The potential of Colombian agroforestry systems to prevent soil erosion and increase the decomposition rate of the soil

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Abstract

The decomposition rate and the soil retention in monoculture and agroforestry coffee fields were measured in Risaralda, Colombia to establish the effect that agroforestry has on them. The Tea Bag Index method was used to determine the decomposition rate of the soil. The erosion was determined using three methods: the Landscape Function Analysis, the Revised Universal Soil Loss Equation and the silt fence method. By comparing the different sediment erosion measurement methods, the RUSLE method appeared to show the best representation of the soil erosion. It was also found that agroforestry systems do not influence the decomposition rate, but are capable at mitigating soil erosion. It appears that agroforestry systems are dynamic systems that show non-linear development over time. Little is known about this development, and therefore it is recommended that more research is done to increase our understanding about the development of agroforestry systems and their effects on ecosystem services.

Keywords: Agroforestry, LFA, RUSLE, TBI index, erosion, decomposition

Table of contents

1. Introduction

Since the beginning of the industrial revolution, the global human population has been exponentially increasing. As a result, the global demand for agricultural goods and services has exponentially increased with it, which, even though agricultural efficiency is also continuously increasing, caused the global surface area used for agriculture to double over the past century (Etter et al., 2006). Although this expansion of agricultural land, combined with the intensification of agricultural practices, has been successful to help towards global food security, it has also caused several negative effects. These negative effects on, for example, biodiversity and the environment, are mainly due to most of this agricultural expansion having happened through the conversion of primary forests into monoculture crop land (Bommarco et al., 2013). These effects will eventually contribute to the degradation of ecosystem services (Daily, 1997; Drescher et al., 2016), such as maintaining air and water quality, carbon storage, climate change mitigation and biodiversity (NATO, 1994; Smith et al., 2013). The continuously rising human population, and the rising global food demand that is associated with it, causes an increased pressure on nature areas and their ecosystem services due to farmers having to cultivate new areas to meet this rising food demand.

An ecosystem service that is also affected by this agricultural expansion, is soil retention. Soil erosion (i.e. the consequence of a decreased sediment retention) is mainly caused by water runoff, especially in tropical regions due to high the precipitation levels (Lal, 2003). Before a (primary) forest is converted into monoculture crop land, the forest floor is well protected against soil erosion. This protection mainly comes from the tropical rainforest's canopy cover and litter layer (Fitriani et al., 2018) that consists of a multi-layered structure which shields the soil from the direct impact of raindrops and also delays the rainwater runoff, increasing the infiltration into the soil (Park, 1992). Apart from a protective cover, a rainforest is also more resistant against soil erosion due to a higher root density. Because of this high root density, there is a large amount of below ground biomass that prevents streams from forming (Gyssels & Poesen, 2003). Amongst other reasons, these two factors mainly contribute to rainforest soils experiencing minimal soil erosion. However, when a rainforest is transitioned into a monoculture, both the canopy and the below ground biomass are greatly reduced (Riswan & Hartanti, 1995). Because of this, the soil gets exposed to direct rainfall, and the rainwater infiltration rate is decreased, causing an increased overland flow of rainwater that can potentially lead to nutrient poor soils due to the water slowly removing organic matter and nutrients from the top layer of the soil (Pardini et al., 2003). It is also possible that the overland flow forms into small streams, bundling the water. Due to the relatively high amount of water that flows through these rills, more force is exerted on the soil, which causes a higher eroding capacity. Both the overland flow of water and the water in the rills cause erosion and eventually lead to the loss of sediment, which causes further loss of organic material and nutrients (NSERL, 2019). Because of these processes, deforestation for agricultural expansion can lead to a decreased fertility of the soil which can have disastrous consequences for the agricultural productivity of the newly formed crop land. In addition to soil erosion having negative effects on a farm level, it can also have effects on the rest of the watershed. Upstream erosion can have large consequences further downstream. Due to a surplus of nutrients and sediment that originates from higher upstream, ecosystems can be negatively affected (Mol & Ouboter, 2004) and urban areas can be damaged by flooding and sedimentation events (Vandaele & Poesen, 1995).

Another important ecosystem service that is negatively affected by the loss of forests due to agricultural intensification is the decomposition rate of the soil (Maheswaran & Gunatilleke, 1988). Due to a monoculture's simplified ecosystem compared to that of a rainforest, aspects such as vegetation complexity are lower. A lower vegetation complexity leads to a lower biodiversity in the soil, which in turn affects the decomposition rate of the soil (Altieri, 1999). Combining this with the nutrient rich top layer being washed away due to the expected higher erosion in monoculture systems suggests a strong decrease in the soil's decomposition rate after deforestation. A decreased decomposition rate means that organic matter in the soil is being decomposed slowly, which leads to a lower nutrient availability in the soil (Power, 2010).

A possible way to mitigate the effects that deforestation has had on both the soil retention and the decomposition rate in monoculture systems could be to introduce trees in the agricultural fields to restore forest characteristics. The agricultural combination of crops and trees is called agroforestry, and is a possible alternative to monoculture farming. Agroforestry is a traditional agricultural model in the tropics that is still used by some farmers to grow, for example, coffee and cacao. Agroforestry systems are polycultures that, in addition to a cash crop (e.g. coffee or cacao), consist out of several other species, including woody species. These supplementary species can also provide products and services, like shade, wood, and food. If implemented well, agroforestry systems can be beneficial for biodiversity and therefore create a more natural and complex ecosystem than a monoculture can facilitate (Toledo & Moguel, 2012). By forming a multi-layered structure, agroforestry systems can reduce soil erosion, as they allow less water to reach the soil by intercepting up to 20% more rain water than less complex structures such as monocultures (de Jong & Jetten, 2007). Besides having a protective canopy, agroforestry systems also help to reduce soil erosion by increasing the above and below ground biomass that prevents rills from forming (Gyssels & Poesen, 2003). Also, agroforestry systems are known to have a positive influence on the productivity, and thus the decomposition rate, of the soil. By integrating different trees and crops, the vegetation complexity increases, allowing more nutrients, like N and P, to be fixated in the soil, which is beneficial for the soil fertility (Jose, 2009), and thus the agricultural productivity. This means that switching from a monoculture system to an agroforestry system could also be beneficial for increasing the decomposition rate of the soil, and by extension the productivity of the soil. Based on this it is hypothesised that an increased nutrient availability results in a higher decomposition rate.

An example of a country where deforestation due to agricultural expansion has been taking place is Colombia (Etter et al., 2006). A large agricultural area in Colombia is the Eje Cafetero, which is the main coffee producing region of the country. The region is located in the Andes mountains, and therefore has a relatively high erosion potential with, depending in the season, 11% to 28% of the coffee field having a severe erosion potential (Hoyos, 2005).

Because of this, several farmers in this region have started to implement agroforestry on their fields. To determine the effect of transitioning from a monoculture to an agroforestry system on both soil retention and the decomposition rate, the state of these two ecosystem services were compared for both land use types. It is hypothesised that the soil erosion will be lower in agroforestry systems due to a higher canopy stratification and higher levels of above and below ground biomass. Due to this reduced erosion, and due to the higher nutrient availability because of the higher below ground biomass, it is also hypothesised that the decomposition rate of the soil will be higher in agroforestry systems than in monoculture systems.

Several earlier studies already show that transitioning from a monoculture to an agroforestry system can have positive effects on several ecosystem services, including sediment retention and decomposition rate (de Aguiar et al., 2010; Kusumandari & Mitchell, 1997; Power, 2010). However, not much research was done to study the development of these services on a temporal scale. To incorporate this aspects in this research, farms with different years since transitioning to agroforestry will be taken into account. It is hypothesised that both sediment retention (Sun et al., 2018) and the decomposition rate are higher on farms with more years since transition (YST) (i.e. older farms).

Two often used erosion measurement methods are the Landscape Function Analysis (LFA) (Tongway & Hindley, 1996) and the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991). Both these methods use indicators such as the steepness of the slope, soil erodibility or soil stability to determine the erosion potential of the soil. Therefore they are indirect soil erosion measurement methods.

Because these methods use indicators, it is important to test the accuracy of these two methods. Determining the accuracy of these two methods can help to assess soil erosion more easily in the future, and therefore help to increase the insight in the effects that agroforestry has on the soil, and to what extend it can be applied as a soil management strategy. Due to this importance, the following research question was formulated:

Which of the two methods for measuring soil erosion potential, RUSLE and LFA, are most accurate for determining soil erosion in Colombian coffee fields?

Besides looking at sediment retention and the decomposition rate of the soil separately, this research will also try to combine these two aspects by studying the relation between soil erosion and the decomposition rate. To do so, the following research question will be answered:

What is the effect of soil erosion on the decomposition rate of the soil in Colombian coffee fields?

Based on studies from Jose (2009) and Power (2010), that suggest that decreasing soil erosion could also benefit the decomposition rate of the soil, it is hypothesised that a higher sediment retention contributes to a higher decomposition rate of the soil.

2. Methods

2.1 Research area description

This research was conducted in a seven week period ranging from the half of April to the end of May 2019. The measurements for this research were conducted on farms spread out through western Risaralda, a department that is located in the Eje Cafetero, which is the main coffee producing region of Colombia. The region is located in the Andes mountains, with altitudes ranging from 1000 to 2000 meters above sea level (Wintgens, 2009). The slope angles at the measurement locations varied between 2° and 65°. The average annual precipitation in Risaralda is 2584 mm (IDEAM, 2014). The region knows two wet seasons (March – May; September – November) and two dry seasons (December – February; June – August) (Hoyos, 2005). The area contains both monoculture and agroforestry systems, mostly for growing *Coffea arabica*, a coffee species that is very well suited to be grown in these high altitude areas due to the ideal temperature and precipitation levels (Wintgens, 2009). On a national level, around 16% of the coffee in Colombia is grown in agroforestry systems, and around 71% is grown in monoculture systems (Armenteras et al., 2004). It is assumed that this ratio is approximately the same for Risaralda.

Figure 1: The location of Risaralda (Medina-Morales et al., 2017).

2.2 Research set-up

For this research, 55 farms were visited. Of these 55 farms, 15 were monoculture farms and 40 were agroforestry farms. The years since transition (YST) of the farms ranged between 0 (monocultures) and 32 years. To analyse the development of decomposition and erosion over time, the years since transition have been allocated into age clusters. The specific grouping of the age clusters varied between measurement methods due to varying sample sizes, and is specified under each graph for which age clusters are used. The farm size ranged from 0,5 to 56 ha. To determine the general characteristics such as the YST and the size, a small interview was conducted with the farmer before starting with the field measurements. To conduct the measurements, a 20x20 meter plot was made at a representative part of each farm. With a representative part is meant that characteristics such as slope angle and tree density are around the average of the whole farm. Six soil samples were taken at each plot to perform the Tea Bag Index (TBI) method used to determine the decomposition rate of the soil. This method is explained below. To gather soil data such as organic matter or silt/sand/clay ratios, four more soil samples were taken within each plot to be send to a local lab for analysis. The altitude, canopy closure and tree density were also measured in each plot. To determine the indicators for the Landscape Function Analysis (LFA), as well as the slope angle for the Revised Universal Soil Loss Equation (RUSLE), eight subplots of 1x1 meter were made within each plot to determine the average value of each indicator within the main plot. To test the accuracy of the two indirect erosion measurements, a direct erosion measurement was also performed. This was done by placing a silt fence in the area close to the plot, depending on the local topography. All three soil erosion measurement methods (LFA, RUSLE and the silt fences) are also explained below.

