Erosion Control and Carbon Sequestration by Bench Terraces and Agroforestry in the West Usambara Mountains, Tanzania

Guillermo Molina

Universiteit Utrecht

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Author: Guillermo Paul Molina Cuasapaz
Student number: 6543308
g.p.molinacuasapaz@students.uu.nl

First supervisor: Geert Sterk
Second supervisor: Rens van Beek

MSc Programme: Earth Surface and Water
Faculty of Geosciences
Department of Physical Geography
Utrecht University

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Abstract

Soil erosion by water on steep slope areas is causing a land degradation problem in The West Usambara Mountains in Tanzania resulting in some land becoming unproductive. **Traditional agroforestry (AF)** practices seemed to have the potential to neutralize these effects maintaining the productivity of the fields and working as a biomass carbon pool, over others soil and water conservation (SWC) measures that have been promoted in the area by the government and private projects for decades like **bench terraces**. The aim of this thesis is to make a comparison between bench terraces, and traditional AF systems, taking into account three aspects a) effectiveness of soil erosion control, b) carbon sequestration rates, and c) net economic profit. In this study, nine agricultural plots located in the Lushoto district were used as experimental fields. The ACED method was used to quantifies soil loss from sites based on field observations and measurements of visual erosion features. The hillslope version of the revised Morgan, Morgan and Finney water erosion model (hMMF) was used to establish the water erosion patterns. C sequestration was estimated on the base of the biomass carbon and the soil organic carbon (SOC). The biomass was estimated using destructive methods and allometric equations, and the Walkley and Black method was used to determine SOC. Finally, socioeconomic information was collected to characterize its influence on the use of a specific SWC and to estimate the net operating profit of the fields. The results showed that traditional AF and terraced fields are equally effective to control soil erosion, but important differences in terms of carbon sequestration and economic benefits are evident between these two SWC measures. AF fields sequestrate six times more carbon than terraced fields, while terraced fields generate net incomes 2.6 higher than AF fields due to the differences in crop market prices and the inadequate management of AF fields.

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1. Introduction

Land degradation is a long-term decline in ecosystem function and productivity (Bai et al., 2008), mainly caused by non-sustainable land management, which is the response to (1) excessive pressure on the natural resources to meet the increased demand for land, food, and economic income; (2) poor access of landholders to capital and knowledge; and (3) deficient government policies (FAO, 2012; 2018; Khresat, 2014). Water erosion is responsible for around 50 % of total land degradation worldwide (Oldeman 1992; Berhe et al., 2007). Four main processes are involved in water erosion: (i) The detachment of particles, (ii) the breakdown of the aggregates, (iii) the transport of the sediments, and (iv) the deposition of the soil material (Lal, 2003). Water erosion causes a reduction in the soil quality due to the loss of organic matter and nutrients present in the topsoil (Kangalawe and Lyimo, 2010). As a consequence, the productive capacity of the soil decreases and the extent of the arable area is continuously reduced (Brown and Young, 1990). These negative effects could be diminished with the application of soil and water conservation (SWC) measures which control soil erosion and sustain agricultural production, especially on steep sloping areas.

Loss of soil organic carbon (SOC) due to water erosion results in an increase in atmospheric CO2, with an estimation of 1.21 billion tons of carbon per year (Lal, 2003). This makes water erosion one of the processes that contributes most to the release of greenhouse gases (GHG) into the atmosphere, leading to global warming. GHG emissions by agriculture represent 30% of global total emissions (IPCC, 2014; 2015). One option to mitigate climate change is offsetting anthropogenic emissions and creating a net negative balance in the atmosphere by sequestering carbon emissions from the atmosphere and depositing it in reservoirs (Lal, 2015).

The West Usambara Mountains in Tanzania are facing a serious land scarcity problem caused by soil erosion and nutrient mining, resulting in unproductive land (Tenge and Hella, 2005). Physical factors such as steep slopes, erodible soils, and high rainfall intensities, in combination with anthropogenic activities like deforestation, intensive cultivation, and a high population density have caused this area to become one of the most eroded in the region (Nyanga et al., 2016; Kimaro et al., 2008). An old practice developed in this area called traditional agroforestry (AF) is based on the integration of trees, shrubs and crops has the potential to decrease land degradation and maintain the productivity of the fields (Reyes et al., 2005). However, in the last decades, the government and private projects have promoted other SWC measures, especially bench terraces, to reduce soil erosion in this area (Mwango, 2015).

