot, except for F14 which was located more to the west. This means the location of the measurement cannot completely explain the differences. The composition of the soil could also have influenced the difference in constant infiltration rate. This is most likely not caused by major differences in silt, clay and sand percentages as the plot is only 6 ha, but this statement cannot be fully made as the composition of silt, clay and sand was not investigated for this research. The colour of the soil could be an indicator for the soil composition mainly indicating the amount of organic matter and minerals in the soil. This could have had an influence on the results, but as the colour was not different for all the deviating locations, this cannot be said to be the main reason.

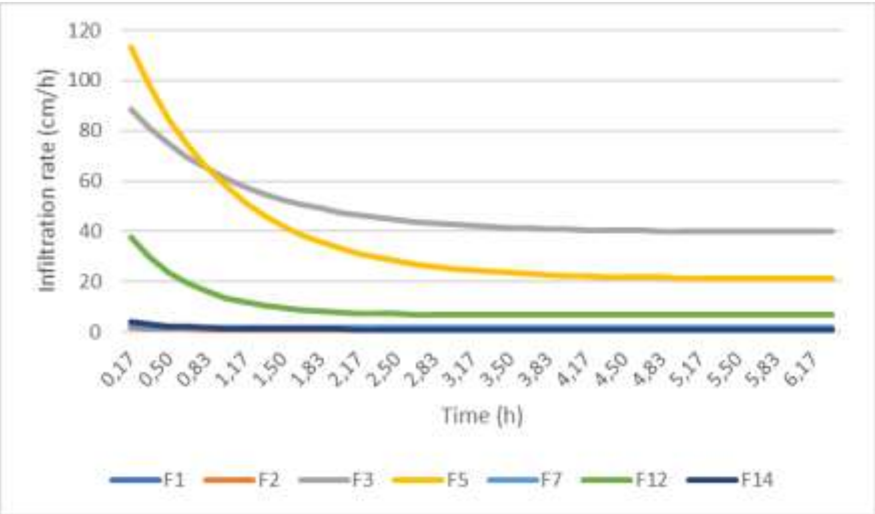

Figure 11: Infiltration rates as a function of time Natural forest

Table 2: Infiltration parameters natural forest

Land use type	f_0 min – max (cm/h)	f_c min – max (cm/h)	k (h^{-1})
Natural forest	3,3 – 131,9	0,9 – 39,6	0,99 – 19,13

3.2.2.2 Old agroforestry

Figure 12 shows the Horton curves for all different measurements within the old agroforestry location. In Table 3 the corresponding range of parameter values are given. The low values for the constant infiltration rate are really remarkable. The constant infiltration rate for the old agroforestry plot is for 4 out of 6 measurements below 0,3 cm/h. This most likely indicates a clayey soil (Brouwer et al., 1988). Besides the soil texture, the compaction of the ground could also have influenced the low infiltration rate. As mentioned in section 3.1.3, the old agroforestry plot is located behind some houses and is used as a plantation for around 15 years. This could have caused compaction of the ground and may have resulted in a lower infiltration rate. In the field there was noticed the soil of the old agroforestry plot could be divided in two different layers based on the colour. The upper layer, which had a dark brown colour (while the lower layer had a more yellow colour) can influence the results of the infiltration rate. The upper soil layer felt a little sandier and the lower layer felt more clayey. As sandy soils have a higher infiltration rate the initial infiltration rate of the soil can be influenced by the difference in soil, the constant infiltration rate will most likely be lower and represents the lower infiltration rate from the lower more clayey soil layer (Brouwer et al., 1988). Also for this land use type some variability can be seen. The results of measurement locations C1, C9 and C13 are quite similar for both the k-value (around 1,80 h^{-1}) and the constant infiltration rate (around 0,18 cm/h). Location C8 has a similar constant infiltration rate as C1, C9 and C13 (0,15 cm/h), but the k-value for this location is different (4,81 h^{-1}). This is most likely caused by the difference in initial infiltration rate. Locations C2 and C6 have a way higher constant infiltration rate (1,2 cm/h and 1,5 cm/h respectively), which is harder to explain. Both C2 and C6 are located at the southwestern part of the plot. If there is spatial variability in the ground compaction or soil texture in this area, this can be a possible explanation of the difference in constant infiltration rate. However, this was not visually seen in the field. Besides, location C1 is also located in this area but has a lower constant infiltration rate, which indicates the location cannot completely explain the differences in constant infiltration rate. Also, the colour of the soil and the soil texture cannot be said to be the main reason for the differences, as there is no difference in soil colour of the deviating measurements and there is assumed the soil texture is (almost) similar for all locations as the plot is only 2 ha. However, this statement cannot be fully made as the texture is not investigated.

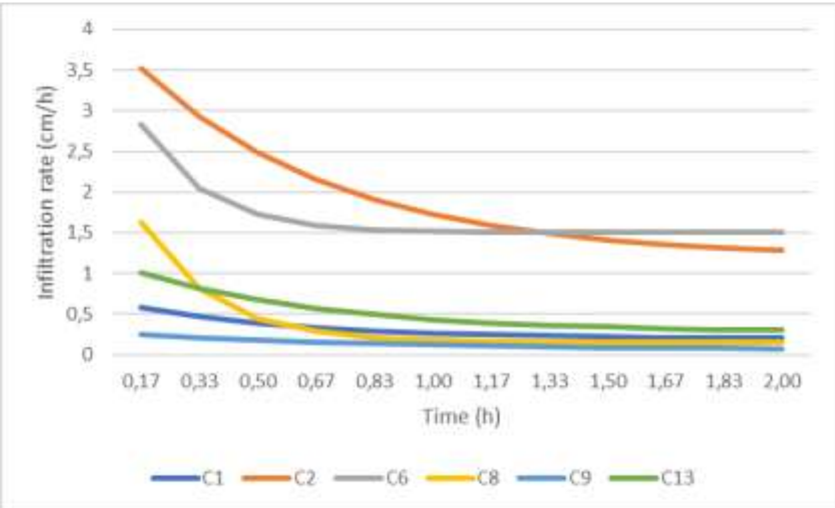

Figure 12: Infiltration rates as a function of time Old agroforestry

Table 3: Infiltration parameters old agroforestry

Land use type	f_0 min – max (cm/h)	f_c min – max (cm/h)	k (h^{-1})
Old agroforestry	0,30 – 4,77	0,06 – 1,50	1,37 – 5,38

3.2.2.3 New agroforestry

Figure 13 shows the Horton curves for all different measurements within the new agroforestry location and Table 4 gives the corresponding range of parameter values. It can be seen that there is variability within this land use type, but there is a clear division between 2 constant infiltration rates and k-values. Measurement locations S1, S3, S8 and S10 have a constant infiltration rate around 3 cm/h, while locations S5, S13, and S14 have a constant infiltration rate around 9,45 cm/h. The division for the k-value gives another composition of locations with equal values. For the k-value location S1, S3 and S10 have a k-value around 1,67 h^{-1}, while the k-value of locations S5, S8, S13 and S14 lays around a value of 0,93 h^{-1}. When comparing the locations and soil colour of the different measurements no pattern was found which could explain the differences in constant infiltration rate or k-value. Also, the soil colour was similar for most measurements. Only the soil at S13 has a darker colour than the soil of the other measurements, but as S14 does not, the soil colour is not the main reason for the difference in constant infiltration rate or k-value. The difference can be caused by spatial variability in vegetation density, soil composition, or compaction which was not clearly seen in the field and therefore cannot be concluded without any further research.

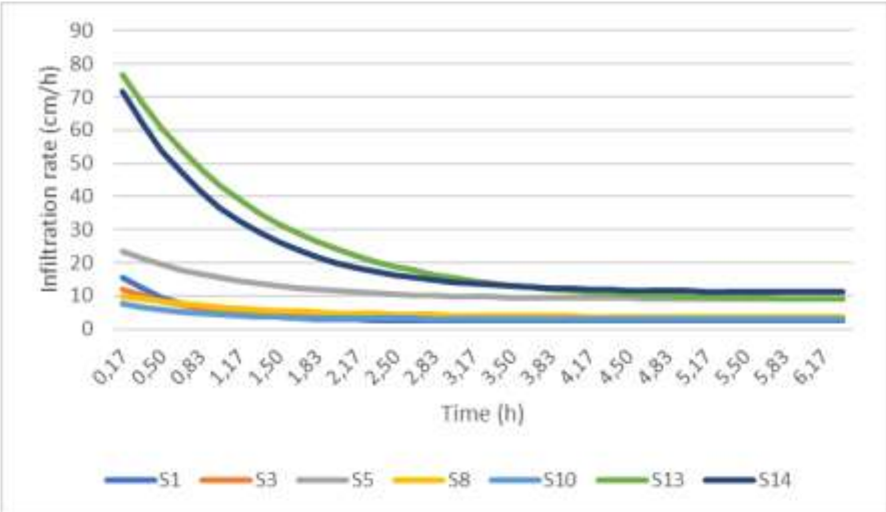

Figure 13: Infiltration rates as a function of time New agroforestry

Table 4: Infiltration parameters New agroforestry

Land use type	f_0 min – max (cm/h)	f_c min – max (cm/h)	k (h^{-1})
New agroforestry	9,0 – 86,3	2,4 – 11,0	0,81 – 1,85