2.3 Decomposition rate

The decomposition rate in the soil was determined by using a method called the Tea Bag Index (TBI). The TBI method was applied to 16 farms, of which four were monoculture systems and 12 were agroforestry systems. How this method can be used to calculate the decomposition rate of the soil is discussed in detail below.

2.3.1 The Tea Bag Index (TBI)

Figure 2: The soil samples as they were set up at the UTP.

The Tea Bag Index (TBI) method, which was developed by Keuskamp et al. (2013), is an easy to perform and economically feasible way to determine the decomposition rate of the soil. This is done by performing a simplified litter bag experiment that uses tea bags as the litter bags. Two types of tea will be used for this experiment; Lipton Green tea, and Lipton Rooibos tea. The tea bags have a small mesh size of 0.25 mm, so that microorganisms and mesofauna can enter the bags, but macrofauna cannot. Also, the bags are made from a synthetic material so that they do not degrade during their time in the soil (Keuskamp et al., 2013). To ensure controlled conditions, the tea bags were not buried on the plots, but instead six soil samples were taken from each plot and kept in plastic bags. All these bags were stored at the local university, the Universidad Technológica de Pereira (UTP), where students helped to keep the samples moisturised by administering water to the soil regularly. The amount of water administered was the same for all soil samples. For each plot there were six bags, three bags for green tea and three bags for rooibos tea. In each plastic bag, a tea bag was buried around five centimetres deep so that is was completely buried in the soil. The bags were kept open so that oxygen was freely available, and water was added regularly so prevent dehydration of the soil. After 21 days in the soil, the tea bags were retrieved and cleaned by removing all the sand from the bag. The tea bags were dried in an oven for 48 hours at 70 °C, after which each bag was weighted to determine the dry weight. To obtain the reference weight, five new bags of both types of tea were also dried in the oven under the same conditions and then weighted, so that an average starting weight could be determined for both types of tea. With the starting weight, and the weight after 21 days, the weight loss was calculated for each tea bag (Teatime4science, 2016).

There are two types of decomposable fractions in organic matter; the easily degradable fraction, which is decomposed relatively fast (the labile fraction), and the more difficult degradable fraction, which is decomposed relatively slow (the recalcitrant fraction). Since the labile fraction decomposes significantly faster than the recalcitrant fraction, it was assumed that the recalcitrant fraction did not decompose within the duration of this research. Therefore, in Keuskamp et al. (2013), these two compounds are combined in the following equation:

$$W(t) = a * e^{-kt} + (1 - a) \qquad \textit{Equation 1}$$

In which W(t) is the weight of the substrate (tea) after incubation time t, a is the labile fraction, (1-a) the recalcitrant fraction, and k is the decomposition rate constant. An overview of all the variables for the TBI method is provided in *table 1*.

Table 1: All variables used to calculate the TBI

Variable	**Description**
W(t)	Weight of the tea
a_g	Decomposable fraction of green tea
a_r	Decomposable fraction of rooibos tea
k	Decomposition rate constant
t	Incubation time
S	Stabilisation factor
H_g	Hydrolysable fraction green tea
H_r	Hydrolysable fraction rooibos tea

The decomposition rate of rooibos tea is relatively low compared to the decomposition rate of green tea. This means that when the labile fraction of green tea has completely decomposed, the labile fraction of rooibos tea is still decomposing. This difference in decomposition rates makes it possible to calculate the decomposition rate constant k.

During the decomposition process, a part of the labile fraction stabilizes and becomes recalcitrant (Prescott, 2010). This causes the actual decomposable fraction to differ from the hydrolysable fraction (H), which is the chemically expected decomposable fraction. Since this stabilization process is related to environmental factors (Berg & Meentemeyer, 2002), this stabilisation factor (S) can be interpreted as a limiting effect of the environmental conditions on the decomposition rate of the labile fraction. The stabilisation factor S is expressed in the following equation from Keuskamp et al. (2013):

$$S = 1 - \frac{a_g}{H_g} \qquad \textit{Equation 2}$$

In Keuskamp et al. (2013) it is shown that there is no significant difference between the stabilisation factors of both types of tea, allowing for the assumption that S is the same for green and rooibos tea. Rewriting *equation 2* allows for the calculation of a_r through the following equation:

$$a_r = H_r * (1 - S) \qquad \textit{Equation 3}$$

Both $W_r(t)$ and (t) were determined through the field experiment with the tea bags, allowing for a_r to be calculated. By inputting these variables into *equation 1*, the decomposition rate constant k can be determined.

2.4 Indirect soil erosion methods

As mentioned in the introduction, soil erosion was measured with the use of two indirect methods that use indicators to determine the level of erosion. These two methods are the Landscape Function Analysis (LFA) and the Revised Universal Soil Loss Equation (RUSLE). These two methods will be explained in detail below.

2.4.1 Landscape Function Analysis (LFA)

The Landscape Function Analysis is an indirect soil erosion measurement method that uses visually assessed indicators to determine the state of three soil aspects. The method is mainly based on surface hydrology processes, such as rainfall, infiltration, runoff, erosion, plant growth and nutrient cycling (Tongway & Hindley, 1996). The main advantage of this method is that a plot can easily be assessed within day, and is thus relatively fast compared to other methods for assessing soil erosion. This is mainly because the method is solely based on visual observations. The LFA method assesses three indicators; soil stability, infiltration rate and nutrient cycling, which are determined through several variables. *Table 2* describes all eight variables that were used for the analysis, together with the methods that were used to measure them, how they were scored, and to which indicator they contribute. As described in chapter 2.2 (research set-up), eight subplots were made within each plot. To gain an average plot value for each variable, the LFA method was applied to each subplot and the average values were calculated. By adding the scores of all the variables corresponding with the indicators, a score per indicator was determined. The indicator index for soil stability ranges from 6-31, for water infiltration from 4-43, and for nutrient cycling also from 4-43. The percentage of the maximum score is an indicator for the state that the variable is in. The soil stability indicator is defined as "the ability of the soil to withstand erosive forces, and to reform after disturbance". So, the soil stability indicator shows how susceptible the soil is to erosion (Tongway & Hindley, 1996).

Table 2: The LFA variables, measuring methods, scoring methods and indicators (Tongway & Hindley, 1996).

Variable	Measuring method	Scoring method	Indicator of variable
Rain splash protection	Assessment of percentage of perennial vegetation of 0.5 m or less, rocks >2 cm, and woody material >1 cm.	5 classes ranging from '1% or less' to 'more than 50%'.	Soil stability
Perennial vegetation cover	Assessment of percentage of canopy cover of trees and shrubs.	4 classes ranging from '20% or less' to 'more than 70%'.	Water infiltration Nutrient cycling
Litter cover	Assessment of percentage of amount, origin and degree of decomposition of plant litter	Amount: 10 classes ranging from '10% or less' to '100%' cover, plus '100% and thickness X' with thickness X going up to 170 mm. Origin: Local or transported. Decomposition: 4 classes ranging from 'nil' to 'extensive'.	Soil stability Water infiltration Nutrient cycling
Cryptogram cover	Assessment of percentage of cover by mosses, algae, fungi, liverworts and lichens.	5 classes ranging from 'no cryptogram cover' to 'more than 50% cryptogram cover'.	Soil stability Water infiltration Nutrient cycling
Soil erosion type and severity	Assessment of presence of rills and gullies, terracettes, sheeting, scalding, or pedestalling erosion and their severity.	5 types of soil erosion with 4 classes of severity, ranging from 'insignificant' to 'severe'.	Soil stability
Deposited materials	Assessment of presence and amount of alluvium.	4 classes ranging from '0-5% cover' to 'more than 50% cover' with varying depth ranges.	Soil stability
Soil surface roughness	Assessment of presence and depth of depressions in the soil surface.	5 classes ranging from 'less than 3 mm relief' to 'more than 100mm relief'.	Water infiltration Nutrient cycling
Stability of soil fragments	Assessment of intactness of dry or air-dried soil after wetting with rainwater.	5 classes ranging from 'no coherent fragments' to 'very stable'.	Soil stability

Originally, the LFA method was designed for dryland ecosystems, so some adaptations had to be made to apply it in Colombia's tropical wet ecosystem. The scoring method's scale for 'perennial vegetation cover' was changed to higher percentages so that it fits the expected perennial vegetation cover range. These new percentages are based on a study performed by Jha & Vandermeer, (2010). The variables 'crust brokenness' and 'surface nature' were not included in the measurements. Based on the LFA manual (Tongway & Hindley, 1996), these two variables are not applicable on wet or moist soils. Since the research area was located in the tropics, the soils were always wet or moist. Especially since the field work (April and May) took place during the first rain season (March – May). Because the results of the LFA method are in percentages, leaving out these variables does not affect the accuracy of the method. Applying the left out variables would result in every subplot gaining the same score, resulting in no effect on the final percentage.

2.4.2 Revised Universal Soil Loss Equation (RUSLE)

The Revised Universal Soil Loss Equation (RUSLE) is a method used to calculate soil loss estimates from sheet and rill erosion caused by rainfall and the resulting overland flow by combining six factors in the following equation from Foster et al. (1999):

$$A = R * K * L * S * C * P \qquad \textit{Equation 4}$$

Table 3 shows a description of each factor, together with the corresponding units. Some of these factors were determined on site and some of them were gathered from existing literature.

Table 3: Descriptions and units for the six RUSLE variables

Var	Description
A	Average annual soil loss (t ha^{-1} yr^{-1})
R	Rainfall erosivity (MJ mm^{-1} ha^{-1} h^{-1})
K	Soil erodibility (t h^{-1} MJ^{-1} mm^{-1})
L	Length of the slope (m)
S	Steepness of the slope (°)
C	Cover management factor (dimensionless)
P	Soil support-practice (dimensionless)

The Rainfall erosivity factor (R)

The amount of erosion that occurs is partly dependent on the climate. This influence of the climate is called the rainfall erosivity factor, and is usually expressed as a combination of rainfall amount and intensity (Hoyos et al., 2005). In the article, Hoyos et al. (2005) developed a method to calculate the R factor for the Dosquebradas Basin, which is located in the Colombian Andes, close to where this research has taken place. They calculated the seasonal R factor for six weather stations in the region of the basin. It is stated in the article that the basin is representative for a tropical mountainous environment, which allows for generalisation to neighbouring regions. Since determining the R factor requires an elaborate calculation, it was assumed that the average rainfall erosivity for this research could be based on the calculations by Hoyos et al. (2005). For this research, the average R factor was calculated for the first rainy season by combining the R factor for this period of all six weather stations. Since all the farms in this research are located relatively close together, it was assumed that the R factor is the same for all farms.