A study conducted in two farming communities of the West Usambara Mountains, Sunga and Shashui, showed that only some (5%) of the farmers use high-quality sustainable land management (SLM) measures. This reality is disappointing, considering that the fight against soil erosion in this area started over 80 years ago (Wickama et al., 2018). According to Reyes et al. (2005) and Mwango (2015), the high cost to implement bench terraces and the delayed positive return of this investment could explain the low adoption percentages of SLM measures. This situation shows that perhaps bench terraces are not the best option to be promoted in this area. Moreover, even when bench terraces are considered as an effective method to decrease soil erosion, it is not the only possible SWC measure. For instance, Veldhuijsen (2018) used a soil erosion model and showed that there is just a slight difference in the effectiveness of reducing soil loss between the traditional AF system and bench terraces. In addition, bench terraces might cause a reduction of biomass and soil organic carbon, due to the removal of bushes and trees during its construction. And it is still uncertain if the economic benefit of traditional AF fields is different to the net income produced by bench terraced fields. Finally, the efficiency of traditional AF systems to store C in the soil should be included in this comparison due to the emerging carbon market, which may provide a new profitable option for landholders through carbon sequestration (Flugge and Abadi, 2006).

Even when the adoption of traditional AF systems seems to be an appropriate SWC measure to promote in the West Usambara Mountains. However, multivariable comparisons between traditional AF systems and bench terraces has not been done yet. Before recommending the traditional AF systems instead of bench terraces in the West Usambara Mountains such multivariable comparison should be done first. In this context, the objective of this thesis research was to make a comparison between two SWC measures, bench terraces, and traditional AF systems, taking into account three aspects: a) effectiveness of soil erosion control, b) carbon sequestration rates, and c) net economic profit.

2. Study area

The West Usambara Mountains are located in the northeastern part of Tanzania, in tropical East Africa. This chain of mountains has elevations that range from 600 to 2300 meters and forms part of the administrative region of Tanga (Figure 1). The region has annual average temperatures between 18 °C and 22 °C, and bimodal annual precipitation which varies from 800 to 1300 mm (Mascarenhas, 2000). The long rainy season “Masika” starts in March and lasts until the end of June, and the short rainy season “Vuli” goes from October to December. Based on the precipitation and elevation conditions, the forest present in this area is “moist tropical forest” (Brown, 1997). According to the US Soil Taxonomy system, the predominant soil type in the sloping areas is Acrisols, Luvisols, and Lixisols, while in the valley bottoms, soil types such as Fluvisols and Gleysols are found (Meliyo et al., 2001).

The presence of smallholder agriculture in this area is mainly dominated by subsistence farming, which includes typical crops such as maize, beans, potatoes, and less common but well established crops like bananas, coffee, and mango. Because of the hilly topography of the area, fields with SWC measures form an integral part of the current landscape, with the predominance of bench terraces, grass strips, and traditional agroforestry (AF) systems.