3.2.2.4 Monoculture

Figure 14 shows the Horton curves for all different measurements within the monoculture location and Table 5 gives the corresponding range of parameter values. The constant infiltration rate for the monoculture plot was found to be very low: all values below 1 cm/h. This most likely indicates a high percentage of clay in the soil (Brouwer et al., 1988). Some variability can be seen within this land use type for all different parameters. Noticeable here is that the differences in the k-value and constant infiltration rate are not extremely big. The differences in constant infiltration rate between M6, M10, M12, and M14, which have a constant infiltration rate around 0,12 cm/h, and M1 and M11, which have a constant infiltration rate of 0,9 cm/h, are not easily to explain. The locations of M1 and M11 are far apart from each other and the other locations are located in between, therefore this is most likely not one of the main reasons for the difference in constant infiltration rate. Also the vegetation at these locations was similar to all other locations. The soil colour of M1 and M11 was also not different from the majority of the other soil samples with a lower constant infiltration rate. So, the specific reason for the difference in constant infiltration rate cannot be concluded from the currently available data and more research should be done in for example the history of the plot, which can give more insight in for example compaction of the soil at certain areas.

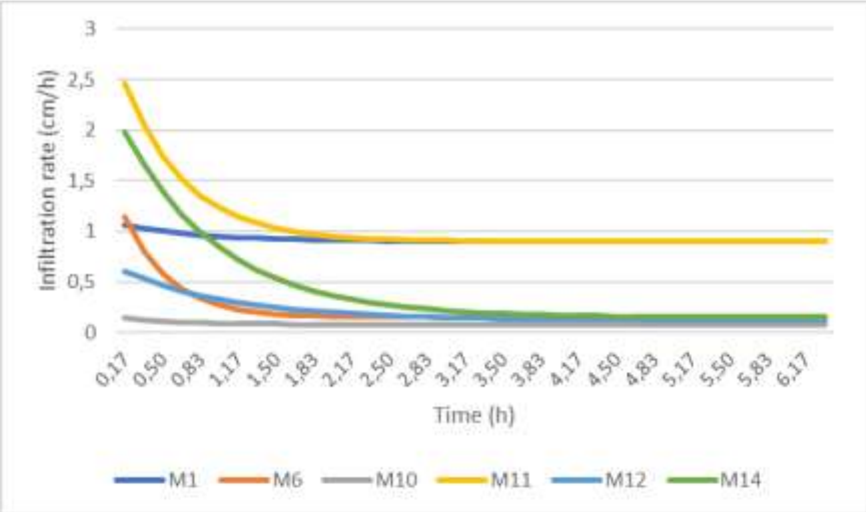

Figure 14: Infiltration rates as a function of time Monoculture

Table 5: Infiltration parameters Monoculture

Land use type	f_0 min – max (cm/h)	f_c min – max (cm/h)	k (h^{-1})
Natural forest	0,16 – 3,02	0,08 – 0,90	1,02 – 2,51

3.3 Difference in soil-water characteristics of different land use types

3.3.1 Water retention curves

Due to the strange results for the water retention curves is it not possible to compare the water retention curves for the different land use types. However, the porosity of the different land use types could be measured. The porosity per land use type is given in Table 6. The difference in porosity can be caused by a difference in soil texture, colour, compaction, and the amount of organic matter (Antosh, 2021). The porosity is only measured for one sample at each location and therefore variability and uncertainties are not taken into account in the results for porosity. This means no certain conclusion can be made for this, but it is likely that the natural forest has a higher porosity than the other land use types.

Table 6: Porosity values different land use types

Land use type	Natural forest	Old agroforestry	New agroforestry	Monoculture
Porosity (-)	0,44	0,29	0,28	0,31

3.3.2 Infiltration rates

The most interesting parameter following from section 3.2.2 to be compared between the different land use types is the constant infiltration rate as the initial infiltration rate and the value for k can be influenced by a lot of factors and the initial infiltration rate also can be time dependant. Figure 15 illustrates the constant infiltration rate for all land use types. In the figure the variability within a land use type is illustrated in the form of a boxplot, in which the maximum and minimum value as well as the 25-75% range and average value are given. In the figure a significant difference between monoculture and old agroforestry on the one hand and new agroforestry and natural forest on the other hand can be observed. Even though the variability of new agroforestry and natural forest is high, there is almost no overlap between these land use types and the monoculture and old agroforestry land use types. This was supported with an independent sample t-test. Following from this test (using a significance level of 0,05) it resulted that the differences in the mean between monoculture – new agroforestry, monoculture – forest, old agroforestry – new agroforestry, and old agroforestry – forests, are significant.

The constant infiltration rates for monoculture and old agroforestry are similar and both extremely low. The average constant infiltration rate of the natural forest is the highest, but this land use has also the biggest variance, which is probably caused by the great diversity of vegetation in this area. Assuming the soil texture for all land use types is (roughly) the same, it can be said that monoculture and old agroforestry have a negative effect on the infiltration rate.

The big difference between the old agroforestry land use and new agroforestry land use is unexpected. However, when using the information from section 3.1 the differences may be explained. Even though the intention of agroforestry is the same, the locations at which the samples were taken differ a lot. When there is looked at the locations big differences can be seen: The old agroforestry has almost no vegetation and is located between houses, while the new agroforestry has a high vegetation density and is located at a more untouched area. This may have caused the difference between these land use types.

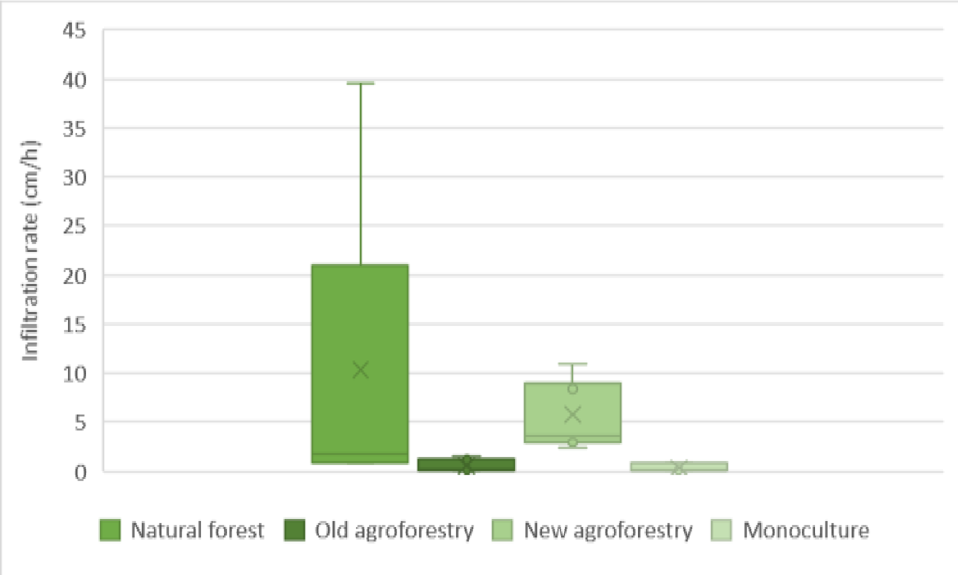

Figure 15: Constant infiltration rate different land use types

The k-value in the Horton equation is a soil specific decay factor. Figure 16 illustrates the decay factor for all land use types. The sample t-test performed on the k-values (using a significance level of 0,05), showed that there is a significant difference between the new agroforestry land use type (mean k-value of 1,25 h^{-1}) and both the old agroforestry (mean k-value of 2,90 h^{-1}) as well as the natural forest (mean k-value of 5,21 h^{-1}) land use types, which both have a significantly larger average k-value. The differences between the other land use types are not significant. This means that for the new agroforestry in general it will take longer to reach the constant infiltration rate when the difference between the initial and constant infiltration rate is the same for all land use types. This difference can be caused by a lot of factors: porosity of the soil, soil texture, the amount of organic matter, etc. However, this result was not expected. The k-value of the natural forest was expected to be lower and closer to the k-value of the new agroforestry, due to its high vegetation density (and with that a high amount of organic matter).