Soil erodibility factor (K)

The soil erodibility factor is the natural capacity of a soil to erode. To determine the Soil erodibility factor for each plot, the following equation from Wischmeier & Smith (1981) was used**:**

$$K = \frac{(2.1 * 10^{-4}(12-a)M^{1.14} + 3.25(b-2) + 2.5(c-3))}{100}$$ *Equation 5*

in which a is the percentage of organic matter, $\mathrm{M} = (\text{percent silt} + \text{very fine sand}) * (100 - \text{percent clay})$, b is the soil structure code used for soil classification, and c is the profile permeability class. To determine these variables, soil samples were taken on each plot and send to a local lab for analysis. The lab results included the percentage of organic matter and the percentages of sand, silt and clay. This data resulted in the a and M variables. To determine the b and c values, two tables were used from (Wall et al., 2002) in which the soil structure code and the soil classification are determined by the ratio of sand, silt and clay.

Length factor (L)

The length factor (i.e. the slope length) was calculated according to the following formula from Wischmeier & Smith (1981):

$$L = (\lambda/22{,}13)^{m}$$ *Equation 6*

In which λ = the slope length in meters, and m = is the slope length exponent. To determine the slope length, the horizontal length of the slope was measured for each plot using Google Earth. Even though this method is fairly subjective, the implications of minor measurement errors are relatively small as slope length is the least contributing factor of the RUSLE equation (Renard et al., 1991). The slope length exponent from the original USLE model was used, as it is better suited for steep slopes than the RUSLE slope length exponent (Liu et al., 2000).

Steepness factor (S)

The following equation from Nearing (1997) was used to calculate the steepness factor, as it was adjusted to be better suited for steep slopes:

$$S = -1{,}5 + {}^{17}\!/_{[1 + e^{(2{,}3 - 6{,}1 \sin\theta}]}$$ *Equation 7*

In which θ = the slope angle in radians. The slope angle was measured at each plot using a clinometer.

Cover management factor (C)

The cover management factor is determined by effects of cover and cover management variables. In a research done by Hoyos (2005), the cover management factor for coffee production in the Dosquebradas Basin was determined. Since the characteristics of the coffee farms used in her research are similar to the characteristics of the farms used in this research, it is assumed that the C values from Hoyos (2005) are also applicable to this research. In het article, Hoyos (2005) determines the C values for sunny systems and for shade systems, and are estimated at 0.035 and 0.030 respectively (Hoyos, 2005).

Soil support practice factor (P)

The soil support factor signifies the effect of support practices, such as contouring or strip cropping. As soil support practice (P) values, the general P values are used as described by Wall et al., 2002. See *table 4*.

Table 4: Five different support practice classifications (Wall et al., 2002).

Support practice	P-value
No support practice	1.00
Cross slope farming (planting done across the slope)	0.75
Contour farming (planting done following topographic contours of the slope)	0.50
Strip cropping (alternating bands of crop and vegetation), cross slope (3-8% slopes)	0.38
Strip cropping, on contour (3-8% slopes)	0.25

2.5 Direct soil erosion method

The LFA and RUSLE methods are used to indirectly calculate the erosion through the use of indicators. To test the accuracy of both the LFA and the RUSLE methods, the direct soil erosion was measured by using the silt fence method. This method is discussed in detail below.

2.5.1 The silt fence method

Silt fences have been a very common method for erosion control at construction sites for several decennia (IFI Claims, 1998), but can also be used as an economically feasible method for measuring hillslope soil erosion. To this end, silt fences were placed on 16 farms in total, 15 of which were agroforestry farms and 1 was a monoculture farm. The silt fence method provided data on the loss of soil and litter through erosion for all 16 farms. A silt fence is made of a synthetic permeable fabric (geotextile) that is commonly used to separate, filter or reinforce soil layers in, for example, gardens. Because the pores in the fabric are very small (0,3 – 0,8 mm), the permeability rate is very low (0.00028 – 0.013 m^3 sec^{-1}). Due to this, the silt fence entraps the water, allowing the sediment to settle, and the water to flow through the textile. The relatively strong structural integrity (0,3 – 0,4 kN) ensures that the fabric can sustain the force that is applied by the entrapped water (Robichaud & Brown, 2002). Even though this method will not be 100% efficient in collecting the sediment, research shows that, depending on the fabric that is used, the trapping efficiency lies between 68 and 99%, and therefore provides a good estimation of the amount of sediment that is being eroded (Britton et al., 2001). The silt fences were placed in a rain water catchment, so that the sediment contribution area could be calculated. To provide optimal results, the steepness of the slope should be between 2 and 35 degrees. This was the case for 15 of the 16 farms. The exact locations of the silt fences was determined on site, as it is dependent on several factors, most importantly the local relief of the ground. The silt fences generally were between two and three meters wide, and the plot length (upslope) was between 5 and 10 meters, depending on the terrain. These measurements are based on the range values that are given by Robichaud & Brown (2002). To limit the sediment contribution area (plot), a barrier was created at the top of the

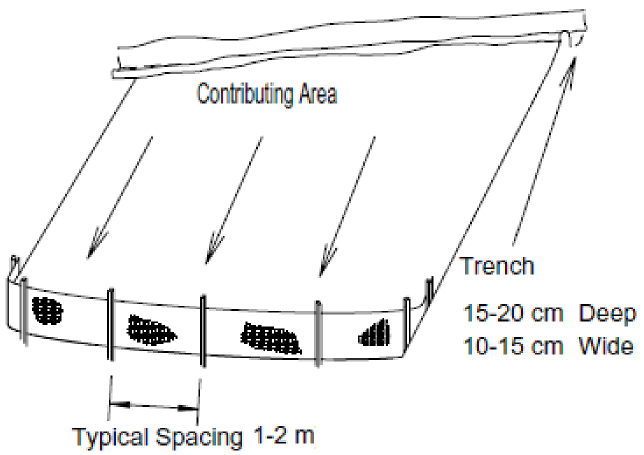

Figure 3: Sketch of a silt fence setup (Robichaud & Brown, 2002)

plot to prevent water from further uphill to contribute sediment to the plot. This barrier was either an existing barrier, such as a road or a small wall, or it was created by building a barricade from organic material found in the area, such as branches, leaves and rocks. The sides of the plots followed the local topography as much as possible, in such a way that the silt fence was generally placed in a natural catchment area. Whenever this was not possible, a catchment area was created by building barriers at the sides of the plot from branches, leaves and sand. A sketch of the proposed plot setup is shown in *Figure 3*. The exact location of each plot was logged by using 'GPS Essentials', which is a mobile phone application.

To determine the amount of erosion, the contents of the silt fences were collected after ±14 days, after which the sediment and litter were dried to evaporate excess water. Due to the limited access to a stove, this was done by air drying the contents in the sun for approximately 48 hours. The dry weight was then measured by using a scientific scale. To relate the amount of erosion to the local rainfall, the precipitation was measured for the same duration as the silt fence was up. This was done by placing a cut open plastic bottle next to the plot to catch the rainwater. To prevent water to evaporate during the collection period, a thin layer of mineral oil was placed on the surface of the water to isolate it from the air. The rainwater was collected at the same time as the contents of the silt fences. The amount of water in the bottle was determined by using a measuring cup. By combining the weight of the sediment with the surface of the plot, the precipitation and the duration, the direct erosion could be calculated.

2.6 Data analysis

The data gathered with the above described methods were statistically analysed using IBM SPSS Statistics 25 (IBM Corp, 2017). To determine whether there were any significant differences between monoculture and agroforestry systems, the mean values for both systems were compared with an independent samples t-test. To test for a possible relationships between two variables, in most cases a linear regression model was made. Curve fitting was used to test whether there was a non-linear function that fitted the data better. The data was always tested for normality using the Shapiro-Wilk test with a significance level of $p<0.05$. When the residuals were not normally distributed, a log^{10} transformation was applied. To analyse the age cluster of the years since transition variable, a one-way anova with a Tukey posthoc test was performed. Before running the one-way anova tests, homogeneity was always tested with a Levene's test with a significance level of $p<0.05$.

In the case that outliers were present, these outliers were only removed from the dataset when it was uncertain whether the data was measured correctly. When tests were ran with data that is related to trees, such as canopy closure, monoculture systems were not taken into account since there are no trees on a monoculture and thus the canopy closure is always 0.

3. Results

3.1 General characteristics of the study area

Table 5 shows statistics on three general characteristics. It can be observed that the average size of monoculture systems is significantly larger than agroforestry systems. Also, the mean altitude for monocultures is significantly higher than the mean altitude of agroforestry systems. No statistics were ran for the years since transition, because this characteristic is not applicable to monocultures. Therefore, all farms with a years since transition higher than zero are agroforestry farms.

Table 5: General statistics of the farm size, altitude and years since transition (YST). The statistics are shown for all farms combined, as well as for monocultures and agroforestry systems separately. Per row, different letters indicate a significant difference between groups for a significance level of p<0.05.

	Statistics	Mean	St. dev.	Min	Max	n
Farm size *(ha)*						
All	F(1,52)=22.935	8,15	13,91	0,85	93,00	54
Monoculture	P<<0.01	18,52[a]	22,78	1,00	93,00	15
Agroforestry		4,16[b]	3,33	0,85	19,80	39
Altitude *(m.a.s.l.)*						
All	F(1,53)=0.090	1534,07	154,15	1205,00	1870,00	55
Monoculture	P=0.043	1603,07[a]	136,10	1320,00	1783,00	15
Agroforestry		1508,20[b]	152,55	1205,00	1870,00	40
Years since transition *(y)*						
Monoculture	-	0,00	0,00	0,00	0,00	15
Agroforestry (all)		10,21	6,26	2,00	32,00	39

Comparing the years since transition (YST) and the canopy closure showed that there is a significant correlation between the YST and the canopy closure (R^2=0.229, F(1,36)=10.665, p=0.002). This positive logarithmic correlation is shown in *Figure 4*.

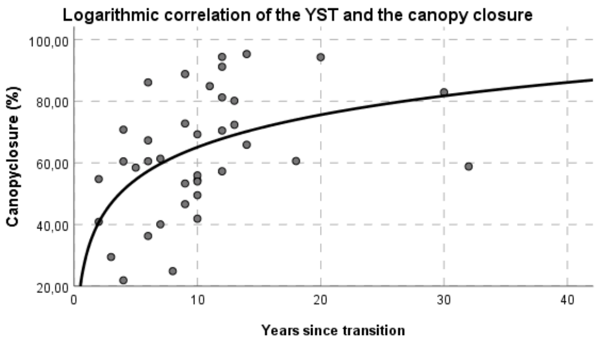

Figure 4: The logarithmic correlation between the years since transition and the canopy closure.