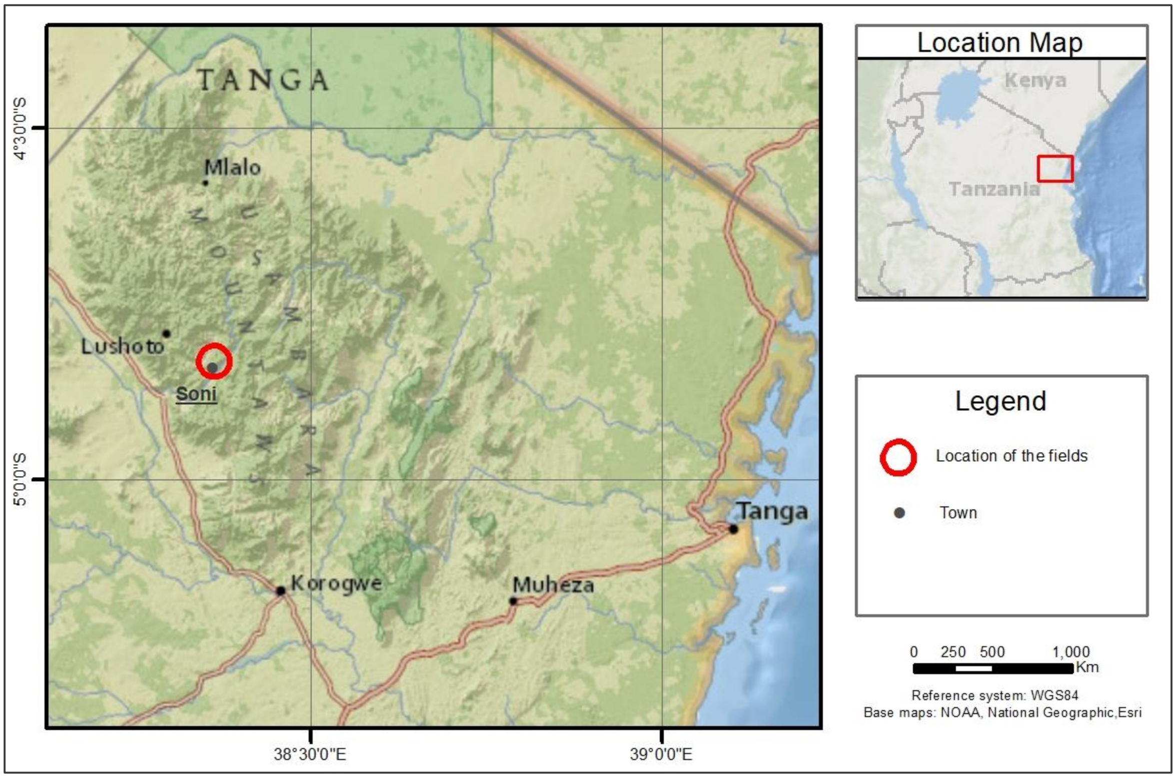

Figure 1. Location of the study site in the West Usambara Mountains, the study site is near Shashui village, close to Soni town, in Lushoto district, Tanzania.

3. Methods

Nine experimental agricultural fields, 3 with traditional AF systems, 3 with bench terraces, and 3 control fields (plots without any SWC strategy) were selected to evaluate the differences between these two SWC measures. They are located in the West Usambara Mountains, at Shashui village, close to Soni town, in Lushoto district, Tanzania (Figure 1). The preliminary fields were selected based on exploratory site-visits and high-resolution satellite images, and for the definitive field selection, the distance between the fields and the accessibility to the sample sites were taken into account. Three aspects of the fields were considered to compare the two measures: Soil erosion control, carbon sequestration, and net economic profit. Finally, the results were analyzed to draw conclusions about the performance of these SWC systems.

Two different sources of rainfall data were used in this study. The first is located 5 km from the fields, at Sakharani mission. This rain gauge has been recording continuous daily rainfall data since 1928, and the second source was a rain gauge installed specifically for this project close to the fields.

3.1 Effectiveness of soil erosion control

The soil erosion reduction effectiveness (Ered) was calculated by comparing the soil erosion rate of the control fields (Ec) against the soil erosion rate of fields which have implemented a specific SWC measure (E) using equation 1.

$$Ered(\%) = \frac{Ec - E}{Ec} \ X \ 100 \qquad (1)$$

Soil erosion rates were obtained through field measurements using the assessment of the current erosion damage (ACED) method.

3.1.1 Assessment of current erosion damage (ACED) method

The ACED method (Herweg, 1996) is an erosion survey designed for field-sized areas, that can be used to quantify soil loss values and to determine field characteristics. This method quantifies soil losses from sites based on field observations and measurements of visual erosion features like rills and gullies. A site is defined by a geographic location with a specific land use type (e.g. cultivated land, grassland, forest).

In this study, each of the 9 agricultural fields were considered as an individual site, which is formed by the main area (the field), the upslope area, and the downslope area. After the site selection, the second step was to identify the management type of the site. Then, the soil erosion features of the main area were measured and classified into different sections. A section can be formed by an individual erosion feature or by a group of them based on their position in the field, and on their width, length, and depth similarities. For example, depth-wide rills, shallow-rills, or wide rills. Finally, all of these sections were represented on individual sketches.

To calculate the soil loss in volume units (m^3) the average measures of each section (length, depth and width) were multiplied by the number of features that belong to that section. This value was converted into mass units (tons) multiplying the volume by the bulk density of the soil. Lastly, to obtain the soil loss per unit area, the sum of the soil loss values of each section was divided by the total area of the field. In some cases, when just a specific part of the plot shows erosion damage, a smaller field area can be used to calculate the soil loss per unit area. The accuracy of the method depends on the expertise of the observers, but it is generally around 15% (Herweg, 1996).

During the short rainy season, the ACED method was performed 3 times. The first one was done after the rainy events of October and the other two times, in mid-November and mid-December respectively. The different field characteristics such as surface roughness, quality of the drainage, depth topsoil, texture, slope, vegetation cover, type of management, and tillage direction were also determined according to the ACED manual.