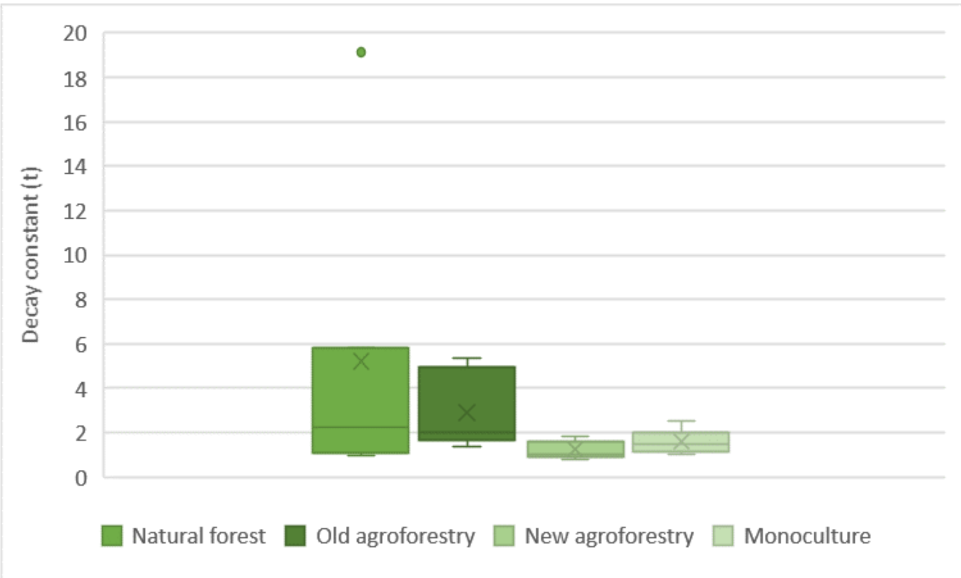

Figure 16: Decay constant Horton different land use types

4 Discussion

4.1 Link to literature

Comparing the results of this research to literature with a similar context is difficult, since there is almost no literature on soil water characteristics related to oil palm monoculture, agroforestry, and natural forest available. The little literature that is available will be compared to the results of this research in this section.

First the features of the different land use types were investigated. This included a comparison of the bulk densities of the soils. In Thomas et al. (2021) research was done into the impact of monoculture and mixed-species plantations on the soil quality. This research was not executed on oil palm plantations but can still be used for comparison with the results of this research. Following from Thomas et al. (2021) there was an increase in bulk density for plantations compared to the forest. This could also clearly be seen in the results following from this research. Thomas et al. (2021) also concluded that there was a small difference in bulk density between the monoculture and agroforestry. Even though the monoculture has a slightly higher average bulk density, in this report the difference between these two land use types was not significant.

The results of the water retention could not be used, but the measurements on porosity were compared. Thomas et al. (2021) indicates an increase in bulk density gives a decrease in porosity which was clearly visible in the results from this research, in which the forest land use type had a way lower bulk density and a way higher porosity than the other land use types.

Another available study is the research of Suprayogo et al. (2020). Suprayogo et al. (2020) concluded that the change from forest to plantations will lead to a decrease in soil water functions like infiltration. Dislich et al. (2017) indicated the same but mentioned the differences are also dependant on the location and soil types of the compared areas. This can also be concluded from this research. The infiltration rate of the forest was significantly higher than the old agroforestry and monoculture. However, there was no significant difference in constant infiltration rate between the forest and new agroforestry plot. This corresponds with the findings of Dislich et al. (2017), that a difference is dependent on location. The insignificant difference between the new agroforestry and forest can be caused by the big variability in infiltration rate of the forest. To check if there is a significant difference between the new agroforestry and forest, more measurements should be done into the infiltration rate, the cause of the variability of measurements within one land use type and the features of the different land use types. Suprayogo et al. (2020) also mentioned that a change from monoculture to agroforestry will lead to increase in constant infiltration rate. In this research this was clearly visible for the new agroforestry plot, but the old agroforestry plot showed almost similar constant infiltration rates as the monoculture plot. This difference could be explained by the variation in features between the different land use types. To make a clear conclusion about the difference in infiltration rate between monoculture and agroforestry, more research should be done into the factors influencing the soil water characteristics, both for the existing locations as well as for other locations so a general conclusion on the differences between monoculture and agroforestry can be made.

4.2 Limitations

The methods used and choices made during the research influence the outcomes. In this section points of discussion will be given on the results of this research. A general point is time limitation and available equipment. Due to these factors repetition on most methods could not have been done. A minimum amount was set for measurements, but a lot of variability was noticed. Whether the differences in outcomes are really caused by spatial variability is not known as no repetition experiments could be executed on the measurements. This was also the case for the filter paper method, which could have given any usable results when the experiment was executed again differently with the knowledge gained from the failed experiment.

4.2.1 Data availability

To make a fair comparison between the different land use types, factors affecting the soil water characteristics other than the land use type should be kept as similar as possible. However, whether this was the case is not really known, as data on the specific features of the areas was hardly available. The research locations were determined by the Gadjah Mada University and could therefore not be chosen based on similar characteristics. Although the research locations are located relatively close to each other (less than 40 km apart), there could still be a change in some features with a big influence on the outcomes of the soil water characteristics. The question is, if it is ever possible to have locations with the required different land use types but with the same features when using real-life examples.

Besides comparing the features between different land use types, the features within one land use type are also important for determining the soil water characteristics for that area and explaining the variability within these outcomes. For this also not enough data was available. Only visual features could be compared, which is mostly not enough to explain certain differences.

4.2.2 Water retention curves

Unfortunately, the investigation for water retention did not lead to useful results. The possible reasons for this are discussed in section 3.2.1. The filter paper method was chosen due to its simplicity and its ability to measure a wide range of suctions. For next research this method can still be used as in literature is it proven to be a good method. Point of attention for further investigation on the water retention curve using the filter paper method are the use of filter paper of good quality and further research in methods for giving a certain water content to the soil samples. As some soil samples did not fully absorb the water due to the clumped texture. This can indicate that the drying process could have changed the soil composition. In literature it is not clearly indicated how to give certain water content to samples. Therefore, it would be good to investigate this more.

4.2.3 Precision of double ring infiltrometer

For the measurements on the soil water infiltration rate a double ring infiltrometer was used. Although this is proven to be a good method for measuring infiltration rates (Youngs, 1991), this method comes with points up for discussion. The first step that was executed in the procedure for the double ring infiltrometer, was cleaning the soil surface, as the aim was to measure the infiltration rate of the soil without any vegetation or organic matter on top. The removal was done manually and was visually checked. Therefore, the removal of the upper layer of soil differs per measurement location, which could have caused a slight difference in infiltration rate within one land use plot. The installation of the rings also could have caused some disturbance of the soil as they were forced into the ground with a hammer or big wooden stick, which could have led to a change in the results.

For measuring the water depth within the inner circle a ruler was used with a precision of 1 mm. Already given in the results is the really low constant infiltration rate at some locations. This meant that at some time steps no different water level could be measured as the difference was less than 1 mm. For creating the curves this was partly solved by combining the differences in water level as time steps of 10 minutes. However, in some cases this was still not enough time to notice a change. This could have let to less accurate results for the water retention.

The weather could also have influenced the results. The measurements were executed in a tropical climate which means there are hot temperatures. This could have caused evaporation of the water in the rings of the infiltrometer (Johnson, 1963). The average evaporation in a tropical climate ranges from 3 to 10 millimetre per day (Benzaghta et al., 2012). This was not taken into account in the results of the infiltration rates. Favaretti & Cossu (2018) indicate a sealed inner ring could be used to eliminate evaporation losses. However, this equipment was not available during the research. All measurements were executed by people which means there can also be bias or errors in reading the water level of the ruler.

4.3 Generalisation

In this research there is focussed on the water retention curves and infiltration rates of four different land use types related to oil palm plantations, located in Jambi, Indonesia. The results can be used to describe the ground water characteristics for these specific areas, but cannot be directly used for other locations, due to the variability within the land use types. The results showed that there was a great significant difference between the infiltration rates of the natural forest and oil palm monoculture land use type, which showed that the natural forest has a higher infiltration rate. Due to this significant difference in infiltration rate, it can be assumed that this difference can be applied in a larger scope, which is limited by some factors. The natural forest investigated in this research is a tropical forest. A tropical forest has a lot of different features than a forest in a non-tropical area. Therefore, the difference between oil palm monoculture and natural forest can only be used in a wider scale for tropical areas. This is the same case for the monoculture. The investigated monoculture land use type focussed on an oil palm plantation. The differences in features between other crops can be really big. The features between plantations of trees related to the palm family and the oil palm plantation will probably be more similar and therefore the "oil palm monoculture" can be generalised into "palm monoculture". This means the generalisation can be made that tropical natural forest has a higher infiltration rate than monoculture palm plantations.
Agroforestry (both new and old) had infiltration values between the natural forest and monoculture. However, the difference between the new agroforestry and old agroforestry was really big, so these land use types cannot be combined to form one general conclusion on agroforestry, which can be used outside the research areas.
Around the research areas, a lot of similar plantations of forest was located. The features of these equal plantations and forests will be similar to the features of the research areas. Therefore, it can be assumed that the groundwater characteristics of the surrounded areas with the same land use types, are in the same range as the results found in this research of the corresponding land use type.

Due to the wrong results on the water retention curves, there is not much to say about this characteristic in relation to other areas or plantation types.

5 Conclusion and recommendations

5.1 Conclusion

The objective of this research was to determine and explain the differences in soil-water characteristics between mono-cultural oil palm plantations, oil palm agroforestry, and natural forest in Indonesia. The previous chapters have described and discussed the results to the research questions, which together will help to formulate a conclusion to the research objective.