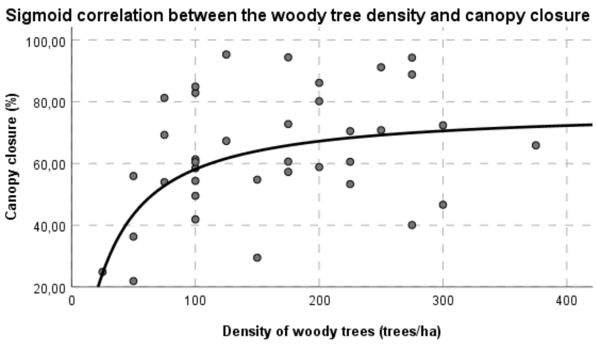

Figure 5: The sigmoid correlation between the woody tree density and the canopy closure

The canopy closure was also compared with the tree density, which showed that the canopy closure has a sigmoid correlation with the density of woody trees (R^2=0.326, F(1,35)=16.935, p<<0.01). This correlation is shown in *figure 5*. However, no significant relation was found between the canopy closure and the banana tree density (R^2=0.109, F(1,31)=3.786, p=0.061), or between the canopy closure and the combined effect of the woody and banana trees (R^2=0.066, F(1,37)=2.610, p=0.115).

3.2 Soil nutrients

Soil samples were taken in the field and send to a local lab for analysis. The results of this analysis for nitrogen, soil organic matter (SOM) and phosphorous will be discussed below.

3.2.1 Nitrogen

Comparing the nitrogen content of monocultures with the nitrogen content of agroforestry systems shows that these do not differ significantly (F(53)=2.092, p=0.400). It was also found that the nitrogen content does not have a significant correlation with the years since transition (R^2=0.044, F(1,37)=1.710, p=0.199), nor where there any significant differences between the six age clusters. This means that the nitrogen content of the soil does not change over time.

3.2.2 Soil organic matter

Comparing the soil organic material of monoculture systems with that of agroforestry systems shows that there is no significant difference in organic material between the two land use types (F(53)=1.801, p=0.427). Also, no significant relation was found between the SOM and the years since transition (R^2=0.044, F(1,37)=1.710, p=0.199). Allocating the years since transition variable into six age clusters shows no significant differences between the age clusters. This means that the SOM also does not change over time.

3.2.3 Phosphorous

The comparison between the phosphorous content of monocultures and agroforestry systems showed that there is no significant difference (F(1,53)=0.947, p=0.927) in phosphorous between these two land use types.

Comparing the phosphorous content with the years since transition variable shows a logarithmic correlation (R^2=0.163, F(1,35)=6.807, p=0.013). This correlation is shown in *figure 6*. Allocating the years since transition into six age clusters to perform a posthoc test was not possible because the data was not homogeiniously distributed.

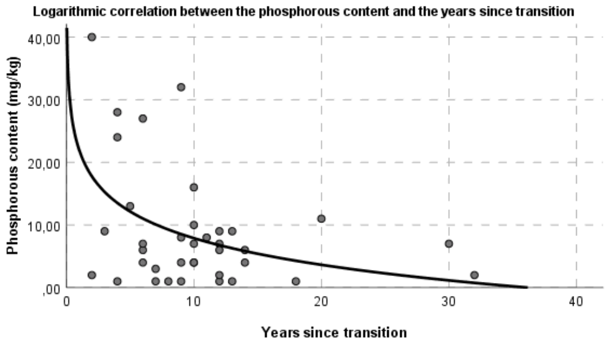

Figure 6: The logarithmic correlation between the phosphorous content and the years since transition.

3.3 Decomposition rate

For an overview of the data used to obtain the results shown below, see appendix I. Comparing the average decomposition rate of monocultures (0.0275 ± 0.0096) with the average decomposition rate of agroforestry systems (0.0139 ± 0.0038) shows a significantly higher decomposition rate in monoculture systems (F(14)=6.228, p=0.026). Allocating the agroforestry systems into four age clusters shows that the decomposition rate in monocultures is only significantly higher when compared to young agroforestry systems (p=0.031). *Figure 7* shows the distribution of the decomposition rates per age cluster. An overview of the posthoc results is shown in appendix II. Further statistical analysis also showed that the decomposition rate also shows a significant positive correlation with the altitude (R^2=0.247, F(1,14)=4.601, p=0.05). This correlation is shown in *figure 8*. A separate (non-significant) trend line estimation of the decomposition rate over time is shown in *figure 9* (R^2=0.074, F(1,10)=0.794, p=0.394). In *figure 9*, it can be observed that, although not significant, the decomposition rate is slightly increasing over time.

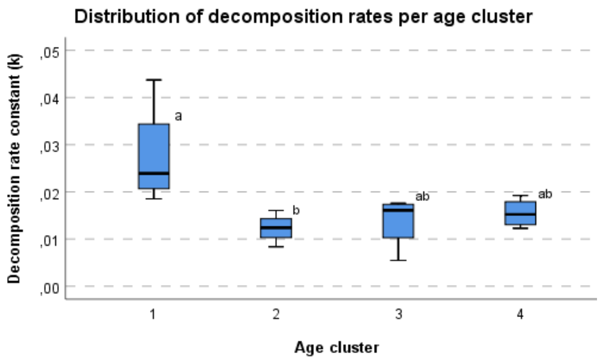

Figure 7: Boxplots showing the distribution of the decomposition rates per age cluster. Age clusters in years since transition: 1 = 0 (Monocultures), 2 = 1-7, 3 = 8-11, 4 = >12. Different letters indicate a significant difference between age clusters for a significance level of p<0.05.

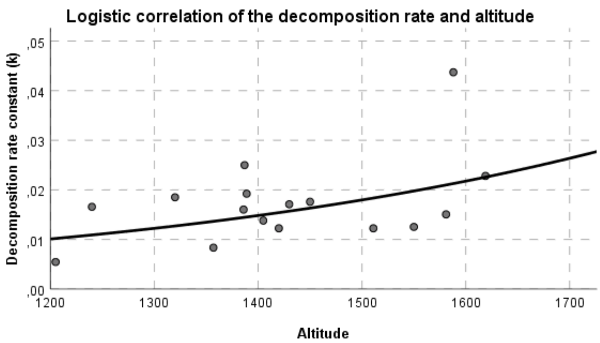

Figure 8: The linear correlation between the decomposition rate and the altitude.

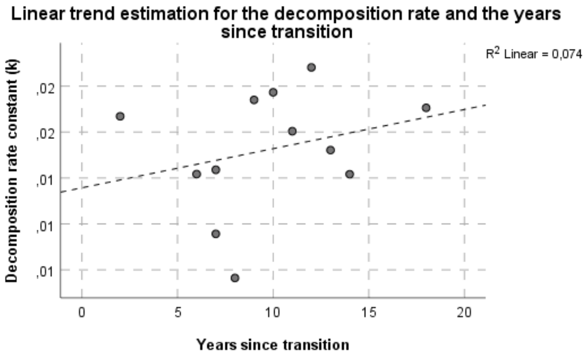

Figure 9: The linear trend estimation for the decomposition rate constant and the years since transition.

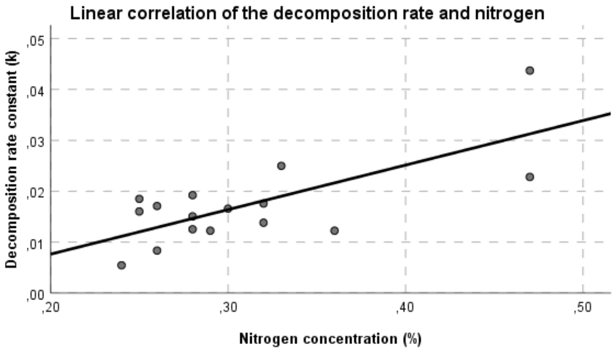

Figure 10: The linear correlation of the decomposition rate and the nitrogen content

Comparing the decomposition rate with the canopy closure showed that there is no significant relation between these two variables (R^2=0.045, F(1,8)=0.378, p=0.556). Further analysis showed that there is also no significant relation between the decomposition rate and the woody trees density (R^2=0.001, F(1,10)=0.009, p=0.928), or between the decomposition rate and banana tree density (R^2=0.011, F(1,10)=0.108, p=0.749). Also, no significant relation between the decomposition rate and the total tree density (woody + banana) was found (R^2=0.013, F(1,10)=0.127, p=0.729).

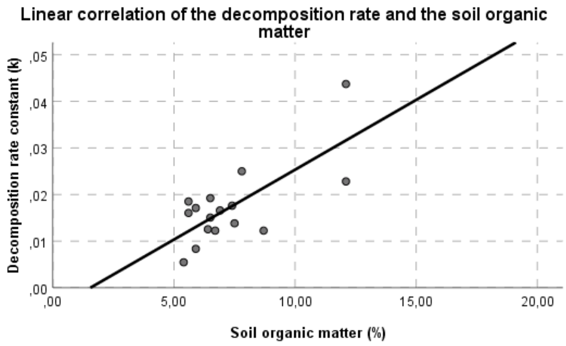

Figure 11: The linear correlation between the decomposition rate and the soil organic matter.

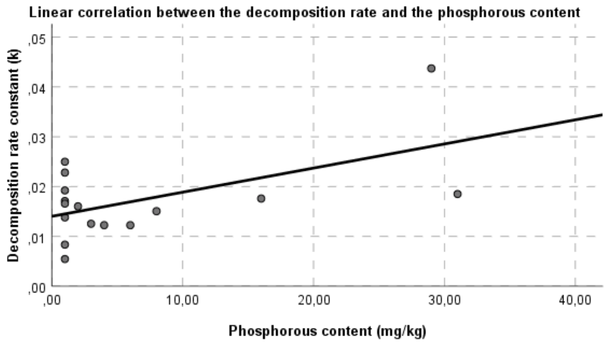

Figure 12: The linear correlation between the decomposition rate and the phosphorous content.

Analysing the relation between the decomposition rate with the nutrient availability shows that there is a linear correlation between the decomposition rate and the nitrogen content (R^2=0.517, F(1,14)=14.963, p=0.002). This linear correlation is shown in *figure 10*. It also showed that there is a linear correlation between the decomposition rate and the SOM (R^2=0.522, F(1,14)=15.301, p=0.002). This linear correlation is shown in *figure 11*. A linear relation between the decomposition rate and the phosphorous content was also found (R^2=0.314, F(1,14)=6.399, p=0.024). This linear correlation is shown in *figure 12*.

3.3 Landscape function analysis

The landscape function analysis (LFA) method results in three different indicators: soil stability, infiltration and nutrient cycling. The results are discussed below. An overview of the results from the analysis is shown in appendix III.