3.1.2 Erosion modelling

The hillslope version of the revised Morgan, Morgan and Finney water erosion model (hMMF; Sterk, 2020) was used to simulate the water erosion processes of the 9 experimental fields. The aim was to quantify the erosion control efficiency of the different SWC measures. Input values were obtained from specific (literature) information of the study area, field measurements, and guide values from Morgan (2005). The model was calibrated for each field with the values of soil losses quantified by the ACED method.

3.1.2.1 rMMF model

In 1984, the Morgan, Morgan and Finney model (MMF; Morgan et al., 1984) was published. Then in 2001, it was revised by Morgan becoming the revised Morgan, Morgan and Finney model (rMMF; Morgan, 2001). This semi-empirical model predicts annual soil loss from field-sized areas on uniform hillslopes considering soil erosion as a result of the detachment of soil particles by raindrop impact (F), the detachment of soil particles by runoff (H), and the transport of those particles by overland flow (TC). It compares the total rate of detachment (F + H) with the runoff transport capacity (TC); the minimum of these two values is the annual soil erosion (E; Mg ha^{-1} y^{-1}) of the field.

$$E = \min\{(F + H), TC\} \qquad (2)$$

3.1.2.2 hMMF model

Since the rMMF model was published, it has been tested in different environments and some adapted versions of the model have extended its applicability. One of the most recent is the hillslope version of the revised Morgan, Morgan and Finney water erosion model (hMMF; Sterk, 2020), which, unlike the rMMF (1) incorporates the effects of SWC measures structures by allowing runoff infiltration, and (2), it simulates erosion process along irregular profiles by splitting the entire hillslope into sections with individual properties. Therefore, the surface runoff of each section corresponds to the sum of the surface runoff produced in that specific section plus the incoming runoff from the immediately upslope section. Furthermore, the sediment transport is calculated from the transport capacity and the detachment of each section, but also taking into account the sediment coming from the upslope section. In Figure 2, the entire modeling process is shown.