Based on the first research question "*What are the features of the different research locations that can influence the soil-water characteristics of that area?*", a description of the research areas of the different land use types was made. Resulting from this was that there are quite some differences in features between the land use types, which might not be able to be all caused by a change in land use. A difference between the different land use types was the vegetation density, which is way higher in the natural forest and new agroforestry plot. Besides, the bulk density also indicated some differences. For this feature the natural forest has a bulk density way lower than the other land use types.

The goal of the second research question was to determine the water retention curves and infiltration rates for the different land use types. Unfortunately, the results gained on the water retention curves were not usable. For the infiltration rates it was noticed that a lot of variation was found within the land use types. Despite the variability it turned out that the values for the constant infiltration rate for the monoculture plot and old agroforestry plot were extremely low (on average less than 0,6 cm/h). The average constant infiltration for the new agroforestry plot is around 5,8 cm/h. The natural forest has the largest variability and a constant infiltration rate of around 10,4 cm/h.

The last research question "What are the differences in soil-water characteristics between monoculture oil palm plantations, agroforestry oil palm plantations and natural forest in the research area?" compares the characteristics from the research questions above and gives an answer to the research objective. It can be concluded that in general plantations have a negative effect on the infiltration rate as well as on the porosity which was compared instead of the water retention curves. The natural forest turned out to have the highest porosity (0,44) as well as the largest infiltration rate. Compared to the soil water characteristics of the forest land use type, the infiltration rate of the new agroforestry land use type is not significantly different, but the porosity of the new agroforestry is way lower (0,28). The monoculture and old agroforestry land use types are not significantly different in constant infiltration rate and have a similar porosity (0,31 and 0,29 respectively). From the research done into the features of the different land use types, the difference between the old agroforestry and new agroforestry in infiltration rate can be partly explained. The features of both locations were very different, which can influence the infiltration rate. This indicates that the soil characteristics investigated are strongly dependent on location (and the features of that location).

To summarise, the conclusion can be made that the natural forest has the most optimal soil water characteristics, namely the highest constant infiltration rate and the highest porosity, followed by agroforestry (with new agroforestry having a way more positive effect than old agroforestry). Monoculture has a negative effect on the soil water characteristics investigated.

5.2 Recommendations

This research project was bounded by limited time and means. Therefore, some recommendations for future research are suggested in this section.

5.2.1 Data collection

The results of this research were based on incomplete data. Therefore, more data should be gathered to give a more certain conclusion. The data that needs to be gathered is more data on the features of the locations, with as most important factor the soil texture as this feature can have the biggest influence on the results of the soil water characteristics. This will most likely allow the results to be more easily explainable. When more data is gathered, the reason for the difference between the old agroforestry and new agroforestry can be better substantiated and a general conclusion can be made on the differences between forest, monoculture, and agroforestry in general. Other date collection that can contribute to this general conclusion is the research into these plantation types at different locations. In this way the conclusion can be applied to a wider range as the results are based on different locations. For further research into the infiltration rate at different locations it is recommended to bring more equipment, when available, so more measurements can be executed at the same time. This will lead to more accurate results when more measurements are executed, or it can save time when the same number of measurements will be executed as used in this research.

5.2.2 Method

In this section some recommendations on the methods used will be made. A general recommendation is about testing the methods before executing it on the actual samples or on a bigger scale. In this research the results for the water retention curves turned out to be not useable. By doing some research it was found that this was most likely caused by the use of wrong equipment (uncertified filter paper). By testing this method, these strange results on the water retention curves could have been discovered in advance and wrong results due to the use of wrong equipment could have been prevented. In the following to sub sections recommendations will be made about the methods used for determining the water retention curves and infiltration rates.

Water retention curves

In this research the results for the water retention curves could not be used. However, water retention is an important characteristic which can tell a lot about the water availability for plants and therefore vegetation growth in an area. This is important as water is one of the main factors affecting oil palm growth and harvest. Therefore, investigating this characteristic again would be valuable. For this research the filter paper method can be used again but some limitations should be taken into account, like the use of qualified filter paper and the process of giving the samples a specific water content could be possibly slightly adjusted. As some soil samples did not fully absorb the water due to the clumped texture. This can indicate that the drying process could have changed the soil composition. In literature it is not clearly indicated how to give certain water content to samples. Therefore, it would be good to investigate this more.

Other options for determining the water retention curves in the lab are for example using the Richards Chamber and Haines funnel, which are also known as quantified methods to determine the water retention curves. However, these methods are expensive and require a lot of time, which limits the use of these methods. The water retention curves can also be determined in the field by using for example tensiometers and drying the soil. But, also for this method a lot of time is needed.

Infiltration rates

The use of the double infiltrometer is recommended for further research, as it is a relatively simple but accurate method. Some small adjustments can be made to this method to improve the accuracy. It is recommended to cover the inner ring to prevent evaporation from happening. Besides it is recommended to use more precise measuring equipment, so smaller differences in water level within the inner ring could be measured and more accurate results on the infiltration rates can be found.

5.2.3 Practical use

The results of this research show that there is a significant difference between the infiltration rates of the natural forest and monoculture land use type. These results can be used on a larger scope, to show the impact of deforestation and transformation of these areas into monoculture. The results of this research can be used combined with already existing research to educate people about the consequences this change in land use has on multiple aspects in the environment. With more research and data collection into this subject a more general conclusion can also be made for the differences of agroforestry plantations and the above-mentioned land use types. This general conclusion can be used to get more understanding about the influence of monoculture plantations. This can be used by the "Strategi Jangka Benah" project to transform more monoculture plantations into agroforestry plantations which are better for the environment and the biodiversity in an area. This can already be done in a small area around the research locations as there can be assumed that these areas have similar characteristics with the researched locations, which show that new agroforestry is better than monoculture.

References

Jangkabenah (2021). Retrieved 20 June 2022, https://jangkabenah.org/

Adams, M. B., Kelly, C., Kabrick, J., & Schuler, J. (2019). Temperate forests and soils. *Developments in Soil Science, 36*, 83-108.

Al-Khafaf, S. (1972). *Evaluation of the Filter Paper Method for Estimating Soil Water Potential.* Logan, Utah, USA: Utah State University.

Antosh, G. (2021, Februari 12). *Soil Porosity: What Is It | Why Its Important | How To Improve It*. Retrieved from Plant Care Today: https://plantcaretoday.com/soil-porosity.html

Austin, K. G., Schwantes, A., Gu, Y., & Kasibhatla, P. S. (2019). What causes deforestation in Indonesia? *Environmental Research Letters 14, https://doi.org/10.1088/1748-9326/aaf6db*.

Bashir, A., Suhel, Azwardi, Atiyatna, D. P., Hamidi, I., & Adnan, N. (2019). The Causality Between Agriculture, Industry, and Economic Growth: Evidence from Indonesia. *Etikonomi, 18*, 155-168.

Bennett, L. (2017). *Deforestation and Climate Change.* Washington: Climate Institute.

Benzaghta, M. A., Mohammed, T. A., Ghazali, A. H., & Soom, M. A. M. (2012). Prediction of evaporation in tropical climate using artificial neural network and climate based models. *Scientific Research and Essays, 7(36)*, 3133-3148.

Bicalho, K. V., Correia, A., Ferreira, S., Fleureau, J. M., & Marinho, F. A. (2007). *Filter paper method of soil suction measurement.*

Brouwer, C., Prins, K., Kay, M., & Heibloem, M. (1988). *Infiltration rate and infiltration test.* Retrieved 25 April 2022 from FAO Irrigation Water Management: Irrigation Methods: https://www.fao.org/3/s8684e/s8684e00.htm#Contents

Brown, K., & Wherrett, A. (n.d.). *Fact Sheets Bulk Density - Measurement*. Retrieved 14 June 2022 from Soil quality: https://soilquality.org.au/factsheets/bulk-density-measurement

Burgy, R. H., & Luthin, J. N. (1956). A test of the single- and double-ring types of infiltrometers. *Eos, 37 (2)*, 189-192.

Bystřický, V., Moravcová, J., Polenský, J., & Pečenka, J. (2017). Land use changes in the last half century and their impact on water retention in the sumava mountains and foothills (Czech Republic). *European Countryside, 1*, 116-131.

Calicioglu, O., Flammini, A., Bracco, S., Bellù, L., & Sims, R. (2019). The Future Challenges of Food and Agriculture: An Integrated Analysis of Trends and Solutions. *Sustainability 2019, 11, article 222*.

Chakravarty, S., Ghosh, S. K., Suresh, C. P., Dey, A. N., & Shukla, G. (2012). Deforestation: Causes, Effects and Control Strategies. In C. A. Okia, *Global Perspectives on Sustainable Forest Management* (pp. 3-28). Rijeka, Croatia : InTech.

Chon, N. Q. (2021, September 5). Soil Water retention - pF curve. Vietnam: Eurofins.