3.3.1 Stability

The comparison between the average stability indicator value of monocultures (50.43 ± 7.40) and agroforestry systems (55.80 ± 4.61) shows that agroforestry system soils are significantly more stable than monoculture soils ((F53)=1.902, p=0.001). Allocating the agroforestry systems into six age clusters shows that the average soil stability is increasing as agroforestry systems get older. This causes significant differences in stability indicator values between monocultures and agroforestry systems in age cluster 5 (p=0.010) and age cluster 6 (p=0.030). These two clusters include all farms that made the transition to agroforestry more than 10 years ago. *Figure 13* shows the distribution of the stability indicator per age cluster. Further statistical analysis showed that there is no relation between soil stability and the altitude at which the plot was located (R^2=0.006, F(1,53)=0.340, p=0.563). However, a significant relation was found between the stability factor and the canopy closure (R^2=0.142, F(1,37)=6.113, p=0.018). *Figure 14* shows the linear correlation between the soil stability indicator and the canopy closure.

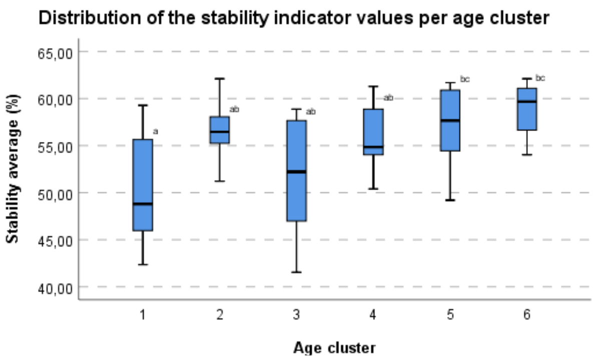

Figure 13: Boxplots showing the distribution of the soil stability indicator per age cluster. Age clusters in years since transition: 1 = 0 (Monocultures), 2 = 1-5, 3 = 6-8, 4 = 9-10, 5 = 11-15, 6 = >16. Different letters indicate a significant difference between age clusters for a significance level of p<0.05.

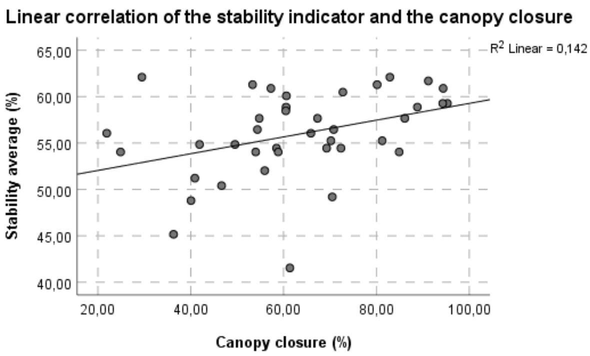

Figure 14: The linear correlation between the soil stability indicator and canopy closure.

Testing for a correlation between the soil stability indicator and the tree density showed that there is no significant correlation between the soil stability and the density of woody trees (R^2=0.000, F(1,38)=0.004, p=0.949) or between the soil stability and the density of banana trees (R^2=0.015, F(1,32)=0.493, p=0.488). Combining these two tree types showed that the soil stability also does not correlate with the total tree density (woody + banana) (R^2=0.006, F(1,38)=0.230, p=0.635).

Comparing the soil stability indicator with the nutrient availability shows that there is no significant relation between the LFA soil stability indicator and the nitrogen content (R^2=0.003, F(1,53)=0.166, p=0.686). It was also found that there is no significant relation between the LFA soil stability indicator and the SOM (R^2=0.019, F(1,53)=1.018, p=0.318), nor is there a significant relation between the soil stability indicator and the phosphorous content (R^2=0.011, F(1,51)=0.544, p=0.464).

3.3.2 Infiltration rate

The infiltration rate in monoculture systems (29.87 ± 7.40) is significantly lower than in agroforestry systems (37.09 ± 8.38) ($F(53)=0.110$, $p=0.006$). Allocating the years since transition variable into six age clusters shows that the infiltration rate indicator of agroforestry systems is only significantly higher than monoculture systems for age cluster 5, with a YST from 11 to 15 years ($p=0.013$). The distribution of the infiltration rate indicator per age cluster is shown in *figure 15*. It can be observed that there is an optimum at age cluster 5. Further analysis shows that there is no significant relation between the infiltration rate and the altitude ($R^2=0.011$, $F(1,53)=0.597$, $p=0.443$). It was found that there is a significant correlation between the infiltration rate and canopy closure ($R^2=0.199$, $F(1,37)=9.202$, $p=0.004$). *Figure 16* shows the logarithmic correlation between the infiltration rate indicator and canopy closure.

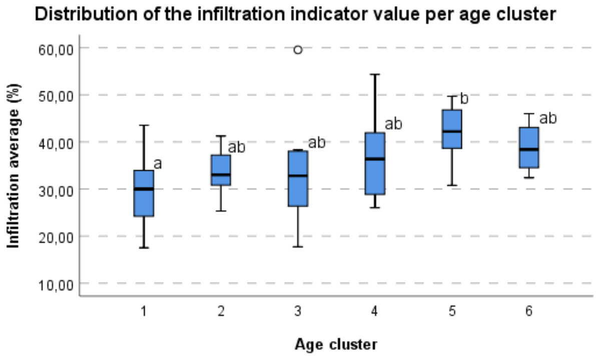

Figure 15: Boxplots showing the distribution of the infiltration rate indicator per age cluster. Age clusters in years since transition: 1 = 0 (Monocultures), 2 = 1-5, 3 = 6-8, 4 = 9-10, 5 = 11-15, 6 = >16. Different letters indicate a significant difference between age clusters for a significance level of p<0.05.

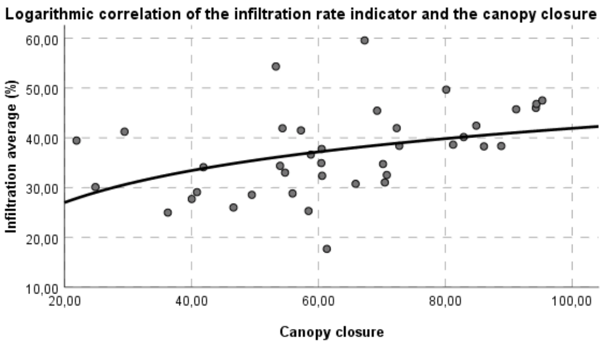

Figure 16: The logarithmic correlation between the infiltration rate indicator and canopy closure.

Comparing the infiltration rate indicator with the tree density showed that there is no significant relation between the infiltration rate and the density of woody trees ($R^2=0.002$, $F(1,38)=0.080$, $p=0.779$) or between the infiltration rate and the density of banana trees ($R^2=0.035$, $F(1,32)=1.167$, $p=0.288$). Combining these two types of trees does not show a significant relation between the infiltration rate and the total tree density ($R^2=0.012$, $F(1,38)=0.463$, $p=0.500$).

3.3.3 Nutrient cycling

The nutrient cycling in monoculture systems (25.18 ± 6.38) is significantly lower than in agroforestry systems (31.87 ± 7.06) ($F(53)=0.241$, $p=0.003$). Allocating the years since transition variable into six age clusters shows that the nutrient cycling indicator in agroforestry systems is only significantly higher than monoculture systems for cluster 5, with a YST from 11 to 15 years ($p=0.014$). The distribution of the infiltration rate indicator per age cluster is shown in *figure 17*. It can be observed that there is an optimum at age cluster 5. No significant relation was found between nutrient cycling and the altitude ($R^2=0.028$, $F(1,53)=1.519$, $p=0.223$).

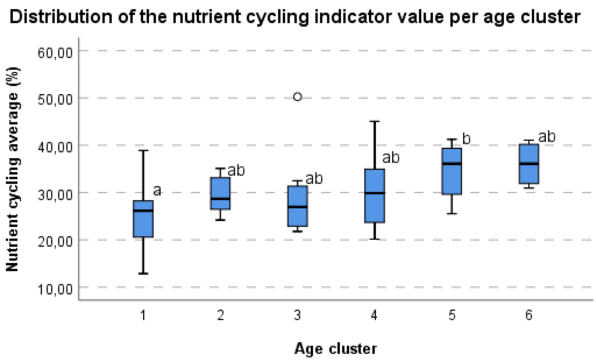

Figure 17: Boxplots showing the distribution of the nutrient cycling indicator per age cluster. Age clusters in years since transition: 1 = 0 (Monocultures), 2 = 1-5, 3 = 6-8, 4 = 9-10, 5 = 11-15, 6 = >16. Different letters indicate a significant difference between age clusters for a significance level of p<0.05.

However, there was a significant relation found between nutrient cycling and the canopy closure (R^2=0.158, F(1.37)=6.953, p=0.012). *Figure 18* shows the logarithmic correlation between the nutrient cycling indicator and canopy closure.

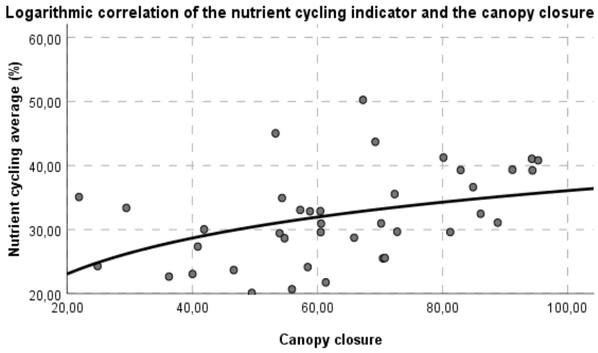

Figure 18: The logarithmic correlation between the nutrient cycling indicator and canopy closure.

Comparing the nutrient cycling indicator with the tree density showed that there is no significant relation between nutrient cycling and the density of woody trees (R^2=0.001, F(1,38)=0.022, p=0.884) or between nutrient cycling and the density of banana trees (R^2=0.018, F(1,32)=0.592, p=0.447). Also, no significant relation was found between the total tree density (woody + banana) (R^2=0.004, F(1,38)=0.153, p=0.698).

3.4 Revised universal soil loss equation

More detailed information on the RUSLE results can be found in appendix IV. Analysing the RUSLE results shows that the soil erosion potential is significantly higher in monoculture systems (328.31 ± 162.55) than in agroforestry systems (232.96 ± 136.55) (F(53)=0.452, p=0.037). Allocating the years since transition variable into six age clusters shows that the soil erosion potential in agroforestry systems is only significantly lower than monoculture systems at cluster 5, with a YST from 11 to 15 years (p=0.050). The distribution of the soil erosion potential per age cluster is shown in *figure 19*. Further statistical analysis shows that there is no significant relation between the erosion potential and the altitude (R^2=0.000, F(1,53)=0.18, p=0.893). Also, no significant relation was found between the soil erosion potential and the canopy closure (R^2=0.045, F(1,37)=1.747, p=0.194).