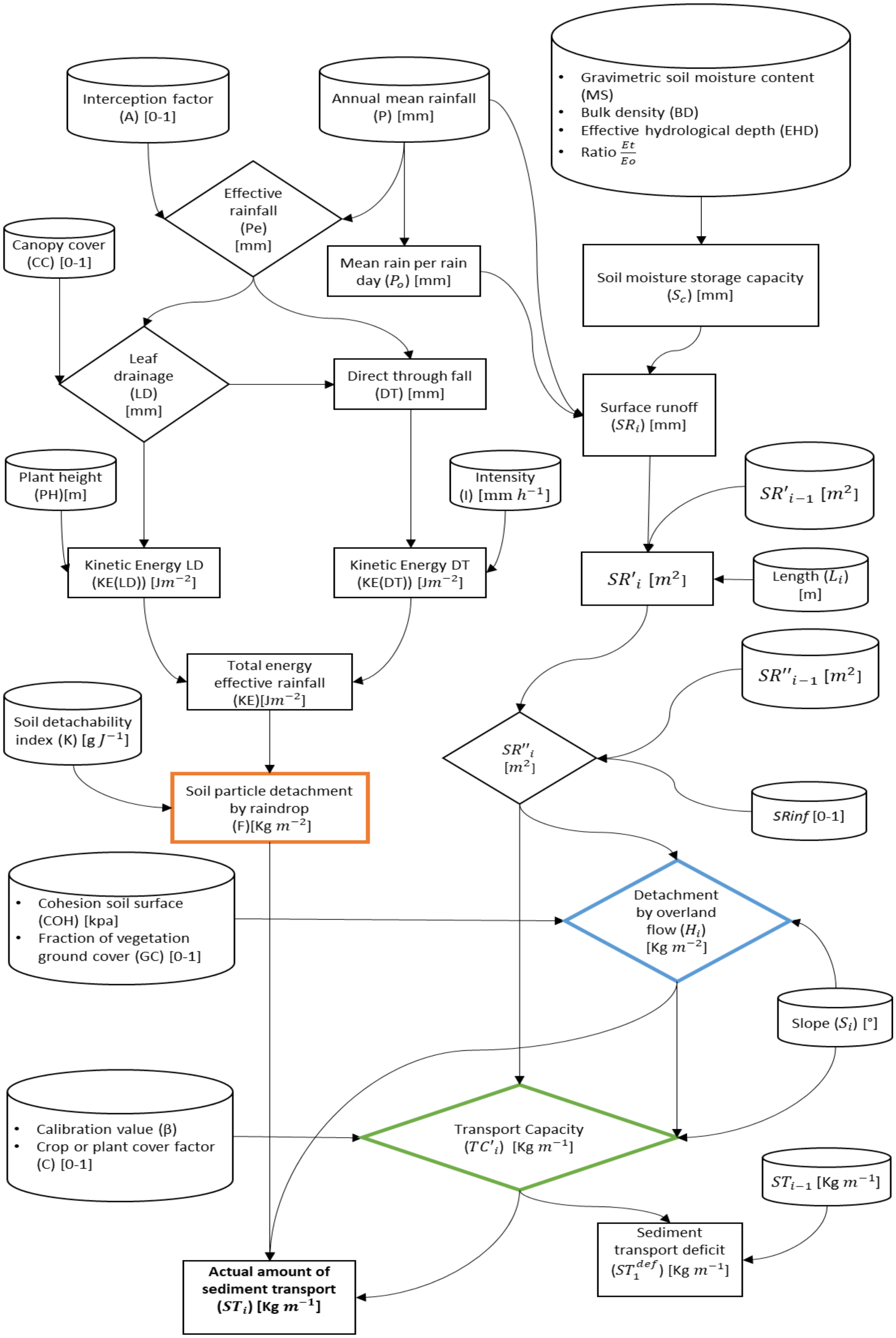

Figure 2.Flowchart of the adapted hMMF soil erosion model, based on Sterk (2020).

Hillslope properties

The hillslope (hMMF) water erosion model can simulate irregular hillslopes splitting the whole length (L) into multiple sections (i= 1,2,3……. n). The first section (i=1) is the top of the hillslope and the nth section (i=n) corresponds to the lowest part of the slope. General variables, like annual mean rainfall are considered homogenous for all the sections. But, variables such as length, slope, angle slope, soil type, and vegetation characteristics can be specific for each of them.

Soil particle detachment by raindrop

Soil particle detachment by raindrops (F_i; kg m^{-2}), for a particular section of the hillslope, is a function of the total energy produced by the effective rainfall and the soil erodibility.

$$F_i = 10^{-3}\, K\, KE \tag{3}$$

Where K (g J^{-1}) is the soil detachability index (weight of soil detached per unit of rainfall energy), and KE (J m^{-2}) is the total energy produced by the effective rainfall, calculated as the sum of the kinetic energy of the leaf drainage (KE[LD]), plus the kinetic energy of the direct through fall (KE[DT]).

$$KE = KE[DT] + KE[LD] \tag{4}$$

KE[LD] (J m^{-2}) is calculated as a function of the plant height (PH; m) and the leaf drainage (LD)

$$KE\,[LD] = [(15.80PH^{0.5}) - 5.875]LD \tag{5}$$

LD (mm) is the amount of the effective rainfall that reach the surface by stem flow or dripping from the leaves after interception by the canopy cover.

$$LD = Pe\; CC \tag{6}$$

Where CC is the canopy cover (0 – 1), and Pe is the effective rainfall (mm), which is the fraction of mean annual rainfall (P; mm) that it is not intercepted by vegetation canopy.

$$Pe = P(1 - A) \tag{7}$$

Where A is the fraction of rain intercepted by vegetation (0 – 1).

KE[DT] (J m^{-2}) is calculated as a function of the rainfall intensity (I) and the direct through fall (DT), several equations have been obtained for different weather conditions. In this thesis, the equation proposed by Hudson (1965) for regions with tropical climates, was considered the most appropriate equation to use (Equation 8).

$$KE\ [DT] = \left[29.8 - \left(\frac{127.5}{I}\right)\right] DT \tag{8}$$

Where I (mm h^{-1}) is the rainfall intensity, and DT (mm) corresponds to the remaining effective rainfall which reaches directly the soil surface.

$$DT = Pe - LD \tag{9}$$

Where Pe is the effective rainfall (mm), and LD is the leaf drainage (mm)

Estimation of Surface Runoff

The surface runoff for the first section (SR; mm) is calculated as:

$$SR\ =\ P\ exp(-\frac{S_c}{P_o}) \tag{10}$$

Where, P (mm) is the mean annual rainfall, S_c (mm) is the soil moisture capacity, and Po (mm) is the mean rain per day, which is calculated as:

$$P_o\ =\ \frac{P}{\#\ of\ rainy\ days} \tag{11}$$

For a certain hillslope section, the soil moisture storage capacity (S_c; mm) is calculated as:

$$S_c = 1000\ MS\ BD\ EHD \left(\frac{E_t}{E_o}\right)^{0.5} \tag{12}$$

Where, MS is the gravimetric soil moisture content at field capacity (kg kg^{-1}), BD is the bulk density (t m^{-3}), EHD is the effective hydrological depth (m), and $\frac{E_t}{E_o}$ (mm) is the ratio between actual and potential evapotranspiration.