Civilengineeringbible. *Determination of Water Content*. Retrieved 18 April 2022 from Civilengineeringbible: https://civilengineeringbible.com/subtopics.php?i=120

Clarke, I. (2020, September 17). *How Farmers Can Reduce Their Environmental Impact*. Retrieved 20 April 2022 from https://greenerideal.com/guides/how-farmers-can-reduce-their-environmental-impact/#Increase_Agricultural_Diversity

Collis-George, N. (1977). Infiltration equations for simple soil systems. *Water Resources Research, 13 (2)*, 395-403.

Cornell University. (n.d.). *Competency Area 2: Soil hydrology AEM*. Retrieved 21 April 2022 from Cornell University: https://nrcca.cals.cornell.edu/soil/CA2/CA0211.1.php

de Almeida, E. L., Teixeira, A., da Silva Filho, F. C., de Assis Junior, R. N., & de Oliveira Leão, R. A. (2015). Filter paper method for the determination of the soil water retention curve. *R. Bras. Ci. Solo, 39*, 1344-1352.

De Vis, S. (2006). *De ontbossing van regenwouden : een economische analyse.* Gent: Universiteit Gent.

Dislich, C., Keyel, A. C., Salecker, J., Kisel, Y., Meyer, K. M., Auliya, M., . . . Töll, M. H. (2017). A review of the ecosystem functions in oil palm plantations, using forests as a reference system. *Biological reviews, 92(3)*, 1539-1569.

Dohnal, M., Dušek, J., & Vogel, T. (2006). The impact of the retention curve hysteresis on prediction of soil water dynamics. *Journal of Hydrology and Hydromechanics, 54 (3)*, 258-268.

Eijkelkamp. (2012). *double ring infiltrometer.* Giesbeek, the Netherlands: Eijkelkamp.

Favaretti, M., & Cossu, R. (2018). Mineral Liners. *Solid Waste Landfilling*, 289-312.

Freie Universität Berlin. *Infiltration rate*. Retrieved 15 June 2022 from Freie Universität Berlin: https://www.geo.fu-berlin.de/en/v/geolearning/glossary/infiltration_rate.html#:~:text=It%20is%20commonly%20measured%20by,the%20soil%20(Tidemann%201996)

Gardner, C. M., Robinson, D., Blyth, K., & Cooper, J. D. (2000). Soil water content. In K. A. Smith, *Soil and Environmental Analysis: Physical Methods, Revised, and Expanded* (pp. 1-64). New York: Marcel Dekker, Inc.

Gebrekiros, M. (2015). Infiltration. In *Watershed properties* (pp. 77-93). Aksum: Aksum University.

Gevaert, A., Teuling, A., Uijlenhoet, R., & Troch, P. (2014). Hillslope experiment demonstrates role of convergence during two-step saturation. *Hydrology and Earth System Sciences Discussions 11(2)*, 3681-3692.

Glen, S.. *Independent Samples T Test: Definition, Excel & SPSS Steps*. Retrieved 11 April 2022 from Statistics how to: https://www.statisticshowto.com/probability-and-statistics/t-distribution/independent-samples-t-test/

Global Forest Watch. (n.d.). *Global*. Retrieved 18 April 2022 from Global Forest Watch: https://www.globalforestwatch.org/dashboards/global/?category=summary&dashboardPrompts=eyJzaG93UHJvbXB0cyI6dHJ1ZSwicHJvbXB0c1ZpZXdlZCI6WyJkb3dubG9hZERhc2hib2FyZFN0YXRzIl0sInNldHRpbmdzIjp7Im9wZW4iOmZhbHNlLCJzdGVwSW5kZXgiOjAsInN0ZXBzS2V5IjoiIn0sIm9wZW4iOnRy

Groundwatergovernance. (2022, March 13). *How To Measure Water Saturation In Soil?* Retrieved 4 May 2022 from groundwatergovernance: https://www.groundwatergovernance.org/how-to-measure-water-saturation-in-soil/

Guitet, S., Freycon, V., Brunaux, O., Pélissier, R., Sabatier, D., & Couteron, P. (2016). Geomorphic control of rain-forest floristic composition in French Guiana: More than a soil filtering effect? *Journal of Tropical Ecology 32(1)*, 22-40.

Haghighi, A., Medero, G. M., Marinho, F., Mercier, B., & Woodward, P. (2012). Temperature Effects on Suction Measurement Using the Filter Paper Technique. *Geotechnical Testing Journal, 35 (1), https://doi.org/10.1520/GTJ103575*.

Haghnazari, F., Shahgholi, H., & Feizi, M. (2015). Factors affecting the infiltration of agricultural soils: review. *International Journal of Agronomy and Agricultural Research (IJAAR), 6 (5)*, 21-35.

Hansell, J. (1981). Central sumatra. Indonesia. Soils. Map 1. *ID3003_1SO*. Land Resources Development Centre, Overseas Development Administration, Tolworth, Subition, Surrey, England.

Henson, I. e., Noor, M. R., Harun, M. H., Yahya, Z., & Mustakim, S. N. (2005). Stress development and its detection in young oil palms in North Kedah, Malaysia. *Journal of Oil Palm Research, 17*, 11-26.

Intara, Y. I., Nusantara, A. D., Supanjani, Caniago, Z., & Ekawia, R. (2018). Oil Palm Roots Architecture in Response to Soil Humidity. *Internationl journal of oil palm, 1 (2)*, 79-89.

Johnson, A. I.(1963). A field method for measurement of infiltration. *Water Supply Paper 1544-F*, https://doi.org/10.3133/wsp1544F.

Johnson, A. I. (1963). *A Field Method for Measurement of Infiltration. Water Supply Paper 1544-F*, https://doi.org/10.3133/wsp1544F.

Kim, H., Prezzi, M., & Salgado, R. (2016). Calibration of Whatman Grade 42 filter paper for soil suction measurement. *Canadian Journal of Soil Science 97(2)*, 93-98.

Kirkham, M. B. (2014). Chapter 13 - Infiltration. In M. Kirkham, *Principles of Soil and Plant Water Relations (Second Edition)* (pp. 201-227). Manhattan: Academic Press.

Leong, E. C., He, L., & Rahardjo, H. (2002). Factors Affecting the Filter Paper Method for Total and Matric Suction Measurements. *Geotechnical Testing Journal, GTJODJ, 25 (3)*, 321–332.

Lili, M., Brilts, V. F., Yinghua, P., Han, L., & Tingwu, L. (2008). Methods for measuring soil infiltration: State of the art. *Int J Agric & Biol Eng., 1 (1)*, 22-30.

Longobardi, P., Montenegro, A., Beltrami, H., & Eby, M. (2016). Deforestation Induced Climate Change: Effects of Spatial Scale. *PLoS ONE 11 (4), https://doi.org/10.1371/journal.pone.0153357*.

Návar, J., & Synnott, T. J. (2000). Soil infiltration and land use in linares, N.L., Mexico. *Terra Latinoamericana, 18 (3)*, 255-262.

NRCS Wisconsin. (n.d.). *Soil Color*. Retrieved 15 June 2022 from USDA: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/wi/soils/?cid=NRCSEPRD1370419

Ochsner, T. (2019, June 17). *6.1 Horton Infiltration Model – Rain or Shine*. Retrieved 25 April 2022 from Open library Okstate: https://open.library.okstate.edu/rainorshine/chapter/6-1-horton-inflitration-model/

Ochsner, T. E. (2017). 3.3 Soil Water Retention. In T. E. Ochsner, *Rain or Shine* (pp. 64-80). Oklahoma: Oklahoma State University Libraries Stillwater.

O'Kelly, B. C. (2005). Oven-Drying Characteristics of Soils of Different Origins. *Drying Technology, Volume 23 (5)*, 1141-1149.

Pereira, J., Coussy, O., Alonso, E., Vaunat, J., & Olivella, S. (2010). Is the degree of saturation a good candidate for Bishop's _ parameter? *Unsaturated Soils*, 913-919.

Poling, K. (2021, July 15). *Understanding primary factors driving plant growth*. Retrieved 18 April 2022 from Ohio's Country Journal: https://ocj.com/2021/07/understanding-primary-factors-driving-plant-growth/#:~:text=The%20primary%20factors%20that%20affect,more%20quickly%20or%20more%20slowly

Rai, R. K., Singh, V. P., & Upadhyay, A. (2017). Soil Analysis. In R. K. Rai, V. P. Singh, & A. Upadhyay, *Planning and Evaluation of Irrigation Projects; Methods and Implementation* (pp. 505-523).

Retnowati, E. (2003, September 21-28). Sustainable development through a complex agroforestry system in Indonesia. *XII World Forestry Congress* . Quebec, Canada.

Robert, T., Martel, R., & Lefebvre, R. (2011). Use of an intermediate scale physical model for 3D in situ trials of LNAPL remediation technology trains. Quebec, Canada: Geohydro.

Rousseva, S., Kercheva, M., Shishkov, T., Lair, G., Nikolaidis, N., Moraetis, D., . . . Banwart, S. (2017). Chapter Two - Soil Water Characteristics of European SoilTrEC Critical Zone Observatories. *Advances in Agronomy, 142*, 29-72.