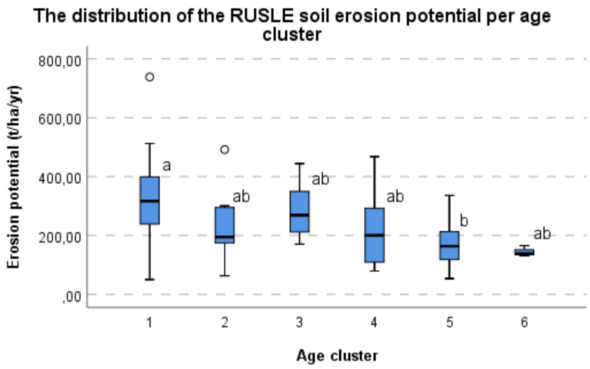

Figure 19: Boxplots showing the distribution of the RUSLE soil erosion potential per age cluster. Age clusters in years since transition: 1 = 0 (Monocultures), 2 = 1-5, 3 = 6-8, 4 = 9-10, 5 = 11-15, 6 = >16. Different letters indicate a significant difference between age clusters for a significance level of p<0.05.

Comparing the soil erosion potential with the tree density shows that there is no significant relation between the erosion potential and the density of woody trees (R^2=0.006, F(1,37)=0.215, p=0.646). A significant correlation was found between the erosion potential and the banana tree density (R^2=0.117, F(1,32)=4.225, p=0.048). The logistic correlation between the erosion potential and banana tree density is shown in *figure 20*. Combining the two tree types shows that there is no significant relation between the erosion potential and the total tree density (R^2=0.076, F(1,37)=3.064, p=0.088).

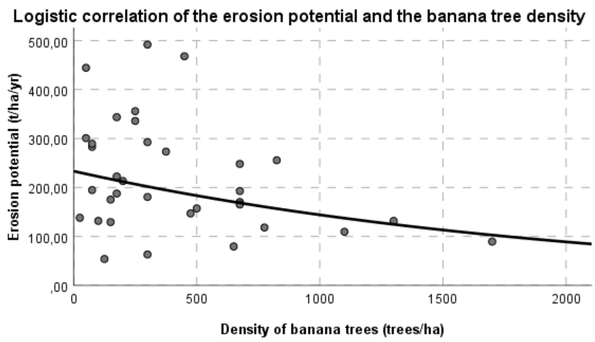

Figure 20: The logistic correlation between the erosion potential and the banana tree density.

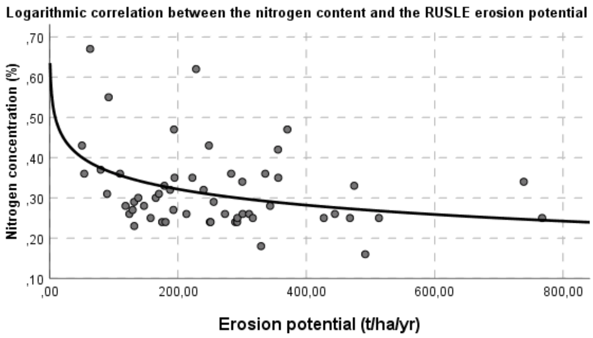

Figure 21: The logarithmic correlation between the nitrogen content and the erosion potential.

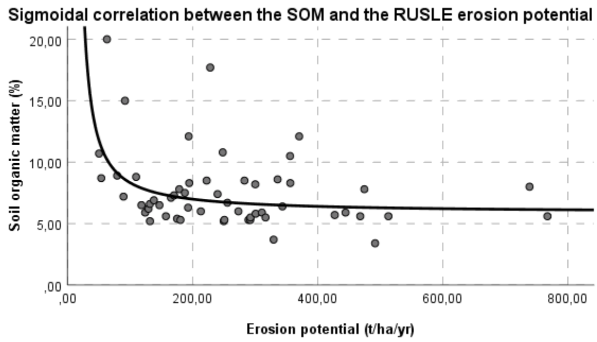

Figure 22: The sigmoidal correlation between the soil organic matter and the RUSLE soil erosion potential.

Analysing the relation between the soil erosion potential and the nutrient availability showed that there is a logarithmic relation between the soil nitrogen content and the soil erosion potential (R^2=0.125, F(1,53)=7.606, p=0.008). This correlation is shown in *figure 21*. It also showed that there is a sigmoidal correlation between the SOM and the soil erosion potential (R^2=0.168, F(1,53)=10.730, p=0.002). This correlation is shown in *figure 22*. No significant relation was found between the soil erosion potential and the phosphorous content (R^2=0.024, F(1,51)=1.279, p=0.263).

3.5 Silt fences

Unfortunately it was only possible to apply the silt fence method on one monoculture farm due to the availability and suitability of monoculture farms in the first weeks of the field work period. Therefore a comparison between monocultures and agroforestry systems could not be made. However, all other analyses were performed for both the measured sediment erosion and the measured litter erosion. An overview of the silt fence data can be found in appendix V.

3.5.1 Sediment erosion

Analysing the sediment erosion data showed that there is no significant relation between the sediment erosion and the altitude (R^2=0.003, F(1,10)=0.029, p=0.868). Also, no significant relation was found between the sediment erosion and the years since transition (R^2=0.008, F(1,12)=0.100. p=0.757). Allocating the sediment erosion into age cluster showed that there were no significant differences between the age clusters. There was also no significant relation between the sediment erosion and the canopy closure (R^2=0.001, F(1,12)=0.011, p=0.919). Comparing the sediment erosion with the tree density showed that there is a significant correlation between the soil erosion and the density of woody trees (R^2=0.394, F(1,12)=7.810, p=0.016). Curve fitting showed that a linear trend was the best fit for the data. The linear correlation between the sediment erosion and the woody tree density is shown in *figure 23*. No correlation between the soil erosion and the density of banana trees was found (R^2=0.005, F(1,9)=0.049, p=0.829), nor was there a relation between the sediment erosion and the total tree density (woody + banana) (R^2=0.053, F(1,12)=0.669, p=0.429).

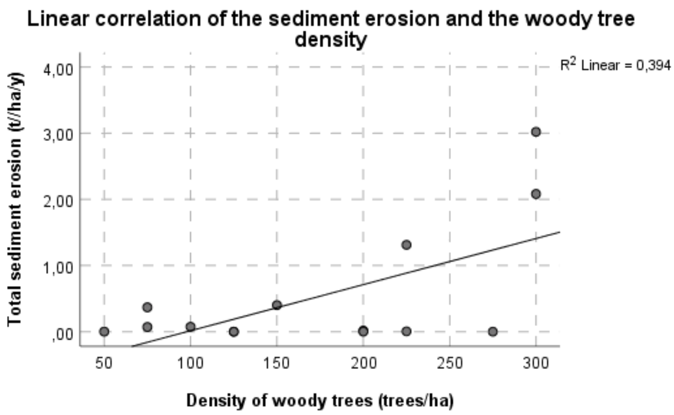

Figure 23: The linear correlation between the sediment erosion and the woody tree density.

Testing the relation between the sediment erosion and the nutrient availability showed that there is no significant relation between the soil nitrogen content and the silt fence sediment erosion (R^2=0.073, F(1,12)=0.942, p=0.351). It also showed that there is no significant relation between the SOM and the silt fence sediment erosion (R^2=0.046, F(1,12)=0.584, p=0.459), nor was there a significant relation between the phosphorous content and the silt fence sediment erosion (R^2=0.066, F(1,12)=0.853, p=0.374).

3.5.2 Litter erosion

Statistical analysis of the litter erosion data showed that the is no significant relation between the litter erosion and the altitude (R^2=0.001, F(1,13)=0.014, p=0.909). There was also no significant relation found between the litter erosion and the years since transition (R^2=0.074, F(1,12)=0.963, p=0.346) or between the litter erosion and canopy closure (R^2=0.000, F(1,11)=0.000, p=0.993). Further analysis shows that there is no significant relation between the litter erosion and the density of woody trees (R^2=0.001, F(1,12)=0.012, p=0.913). Also, no relation was found between the litter erosion and the density of banana trees (R^2=0.113, F(1,9)=1.152, p=0.311). The total tree density (woody + banana) also showed no significant relation (R^2=0.000, F(1,12)=0.004, p=0.952). Comparing the litter erosion and the nutrient availability showed that there is no significant relation between the soil nitrogen content and the litter erosion (R^2=0.060, F(1,13)=0.836, p=0.377). Also, no significant relation between the SOM and the litter erosion was found (R^2=0.019, F(1,13)=0.249, p=0.626), nor was there a relation between the phosphorous content and the litter erosion (R^2=0.150, F(1,13)2.295, p=0.154).

3.6 Comparing the soil erosion methods

Statistically comparing the stability factor from the LFA method with the erosion potential from RUSLE method showed that there is a strong significant relation between the soil stability and the erosion potential (R^2=0.227, F(1,51)=14.990, p<<0.01). The graph in *figure 24* shows the linear correlation between the soil stability and the erosion potential. It can be observed that soils with a higher soil stability have a lower erosion potential.

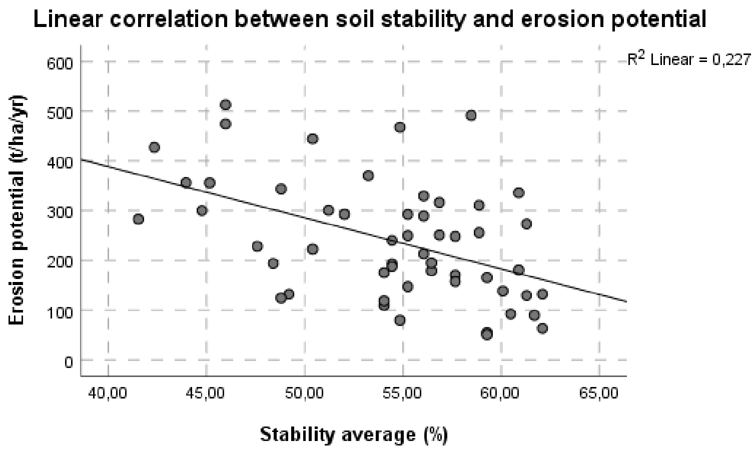

Figure 24: Linear correlation between soil stability and erosion potential.

Comparing the soil stability indicator from the LFA method with the results from the silt fence method showed no significant relation with either the collected sediment erosion (R^2=0.044, F(1,13)=0.592, p=0.456) or with the collected litter erosion (R^2=0.014, F(1,13)=0.188, p=0.672). Also, no significant relation was found between the RUSLE erosion potential and the sediment erosion (R^2=0.003, F(1,12)=0.033, p=0.858), or between the RUSLE erosion potential and the litter erosion (R^2=0.022, F(1,12)=0.270, p=0.613).

Analysing the results for both the sediment erosion and the litter erosion from the silt fence method showed that there is no significant relation between these two variables (R^2=0.022, F(1,13)=0.286, p=0.602).