The amount of surface runoff for the first section (SR_1; mm) is converted to a volume per meter width (SR'_1; m^2) multiplying SR_1 by the length of the first section (L_1).

$$SR'_1[m^2] =\ 10^{-3} SR_1\, L_1 \tag{13}$$

The surface runoff of the second section (SR'_2; m^2) is equal to the volume generated in the second section, plus the surface runoff from the first section.

$$SR'_2 =\ 10^{-3} SR_2\, L_2 +\ SR'_1 \tag{14}$$

It is generalized for *n* sections (i= 1,2,3……. n) as:

$$SR'_i =\ 10^{-3} SR_i\, L_i +\ SR'_{i-1} \tag{15}$$

It is assumed that the runon from the upslope area is equal to 0 (SR'_0 =0).

Infiltration

To simulate the infiltration of the surface runoff the variable "*SRinf*" is used in the model. This variable corresponds to the fraction (0-1) of surface runoff infiltrated in a particular section. The resultant surface runoff (SR''_i; mm) subtracting the amount of water infiltrated in each section, is calculated as:

$$SR''_i = (SR'_i + SR''_{i-1})\,(1 - SRinf_i) \qquad (16)$$

The variable "*SRinf*" is strongly related to the SWC measure applied in each field.

Estimation of detachment by overland flow

The soil particle detachment by overland flow (H_i; kg m^{-2}) for a particular section is calculated as:

$$H_i = (0.5COH_i)^{-1}\ (SR''_i)^{1.5}\, S_i(1 - GC_i) \qquad (17)$$

Where, COH_i is the soil surface cohesion (k Pa), GC is the fraction of vegetation ground cover (0-1), and S is the slope (°).

Runoff transport capacity

The runoff transport capacity (TC_i; kg m^{-1}) is the maximum quantity of sediments that could be transported, given a specific volume of surface runoff. It is calculated for each section as:

$$TC_i = C_i(SR''_i)^{\beta} S_i \qquad (18)$$

Where ß is a calibration value for the sediment transport, and C is a factor (0-1) that represents the amount of soil loss compared with the soil loss from a bare soil. "C" is related to different tillage practices and the level of the crops.

Actual amount of sediment transport

The quantity of sediment transported out of each section (ST_i) depends of: (1) the transport capacity of the section (TC_i), and (2) the sediment detached in the section plus the sediment already in transport from the upslope section ($[F_i + H_i] + ST_{i-1}$).

To calculate ST_i, a variable called sediment transport deficit "$ST^{def}{}_i$" is included in the model, this variable is the result of removing the sediment transported from the upslope section (ST_{i-1}) from the transport capacity of the section TC_i.

$$ST^{def}{}_i = TC_i - ST_{i-1} \qquad (19)$$

Based on the sediment transport deficit (ST^{def}_i), the quantity of sediment transported out of each section (ST_i) is calculated as:

1) If $ST^{def}{}_i < 0$, there is deposition on the section. Thus, $ST_i = TC_i$
2) If $ST^{def}{}_i = 0$, no soil loss or deposition would occur in the section. Thus, $ST_i = TC_i$
3) If $ST^{def}{}_i > 0$, ST_i depends on the total detachment of the section ($F_i + H_i$):
    - If $(F_i + H_i)\ L_i \geq TC_i$.Thus, $ST_i = TC_i$
    - If $(F_i + H_i)\ L_i < TC_i$. Thus, $ST_i = ST_{i-1} + (F_i + H_i)\ L_i$

Several variables and parameters were used in the hMMF model. Field characteristics like length and slope were measured during the field campaigns. Lab analysis of field samples were used to obtain soil properties such as texture, bulk density, and soil moisture at field capacity. Rainfall characteristics like the amount of rainfall and the number of rainy days were obtained from rain gauges located close to the fields. The rainfall intensity value was assumed based on the weather conditions. The fraction of surface runoff infiltrated per section (SRinf) and ß, which affects the transport capacity, were used as calibration values. The rest of the parameters used in the hMMF model, were values based on vegetation characteristics and soil properties obtained from Morgan (2005) (Table 6).