Safitri, L., Suryanti, S., Kautsar, V., Kurniawan, A., & Santiabudi, F. (2018). Study of oil palm root architecture with variation of crop stage and soil type vulnerable to drought. *Earth and Environmental Science 141,* https://doi.org/10.1088/1755-1315/141/1/012031.

Schwyter, A. R., & Vaughan, K. L. (2021, June 26). *Slope and Runoff*. Retrieved 20 April 2022 from https://geo.libretexts.org/Bookshelves/Soil_Science/Introduction_to_Soil_Science_Laboratory_Manual_(Schwyter_and_Vaughan)/09%3A_Field_Lab/9.07%3A_Slope_and_Runoff#:~:text=The%20steeper%20the%20slope%20and,rate%20for%20a%20given%20soil

Sen, S. (2015, June 27). *Infiltration: Concept and Factors Affecting Infiltration*. Retrieved 16 April 2022 from Your Article Library: https://www.yourarticlelibrary.com/water/infiltration/infiltration-concept-and-factors-affecting-infiltration/60457

SJB. (2021). *Pemilihan Jenis dan Pola Tanam*. Retrieved 28 April 2022 from Jangkabenah: https://jangkabenah.org/pemilihan-jenis-dan-pola-tanam/

Sollen-Norrlin, M., Ghaley, B. B., & Rintoul, N. L. (2020, August 27). Agroforestry Benefits and Challenges for Adoption in Europe and Beyond.

Spos Indonesia. (2019, December 20). *Strategi Janka Benah (SJB) offers solutions to the problem of palm inside forest*. Retrieved 28 April 2022 from Spos Indonesia: https://sposindonesia.org/news-article/strategi-jangka-benah-sjb-solusi-sawit-dalam-hutan/

Suits, L. D., Sheahan, T. C., Power, K. C., Vanapalli, S. K., & Garga, V. K. (2008). A Revised Contact Filter Paper Method. *Geotechnical Testing Journal, 31 (6), 461-469*.

Suprayogo, D., van Noordwijk, M., Hairiah, K., Meilasari, N., Rabbani, A. L., Ishaq, R. M., & Widianto, W. (2020). Infiltration-Friendly Agroforestry Land Uses on Volcanic Slopes in the Rejoso Watershed, East Java, Indonesia. *Land, 9(8), 240.*

Tarigan, S. D., Sunarti, Wiegand, K., Dislich, C., Slamet, B., Heinonen, J., & Meyer, K. (2016). Mitigation options for improving the ecosystem function of water flow regulation in a watershed with rapid expansion of oil palm plantations. *Sustainability of Water Quality and Ecology, 8*, 4-13.

Thomas, E., Kurien, V. T., Viswanathan, S. P., & Thomas, A. P. (2021). Monoculture vs. mixed-species plantation impact on the soil quality of an ecologically sensitive area. *Journal of Agriculture and Environment for International Development, 114 (2)*, 41-62.

topographic-map.com. *Jambi topographic map, elevation, relief*. Retrieved 14 June 2022 from topographic-map.com: https://en-gb.topographic-map.com/maps/r4vc/Jambi/

van Heijst, L. (2021, October 27). *Wat is correlatie en hoe bereken je het?* Retrieved 23 June 2022 from Scribbr: https://www.scribbr.nl/statistiek/correlatie/#:~:text=De%20waarde%20van%20de%20correlatieco%C3%ABffici%C3%ABnt,gewicht%20en%20lengte%20zwakker%20is.

Vicky. (2019, Januari 9). *Water Content Determination by Various Methods*. Retrieved 20 April 2022 from https://civilengineeringnotes.com/water-content-various-methods/

Vittucci, C. (2015). *Microwave analysis of soil moisture and its implication in hydrology and forest monitoring.* Rome: University of Rome.

Wang, L., Zhong, C., Gao, P., Xi, W., & Zhang, S. (2015). Soil Infiltration Characteristics in Agroforestry Systems and Their Relationships with the Temporal Distribution of Rainfall on the Loess Plateau in China. *PLoS One. 2015; 10(4)*.

Wang, Y., Zhang, B., & Banwart, S. A. (2017). Chapter Three - Reduced Subsurface Lateral Flow in Agroforestry System Is Balanced by Increased Water Retention Capacity: Rainfall Simulation and Model Validation. *Advances in Agronomy, 142*, 73-97.

Youngs, E. G. (1991). Infiltration measurements- A review. *Hydrological Processes, 5 (3)*, 309-320.

Appendix A

Equations research question 2.1

In this appendix equations are given, which will be used for step 2 in determining the water retention curve.

Determine the water content

In this step the Volumetric water content need to be determined, this can be done by using Equation A1:

$$\theta = \frac{w * \rho_b}{\rho_w}$$

Equation A1

In which:

- θ is the water content ($m^3\ m^{-3}$)
- w is the water content as a mass fraction
- ρ_b is the dry bulk density of the soil (kg m^{-3})
- ρ_w is the density of free water (1000 kg m^{-3})

In this formula the water content as a mass fraction can be determined by using Equation A2 (Vicky, 2019):

$$w = \frac{M_w}{M_s}$$

Equation A2

In which:

- M_w is the mass of the water present in a given soil (kg)
- M_s is the mass of the dry soil (kg)

Appendix B

In this appendix the exact measurement locations and elevation map for each land use plot are given.

Natural forest location

Figure B1 shows the research area for the natural forest location. Within this area the measurement locations are shown. At each location soil samples for establishing the water retention curve were taken. The locations at which the infiltration rate was measured are F1, F2, F3, F5, F7, F12, and F14.

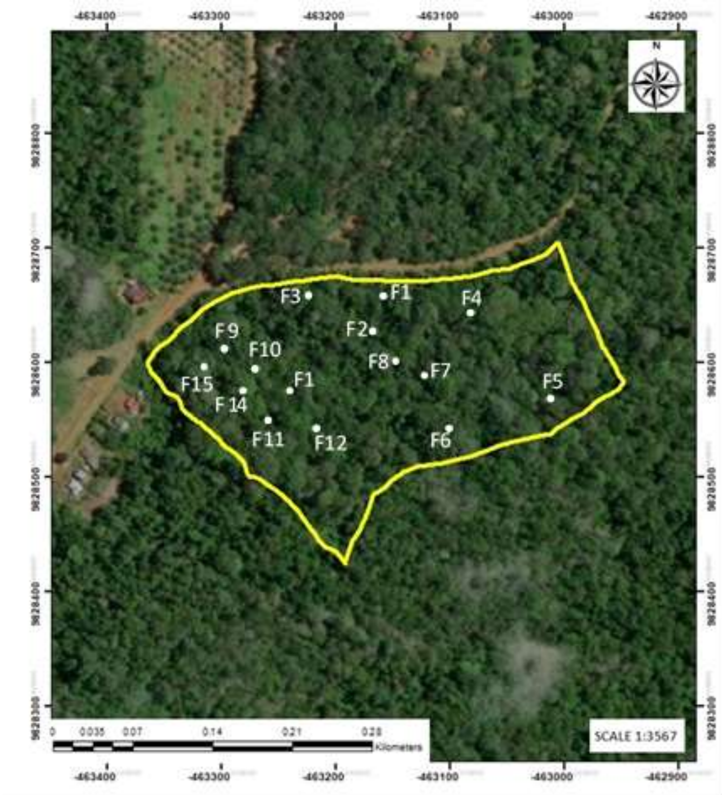

Figure B1: Measurement locations natural forest

Figure B2 shows the elevation in the research area of the natural forest (black box).

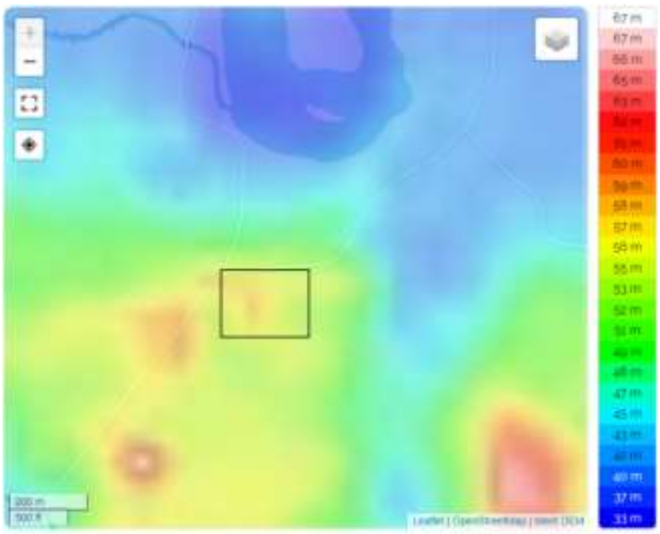

Figure B2: Elevation map Natural forest (topographic-map.com)

Old agroforestry

Figure B3 shows the research area for the old agroforestry location. Within this area the measurement locations are shown. The area is really small on the map but could not be made bigger when making the figure, to better see the measurement locations a close-up version is added (see Figure B4). At each location soil samples for establishing the water retention curve were taken. The locations at which the infiltration rate was measured are C1, C2, C6, C8, C9, and C13.