3.7 Comparing decomposition and erosion

To test whether there is a relation between the decomposition rate and the erosion, the decomposition rate was compared to the three soil erosion measurement results. This showed that there is no significant relation between the decomposition rate and the LFA soil stability indicator (R^2=0.107, F(1,13)=1.560, p=0.234) or between the decomposition rate and the RUSLE erosion potential (R^2=0.082, F(1,14)=1.253, p=0.282). The decomposition was compared with both the sediment erosion and the litter erosion that resulted from the silt fence method. This showed that there is no significant relation between the decomposition rate and the sediment erosion (R^2=0.016, F(1,6)=0.098, p=0.765) or between the decomposition rate and the litter erosion (R^2=0.037, F(1,7)=0.267, p=0.621).

4. Discussion

4.1 Decomposition

4.1.1 Comparison of monoculture and agroforestry decomposition rates

It was hypothesised that the decomposition rate constant would be lower in monoculture systems than in agroforestry systems. However, the results show that the average decomposition rate constant on monoculture farms (0.0275) is almost double the average decomposition rate constant on agroforestry farms (0.0139). This means that the posed hypothesis is incorrect. A possible explanation for this could be the relation that was found between the decomposition rate and the altitude at which the farms were located (see *figure 8*). This relation shows that the decomposition rate constant increases as the altitude increases. This is an interesting relation, since the average altitude of the monoculture farms was 100m higher than the average altitude of agroforestry farms (see *table 5*). This leads to the question whether the higher decomposition rate constants on monoculture farms are due to their agricultural practice or due to their altitude. In previous studies, it was found that the decomposition rate of the soil decreases on higher altitudes because the lower temperatures slow down enzymatic activity (Coûteaux et al., 2002; Schinner, 1982). This contradicts the positive relation between the decomposition rate constant and the altitude that was found in this study, which suggests that the difference in measured decomposition rates between monoculture and agroforestry farms cannot be explained by the altitude. This means that the decomposition rate constants on monoculture systems are higher than on agroforestry systems due to the difference in agricultural practice and not due to the difference in altitude.

4.1.2 Analysing the development of the decomposition rate over time

It was hypothesised that the decomposition rate constant would be higher in older agroforestry systems than in younger agroforestry systems. As discussed in chapter 4.1.1, the average decomposition rate constant in monocultures is higher than in agroforestry systems. However, dividing the agroforestry systems into different age clusters showed that there was only a significant difference in decomposition rates between monoculture farms and the youngest agroforestry farms, which had trees between one and seven years old (see *figure 7*). This suggests that the decomposition rate is negatively affected by the transition from a monoculture system to an agroforestry system. However, although not significant, a slight trend towards higher decomposition rates in agroforestry systems was observed from approximately seven years onwards (see *figure 9*). Because of this, the hypothesis that the decomposition rate is higher in older agroforestry systems than in younger agroforestry systems could not be confirmed. Since all the agroforestry farms included in this research used to be monocultures, it is interesting that the decomposition rate is only significantly lower in the first years after the first implementation of agroforestry. Based on this data, no relation was found that can explain this decrease in decomposition rate. As existing literature also couldn't provide a possible explanation for this rapid decrease of the decomposition rate after implementing agroforestry, further research is required to gain a better insight in the effects of agroforestry implementation on the decomposition rate of the soil.

4.1.3 Nutrient availability and the decomposition rate

It was hypothesised that an increase in the availability of nutrients and soil organic material (SOM) would result in a higher decomposition rate. Comparing the decomposition rate with the nutrient data showed that the decomposition rate has a positive correlation with nitrogen, soil organic matter and phosphorous (see *figure 10-12*). This is in line with previous studies that also showed the positive effect of nutrient availability on the decomposition rate (Hobbie & Vitousek, 2000; Jose, 2009). However, comparing the nutrient availability with the years since transition showed that there is no significant change over time in the nitrogen content and the soil organic matter, and even a decrease in phosphorous content can be observed (see *figure 6*). The constant or decreasing availability of nutrients and the SOM could explain why the hypothesis that de decomposition rate is higher in agroforestry farms than in monoculture farms was shown to be incorrect. Another thing that can be observed is that the nutrient availability is relatively low compared to the ideal level (FNC, 2019). This indicates that the decomposition rate might be inhibited by the nutrient availability.

4.2 Erosion

4.2.1 Comparison of monoculture and agroforestry erosion

It was hypothesised that the erosion would be higher in monoculture systems than in agroforestry systems. The LFA method results in three different indicators. The stability indicator can be seen as an indicator for the soil's susceptibility to erosion. The results show that the average soil stability in monoculture systems (50.43) is significantly lower than the average soil stability in agroforestry systems (55.80). This means that the soils in monocultures are more susceptible to erosion, and thus that, based on the LFA method, the posed hypothesis correct. This relation between soil stability and agroforestry can, at least partly, be explained by the relation that was found between the soil stability indicator and the canopy closure (see *figure 14*). This positive linear correlation shows that farms with a more closed canopy have more stable soils, which is in line with what was found in existing literature (de Jong & Jetten, 2007). However, in other studies it was found that the canopy closure in agroforestry systems only has very little effect on the cover function of trees, and might even have negative effects. Instead, these studies found that the litter layer has a much larger effect on the soil cover (Bregman, 1993; Young, 1989). It might be hypothesised that a more closed canopy automatically leads to a thicker litter layer, but no exact data on the litter layer was gathered for this study. To better understand the relation between the canopy closure, the litter layer and the soil stability, further research is needed to gain more insight into the effect of the canopy closure on the soil stability.

The results from the RUSLE method show that the potential erosion in monoculture systems (328.31) is higher than in agroforestry systems (232.96). This means that, based on the RUSLE results, the hypothesis that monoculture systems experience more erosion than agroforestry systems is correct. This is corroborated by the logistic correlation between the soil erosion potential and the banana tree density that shows that the soil erosion potential decreases when the banana tree density increases (see *figure 20*). This relation is interesting, because the presence of banana trees is generally not considered as a soil erosion mitigation method. Only one article was found that shows that land that was used to grow banana trees has a relatively low erosion compared to other land uses (Van De et al., 2008). More research into the effect of banana trees in soil erosion could help to determine the feasibility of banana trees as a soil erosion mitigation measure.

Because the silt fence method could only be applied on one monoculture farm, a comparison between monoculture systems and agroforestry systems could not be made for the measured sediment and litter erosion. Based on this, the hypothesis that erosion is less on agroforestry farms than on monoculture farms can only be assessed based on the results from the LFA and RUSLE methods. Both of these methods show that erosion is lower on agroforestry farms than on monoculture farms, this means that the hypothesis is correct. This support the results found in other studies (Blanco Sepúlveda & Aguilar Carrillo, 2015; Fitriani et al., 2018; Gyssels & Poesen, 2003). However, the silt fence method did show a positive relation between the sediment erosion and the woody tree density (see *figure 23*). Combined with the sigmoid correlation that was found between woody tree density and canopy closure (see *figure 5)*, this result supports the claims from Bregman (1993) and Young (1989) that the canopy closure can have a negative effect on soil erosion.

4.2.2 Analysing the development of erosion over time

It was hypothesised that the soil erosion would be lower in older agroforestry systems than in younger agroforestry systems. After allocating the LFA stability indicator into six age clusters, it was observed that the soil stability in agroforestry systems increases over time (see *figure 13)*. Due to this increase, the stability indicator of agroforestry systems becomes significantly different from monoculture systems after approximately 11 years. Although not significant, curve fitting showed that this increase of soil stability over time appears to be linear. This means that older agroforestry systems have a higher soil stability, and thus experience less erosion. Based on these LFA results, it can be stated that the posed hypothesis is correct. This is corroborated by the relation that was found between the stability indicator and the canopy closure (see *figure 14)*. A detailed discussion on the linear correlation between the stability indicator and the canopy closure can be found in chapter 4.2.1. Even though not much research has been performed to study the development of agroforestry systems over time, a recent study did find that older plantations have a better sediment retention than younger plantations (Sun et al., 2018). This supports the results that were found in this research.

After allocating the erosion results from the RUSLE method into six age clusters, it was observed that the potential erosion is agroforestry is decreasing as the agroforestry system gets older. This decrease results in a significant lower erosion potential for agroforestry systems between 11 and 15 years old (see *figure 19*). However, in agroforestry systems older than 16 years, the potential erosion appears to increase slightly again, resulting in a non-significant difference in erosion potential between monoculture systems and the oldest agroforestry systems. This means that, based on the RUSLE data, there appears to be an optimum agroforestry age for sediment retention between 11 and 15 years old. The increase of soil erosion potential in older agroforestry systems could, at least partly, be explained by the logarithmic correlation between the years since transition and the canopy closure (see *figure 4*), which indicates that the oldest trees have the most closed canopy. Even though no significant relation was found between the RUSLE erosion potential and the canopy closure, according to Bregman (1993) and Young (1989) the large canopy closure of the oldest trees could have a negative effect on the soil erosion.

Due to the small amount of data points with a value higher than zero that resulted from the silt fence method, no significant correlation with the years since transition was found. Because of this, the hypothesis that the erosion is lower in older agroforestry systems than in younger agroforestry systems can only be assessed based on the results from the LFA and RUSLE methods. Both LFA and RUSLE show that the erosion potential decreases as agroforestry systems get older. Even though the RUSLE results show a slight increase in erosion potential for the oldest agroforestry systems, it can still be concluded that the erosion in older agroforestry systems is lower than in younger agroforestry systems, and thus that the posed hypothesis is correct.

Because the soil erosion is less in agroforestry systems than in monoculture systems, and the erosion potential keeps decreasing for at least 15 years, agroforestry systems retain sediment. Because of this, agroforestry could be a good agricultural practice to protect downstream ecosystems and urban areas from being damages by soil erosion.

4.2.3 Nutrient availability and erosion

Comparing the soil organic matter (SOM) and the nutrient availability with the stability indicator from the LFA method shows that there is no relation between the nutrient availability and the soil stability. Since the soil stability is an indicator for soil erosion, this means that based on the LFA method, there is no relation between soil erosion and nutrient availability. This is corroborated by the results of the silt fence method. This method shows that there is no relation between the SOM and the nutrient availability, and the sediment or litter erosion. This contradicts existing literature that shows that an increase in erosion leads to a decrease in nutrient availability due to runoff processes (NSERL, 2019; Pardini et al., 2003). However, the same literature is corroborated by the RUSLE results, which show that the nitrogen content and the SOM decrease as the erosion potential increases (see *figure 21 & 22*).