3.2 Carbon sequestration rates

The terrestrial carbon (TC) sequestration was quantified by measuring the rate of carbon (C) accumulated in the fields during the short rainy season (3 months). TC sequestration was assumed to be equal to the difference between the terrestrial carbon stock at the beginning and at the end of this period.

$$TC\ Sequestration = \frac{\Delta\ (\text{TC stock})}{\Delta t} \qquad (20)$$

The TC stock is the sum of the total carbon (C) stored in several pools. It includes aboveground (AGB) biomass, belowground biomass (BGB), dead organic matter biomass (DOMB), soil organic carbon (SOC), and the relatively stable forms of inorganic carbon (SIC) present in the soils (Nair et al., 2009).

The SOC cycle starts when the plants through photosynthesis transform the CO_2 of the atmosphere into biomass. Then, it could be incorporated and stored into the soil by different plant-soil interactions. SOC returns to the atmosphere when events like fires and droughts occur; during natural processes such as soil organic matter decomposition; or by anthropogenic activities like deforestation and agriculture practices (Lal, 2005).

Soil inorganic carbon (SIC) is formed when the atmospheric CO_2 is converted by chemical reactions into C compounds such as calcium and magnesium carbonates. The results of this process include minerals like calcite, dolomite, and silicates (Soil Science Society of America, 2001). The formation time of these minerals depends on many variables, but it is in the range of several thousands of years (Gile, 1970). By contrast, the accumulation of soil organic carbon

(SOC) occurs at different time scales, going from weeks in the case of easily mineralizable sugars to centuries for recalcitrant aliphatic compounds (Wattel-Koekkoek et al., 2003).

In this thesis, C sequestration was estimated for the short rainy season. Thus, no difference in SIC was expected in this period. Therefore, just **SOC** and **biomass carbon** were considered for the determination of the total carbon stocks.

3.2.1 Biomass carbon stock

The biomass carbon stock was separated into 3 groups. The first one corresponds to the arboreal biomass (above and below ground), the second group is composed of non-arboreal biomass, which includes: (1) small size crops such as beans, maize, potato, and shrubs; and (2) big size crops like banana and coffee. The final group corresponds to the dead organic matter biomass composed of dead standing trees and litter (Figure 3).

In in this study, destructive methods and allometric equations were used to estimate the biomass of the fields. The destructive methods require first to cut and weigh the biomass of the sample area. After that, the harvested fresh biomass is dried and weighed. Finally, to obtain the C amount of the samples, the weight of the dry biomass was multiplied by the carbon fraction (CF). The carbon fraction of dry biomass has a default value of 0.5 (IPCC, 1997).

The allometric equations are empirical relations obtained from the results of destructive methods. These equations are applied depending on the field characteristics. For example, the age of the forest, the tree species, or the weather conditions of the region. In the case of tree biomass, physical measurements are needed as inputs for these equations. This data may include the density, the height, and the diameter at breast height (DBS). For small crops, allometric equations only can be applied to estimate AGB. In the case of BGB, a destructive technique is recommended (Pearson et al., 2007).