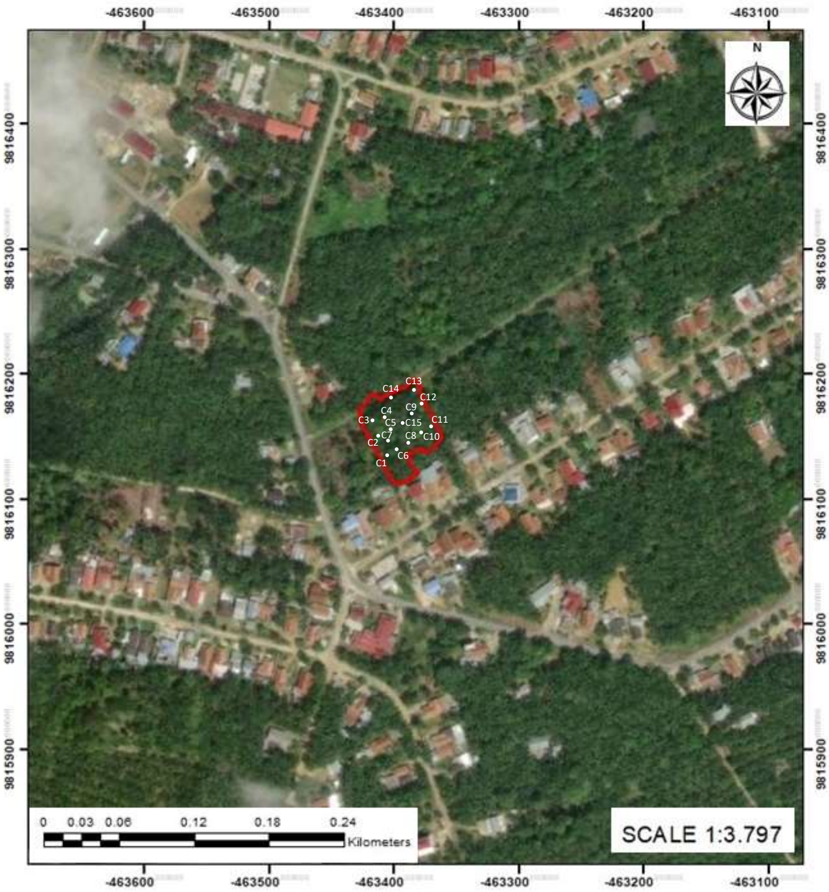

Figure B3: Measurement locations Old agroforestry

Figure B4: Close-up measurement locations Old agroforestry

FigureB5 shows the elevation in the research area of the natural forest (black box).

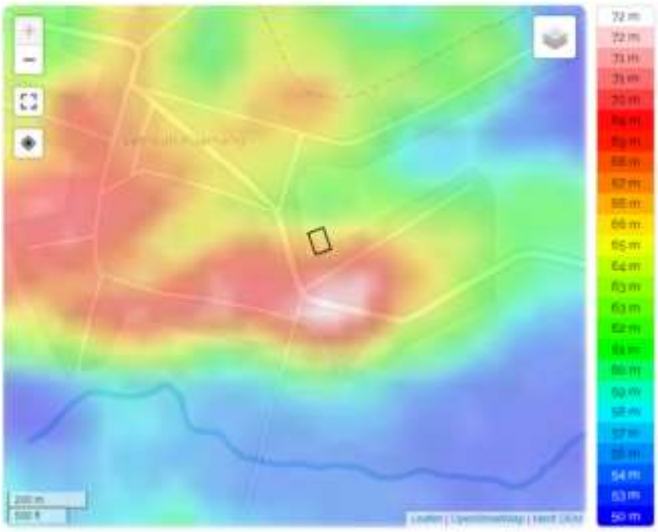

Figure B5: Elevation map Old agroforestry (topographic-map.com)

New Agroforestry

FigureB6 shows the research area for the new agroforestry location. Within this area the measurement locations are shown. At each location soil samples for establishing the water retention curve were taken. The locations at which the infiltration rate was measured are S1, S3, S5, S8, S10, S13, and S14.

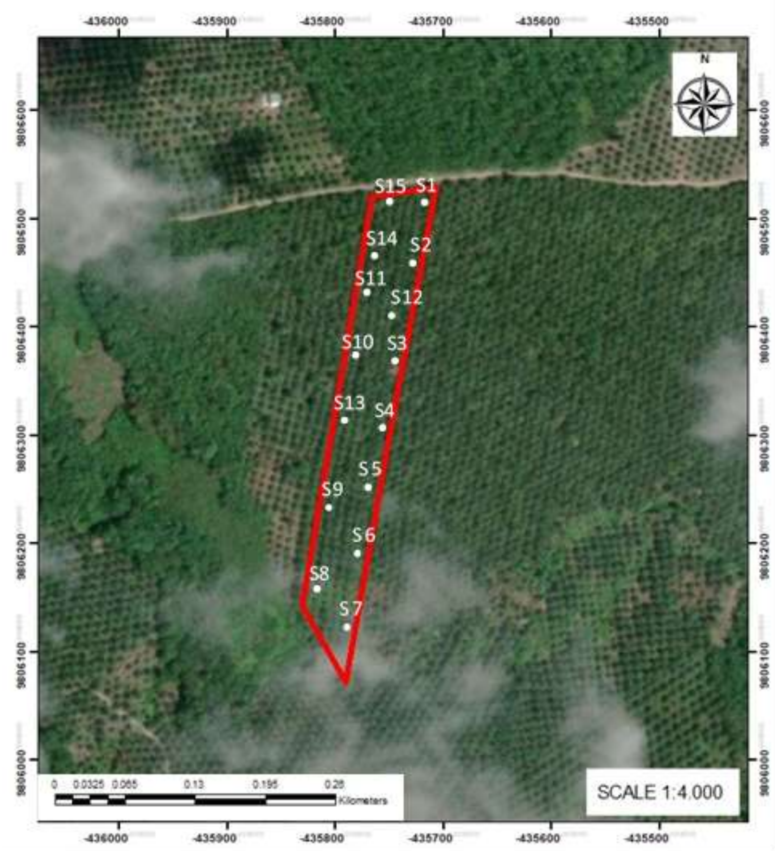

Figure B6: Measurement locations New agroforestry

FigureB7 shows the elevation in the research area of the new agroforestry plot (black box).

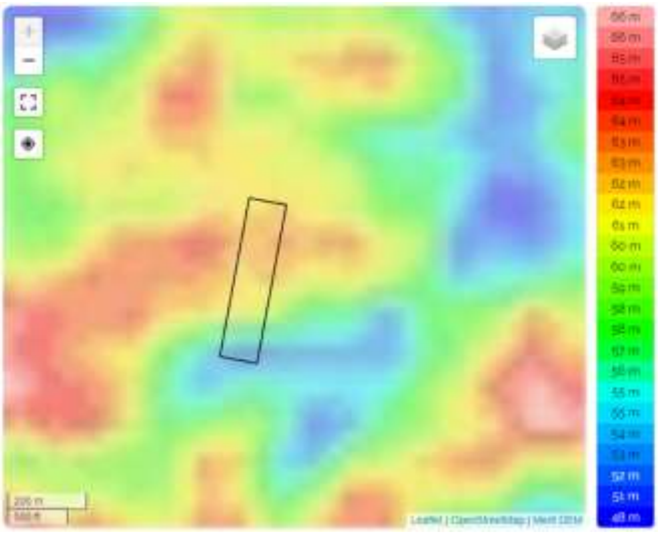

Figure B7: Elevation map New agroforestry (topographic-map.com)

FigureB8 shows an example of the lay-out which has been used for the new agroforestry plot.

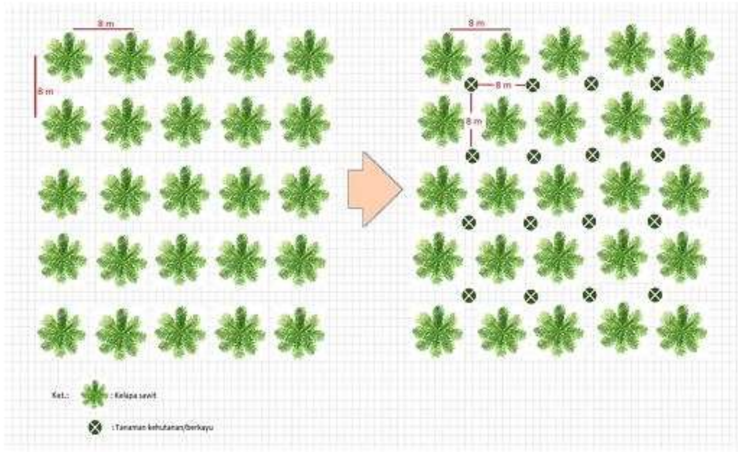

Figure B8: Plantation lay-out New agroforestry (SJB, 2021)

Monoculture

Figure B9 shows the research area for the monoculture location. Within this area the measurement locations are shown. The area is really small on the map but could not be made bigger when making the figure, to better see the measurement locations a close-up version is added (see Figure B10). At each location soil samples for establishing the water retention curve were taken. The locations at which the infiltration rate was measured are M1, M6, M10, M11, M12, and M14.