4.2.4 Comparison of erosion measurement methods

As expected, the comparison between the soil stability indicator from the LFA method, and the erosion potential from the RUSLE method show that when the soil is more stable, the erosion potential decreases significantly (see *figure 24*). This result is corroborated by previous studies that showed that more stable soils reduce the amount of erosion from those soils. The strong correlation between the LFA soil stability and the RUSLE erosion potential indicates that these two methods show similar results on soil erosion. In the LFA manual, it can be found that the soil stability indicator has a significant correlation with the soil aggregate stability. Other research shows that, especially in the tropics, aggregate stability is a good indicator for the soil's susceptibility to erosion (Barthès & Roose, 2002). This corroborates the relation between the soil stability and erosion potential. However, when comparing these two methods with the direct erosion measurements from the silt fence method, no correlations were found with either the sediment or the litter erosion. A possible explanation for this difference could be that the research area was located in the Andes Mountains, which is known for its volcanic activity. This means that the soil in the research area mainly consists out of volcanic ash based soil types called Andosols (Esri, 2011), which generally have a strong resistance to water erosion (Shoji et al., 1993). However, research from Poulenard et al., (2001) shows that the erodibility of Andosols increases rapidly on agricultural land (Poulenard et al., 2001). This means that the innate soil retention capacity of the Andosol soils on the researched coffee fields is greatly reduced, and thus cannot explain the different results between the indirect soil erosion measurement methods and the silt fence method. Another possible explanation for this difference could be that the silt fences were only set up for around 14 days per fence, which is a relatively short period. That this period was short was known before starting this experiment. However, it was expected that the normally high precipitation levels in Risaralda during the first rainy season (250.1 mm) (IDEAM, 2014) could compensate for this shorter time period. Unfortunately, the precipitation measured during the silt fence experiments varied between 9.0 and 135.6 mm. This combination of a short measurement duration and the low precipitation levels have caused very little, or sometimes no, sediment to be deposited in the silt fences. The resulting small data set could have caused inaccuracy in the results of the silt fence method, causing uncertainty in the results. Because the silt fence method shows no similarities with the LFA and RUSLE methods, and the results of the silt fence might be questionable, the LFA and RUSLE methods were not calibrated with the silt fence method. Because of this, the accuracy of the LFA and RUSLE methods could not be established with certainty. However, because the LFA and RUSLE results are so similar, and because the RUSLE method shows expected results then compared to the nutrient availability, is seems that, based on this research, the RUSLE method is most applicable to the Eje Cafetero. To support this apparent accuracy of the RUSLE method, the silt fence experiment should be repeated over a longer time period to ensure that enough sediment is collected so that the certainty of the results can be guaranteed.

4.3 Comparing decomposition and erosion

It was hypothesised that a higher sediment retention would contribute to an increased decomposition rate. However, comparing the decomposition rates with the results from the erosion measurement methods shows that there is no relation between the decomposition rate and soil erosion, independent of which measurement method is used for soil erosion. This is in contrast with existing literature, which suggest that a decrease in erosion benefits the decomposition rate of the soil (Almagro & Martínez-Mena, 2014; Altieri, 1999; NSERL, 2019). Nevertheless, it can be observed in the results that the decomposition rate is slightly increasing over time (see *figure 9*), while the erosion estimated by both the LFA stability indicator and the RUSLE erosion potential are decreasing over time. Although not significant, this could indicate a relation between the decomposition rate and soil erosion. Further research is required to gain a better understanding of the relation between the decomposition rate and soil erosion.

5. Conclusion

Several results from this research are relevant for the study into agroforestry systems in the Eje Cafetero. It was found that the erosion potential in agroforestry systems is lower than in monoculture systems, and that the decomposition rates of these two land use types do not differ. However, it was also found that agroforestry systems are dynamic systems that cause a non-linear development of the soil erosion and decomposition rate. Very little research has been done into the development of agroforestry systems over time, therefore it is recommended that more research is done to study this development and the effect is can have on the ecosystem services. It is also concluded that little is known about the effect of banana trees on preventing soil erosion, but in this research is was found that banana trees might improve the sediment retention. Further research is required to increase the understanding of the capacity of banana trees to mitigate soil erosion. Finally, it was concluded that the RUSLE method is more suitable than the LFA method for measuring soil erosion in the Eje Cafetero. However, to calibrate both the LFA and the RUSLE methods, the silt fence experiment has to be repeated to help validate these two indirect soil erosion measurement methods.

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7. Appendix

7.1 Appendix I: Decomposition data

Table I-1: The weight of the tea bags after being buried in the soil samples. Weight R.. stands for the Rooibos tea, Weight G.. stands for the green tea.

Parent code	Weight R1 (g)	Weight R2 (g)	Weight R3 (g)	Weight G1 (g)	Weight G2 (g)	Weight G3 (g)
SANMSA	1,76	1,77	1,77	0,90	0,70	0,75
SANMSB	1,82	1,79	1,91	0,80	0,80	0,79
SANAFSA	1,95	1,87	1,79	0,87	0,82	0,81
SANAFSB	1,93	1,78	1,93	1,15	0,80	0,84
SANMS4	1,66	1,91	1,76	0,70	1,76	1,23
SANAFS8	1,99	2,04	2,05	0,82	1,09	1,14
SANAFS9	1,88	1,94	1,83	0,91	0,85	0,84
SANAFS10	1,77	1,83	2,05	0,72	0,81	0,82
BELAFSB	1,93	1,88	1,87	1,90	0,98	0,99
BELMS1	1,82	1,85	1,84	0,87	1,11	0,88
BELAFSC	1,88	1,90	1,91	0,92	0,94	1,10
BELAFSA	1,84	1,98	1,94	0,98	0,97	0,70
BELAFSD	1,94	1,95	1,97	1,09	0,98	0,99
BELAFS1	1,91	1,94	1,95	0,96	0,90	0,83
BELAFS2	2,20	2,01	1,89	1,09	0,92	1,03
BELAFS3	1,92	2,01	1,94	1,06	1,16	0,99

Table I-2: The weights of the unused tea bags.

Control						
Type of tea	Weight 1 (g)	Weight 2 (g)	Weight 3 (g)	Weight 4 (g)	Weight 5 (g)	Average weight (g)
Rooibos	2,11	2,11	2,09	2,08	2,12	2,10
Green	1,97	1,97	1,89	1,84	1,86	1,91

7.2 Appendix II: Decomposition rate results

Table I-1: General statistics for the TBI results shown for the total amount of farms, as well as for the monoculture and agroforestry systems separately. Different letters nidicate significance for a significance level of p<0.05.

	Mean	St. dev.	Min	Max	n
Decomposition rate (g/d)					
All	0,0173	0,0083	0,0055	0,0437	16
Monoculture	0,0275[a]	0,0096	0,0185	0,0437	4
Agroforestry	0,0139[b]	0,0038	0,0055	0,0192	12

Table I-2: The result of the posthoc test performed for decomposition rate and the age clusters. Different letters indicate significance for a significance level of p<0.05.

	Age cluster				Total
	1	2	3	4	
n	4	4	4	4	16
Mean	0.028[a]	0.012[b]	0.014[ab]	0.015[ab]	0.017
St. dev.	0.011	0.003	0.006	0.003	0.009

7.3 Appendix III: Landscape function analysis results

Table III-1: General statistics for the three LFA indicators shown for the total amount of farms, as well as for monoculture and agroforestry systems separately. Different letters indicate significance for a significance level of p<0.05.

	Mean	**St. dev.**	**Min**	**Max**	**n**
Stability					
All	54,33	5,37	41,53	62,10	55
Monoculture	50,43[a]	7,40	17,50	43,52	15
Agroforestry	55,80[b]	4,61	41,53	62,10	40
Infiltration					
All	35,12	8,74	17,50	59,55	55
Monoculture	29,87[a]	7,40	17,50	43,52	15
Agroforestry	37,09[b]	8,38	17,70	59,55	40
Nutrient cycling					
All	30,05	7,49	12,85	50,25	55
Monoculture	25,18[a]	6,38	12,85	38,87	15
Agroforestry	31,87[b]	7,06	20,13	50,25	40

Table III-2: The result of the posthoc test performed for the soil stability indicator and YST. Different letters indicate significance for a significance level of p<0.05.

	Age cluster						Total
	1	2	3	4	5	6	
n	15	7	8	10	10	4	54
Mean	50.43[a]	56.63[ab]	51.76[ab]	55.77[ab]	57.30[bc]	58.87[bc]	54.32
St. dev.	5.46	3.39	6.37	3.53	4.15	3.44	5.47

Table III-3: The result of the posthoc test performed for the infiltration rate indicator and YST. Different letters indicate significance for a significance level of p<0.05.

	Age cluster						Total
	1	2	3	4	5	6	
n	15	7	8	10	10	4	54
Mean	29.87[a]	33.66[ab]	33.95[ab]	37.04[ab]	41.61[b]	38.80[ab]	35.13
St. dev.	7.66	5.55	12.47	8.65	6.52	5.76	8.90

Table III-4: The result of the posthoc test performed for the nutrient cycling indicator and YST. Different letters indicate significance for a significance level of p<0.05.

	Age cluster						Total
	1	2	3	4	5	6	
n	15	7	8	10	10	4	54
Mean	25.18[a]	29.59[ab]	29.30[ab]	30.84[ab]	34.98[b]	36.04[ab]	30.03
St. dev.	6.60	4.23	9.37	8.54	5.52	4.90	7.63

7.4 Appendix IV: RUSLE results

Table IV-1: General statistics for the RUSLE results shown for the total amount of farms, as well as for the monoculture and agroforestry systems separately. Different letters indicate significance for a significance level of p<0.05.

	Mean	St. dev.	Min	Max	n
Erosion (t/ha/y)					
All	258,96	150,23	50,53	767,41	55
Monoculture	328,31[a]	162,55	50,53	738,75	15
Agroforestry	232,96[b]	136,55	54,08	767,41	40

7.5 Appendix V: Silt fence data

Table V-1: The data that was used to calculate the results for the silt fence erosion measurement method

Parent code	Sediment dry weight (g)	Litter dry weight (g)	Sediment contribution area (m2)	precipitation (mL)	Precipitation surface (cm2)	Number of days
SANAFSA	442,53	66,22	21,46	50,00	50,27	13
SANAFSB	5,16	68,16	17,15	70,00	33,18	11
BELAFSA	73,98	25,03	10,50	200,00	33,18	11
BELAFSB	4,19	65,90	11,34	450,00	33,18	13
BELAFSC	0,00	18,21	5,97	250,00	33,18	12
BELAFSD	0,00	1,31	10,13	250,00	33,18	11
BELAFSE	102,71	34,11	15,11	280,00	33,18	14
BELAFSF	1,19	36,35	4,56	300,00	33,18	13
BELAFSG	0,05	3,34	6,57	400,00	33,18	12
BELAFSH	0,00	3,29	10,35	150,00	33,18	11
SANAFS9	5,48	1,22	38,99	30,00	33,18	12
BELAFS1	22,86	87,61	7,47	200,00	33,18	11
BELAFS2	0,18	37,20	10,15	300,00	33,18	13
BELMS1	0,59	6,76	8,88	175,00	33,18	11
BELAFS6	0,03	0,97	6,40	275,00	33,18	13
BELAFS8	0,35	58,25	12,50	150,00	33,18	11