Figure B9: Measurement locations Monoculture

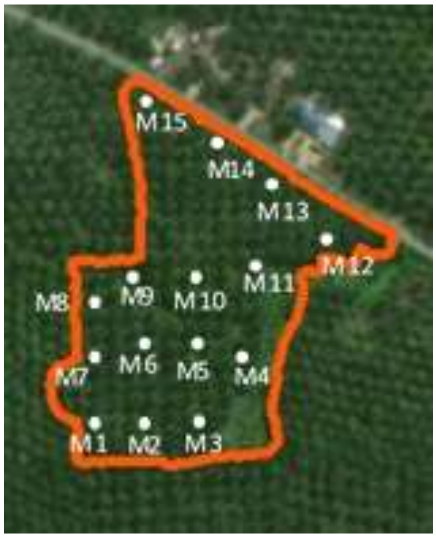

Figure B10: Close-up measurement locations Monoculture

Figure B1117B11 shows the elevation in the research area of the monoculture plot (black box).

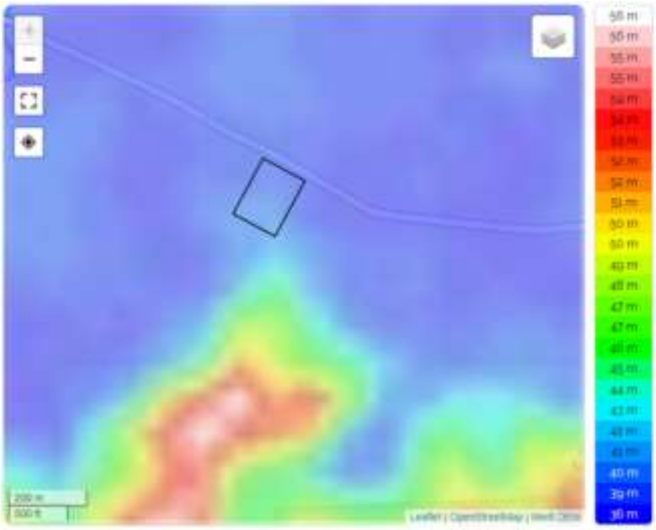

Figure B1117: Elevation map Monoculture (topographic-map.com)

Appendix C

In this appendix the results on the water retention curves for the other land use types are given.

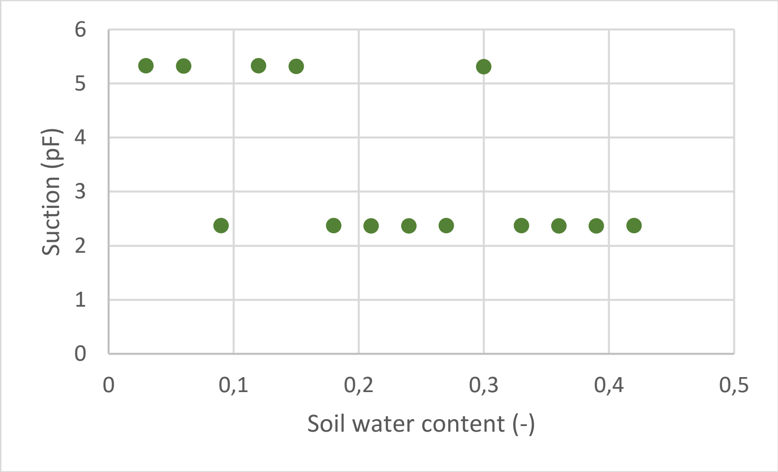

Figure C1: Soil water retention curve Natural forest

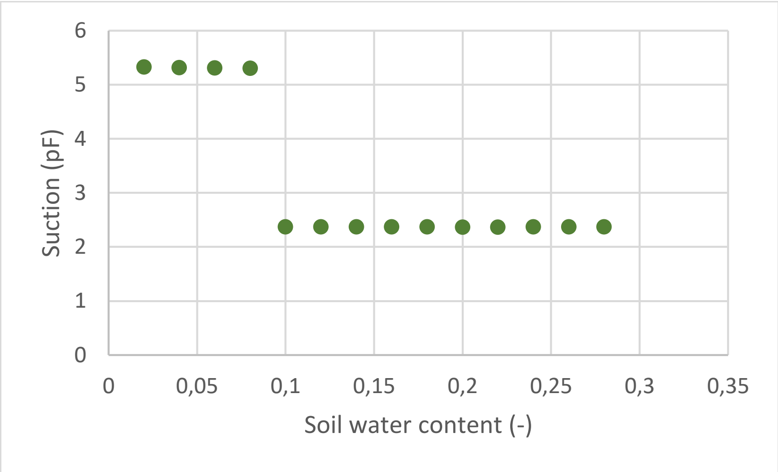

Figure C2: Soil water retention curve Old agroforestry

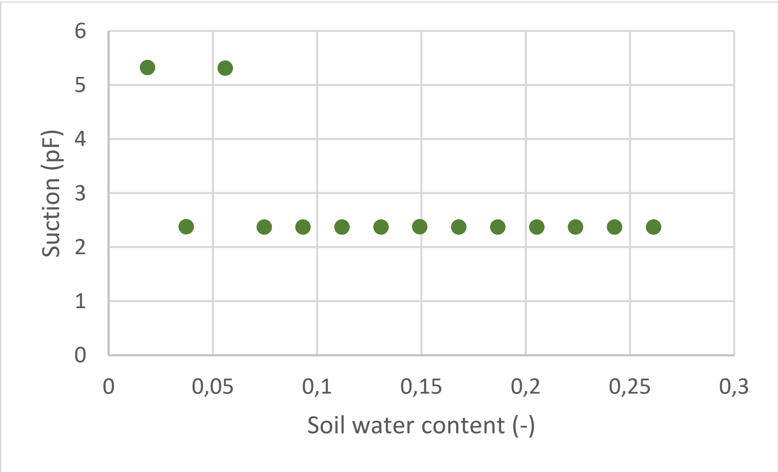

Figure C3: Soil water retention curve New agroforestry

Appendix D

Correlation

TableD1, TableD2, TableD3, and TableD4 show the correlation between all measured data and the fitted Horton curve per land use type.

Table D1: Correlation Horton equation and measured data Natural forest

Measurement location	Correlation coefficient
F1	0,97
F2	0,97
F3	0,98
F5	0,97
F7	0,99
F12	0,86
F14	0,86

Table D2: Correlation Horton equation and measured data Old agroforestry

Measurement location	Correlation coefficient
C1	0,66
C2	0,97
C6	0,99
C8	0,68
C9	0,87
C13	0,81

Table D3: Correlation Horton equation and measured data New agroforestry

Measurement location	Correlation coefficient
S1	0,86
S3	0,97
S5	0,91
S8	0,77
S10	0,89
S13	0,96
S14	0,99

Table D4: Correlation Horton equation and measured data Monoculture

Measurement location	Correlation coefficient
M1	0,79
M6	0,83
M10	0,79
M11	0,91
M12	0,66
M14	0,65

Horton parameters for different land use types

In this section all parameters of the Horton equation are given for all infiltration measurements. The parameters are given per land use type.

Natural forest

Table D5: Horton parameters Natural forest

Measurement location	F1	F2	F3	F5	F7	F12	F14
k (t^{-1})	5,84	5,38	0,99	1,10	19,13	1,80	2,23
f_c (cm/h)	1,8	0,9	39,6	21,0	1,8	6,6	0,9
f_0 (cm/h)	4,0	3,3	97,2	131,9	16,9	48,4	5,2

Old agroforestry

Table D6: Horton parameters Old agroforestry

Measurement location	C1	C2	C6	C8	C9	C13
k (t^{-1})	2,20	1,78	5,38	4,81	1,37	1,83
f_c (cm/h)	0,2	1,2	1,5	0,2	0,1	0,3
f_0 (cm/h)	0,8	4,3	4,8	3,4	0,3	1,3

New agroforestry

Table D7: Horton parameters New agroforestry

Measurement location	S1	S3	S5	S8	S10	S13	S14
k (t^{-1})	1,85	1,56	0,98	0,88	1,61	1,04	0,81
f_c (cm/h)	2,4	3,0	9,0	3,6	3,0	11,0	8,4
f_0 (cm/h)	20,4	14,6	25,9	10,9	9,0	82,9	86,3

Monoculture

Table D8: Horton parameters Monoculture

Measurement location	M1	M6	M10	M11	M12	M14
k (t^{-1})	1,38	2,51	1,65	1,85	1,02	1,16
f_c (cm/h)	0,9	0,1	0,1	0,9	0,1	0,1
f_0 (cm/h)	1,1	1,7	0,2	3,0	0,7	2,4