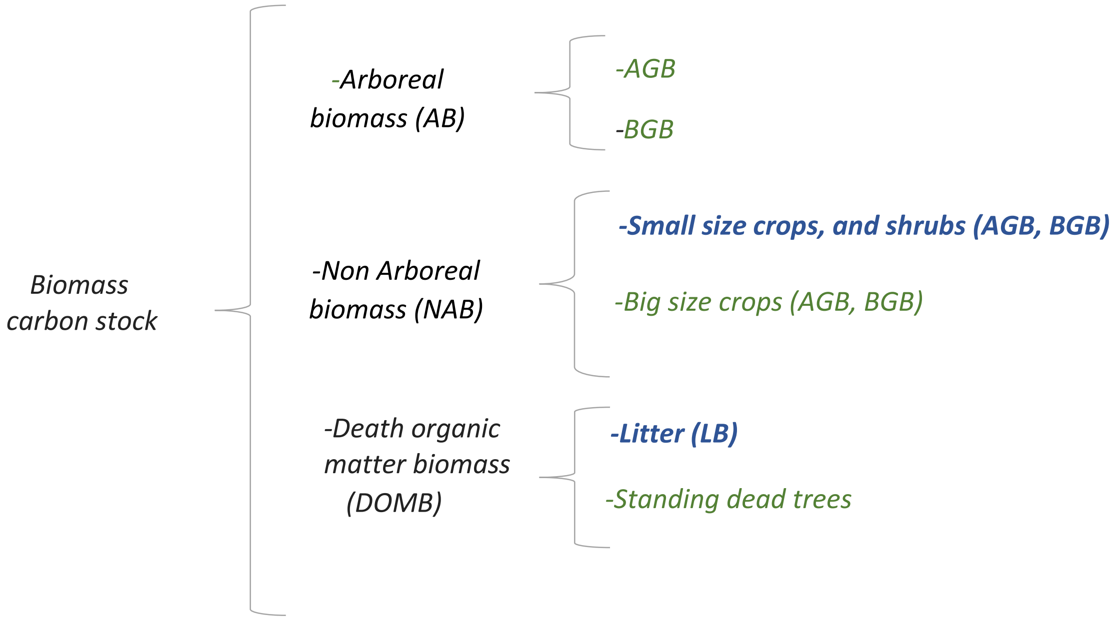

Figure 3. Distribution of the biomass carbon stock in the groups that were used during the sampling and the estimation of the biomass C stock of the nine experimental fields located in Shashui village, close to Soni town, in Lushoto district, Tanzania. AGB: Aboveground biomass, BGB: Belowground biomass. In green: the items estimated by allometric equations, in blue: the items estimated by destructive methods.

3.2.1.1 **Arboreal biomass (AB) carbon**

The arboreal biomass carbon is obtained as the sum of the arboreal above and below ground carbon.

$$\mathrm{C(AB)} = \text{Arboreal (AGB) carbon} + \text{Arboreal (BGB) carbon} \qquad (21)$$

Arboreal AGB carbon

An allometric equation developed by Chave et al. (2005), based on measurements at several locations with similar weather conditions (moist forest) around the world, was used to estimate the value of the arboreal AGB per tree (Equation 22).

$$\text{Arboreal AGB} = \mathrm{EXP}\ (2.977 + \ln(\rho\ DBH^2\ \mathrm{H})) \qquad (22)$$

Where DBH is diameter of the tree at breast height, H the tree height, and ρ the density of the tree. In this study, The DBH and the height were obtained from field measurements, and the density was obtained from the literature. The standard error of this model is 12.5% (Chave et al., 2005). Finally, the arboreal AGB carbon was obtained by multiplying the arboreal AGB by the carbon fraction (CF).

$$\text{Arboreal AGB carbon} = \text{Arboreal AGB} * \mathrm{CF} \qquad (23)$$

Arboreal BGB carbon

Cairns et al. (1997) proposed an equation to estimate arboreal roots biomass (BGB) in tropical forests using as input the value of the arboreal AGB (Equation 24). Then, the arboreal BGB carbon was obtained by multiplying the arboreal BGB by the carbon fraction (CF).

$$\text{Arboreal BGB} = \exp(-1 - 0.587 + 0.8836 \ln(\text{AGB})) \tag{24}$$

$$\text{Arboreal BGB carbon} = \text{Arboreal BGB} * \text{CF} \tag{25}$$

3.2.1.2 Non-Arboreal biomass (NAB) carbon

The non-arboreal vegetation is composed of herbaceous plants, shrubs, and grass. The non-arboreal biomass (NAB) carbon is obtained as the sum of the small size crops carbon plus the big size crops carbon.

$$\text{C(NAB)} = \text{Small size crops carbon} + \text{Big size crops carbon} \tag{26}$$

Small size crops carbon

To estimate the carbon of the small size crops, the procedure explained by Rügnitz et al. (2009) was used. This method requires cutting and weighing the fresh biomass of a sample area. Then, a sub-sample is extracted and dried in an oven until the weight is constant After obtained the weight of the dry biomass, the relation between the sub-sample and the sample needs to be calculated to obtain the actual value of the small size crop biomass of the sampling area. Finally, the dry biomass of the sample area is upscaled to the field area and multiplied by the carbon fraction (CF = 0.5). The complete methodology comprises the following steps:

- ✓ Throw a square frame of known area (sample area = 0.50 m^2, 1 m^2 or 2 m^2)
- ✓ Remove the plants from the soil including the roots from the sample area
- ✓ Weigh all the removed plants (FW sample)
- ✓ Take a sub-sample of 200g from the sample (FW sub-sample = 200g)
- ✓ Dry the sub-samples in the oven at 60^{o} Celsius, until the weight is constant
- ✓ Obtain the dry weight (DW sub-sample)

To obtain the biomass of the small size crops, the following equation was applied.

$$Small\ size\ crop\ biomass(sample\ area) = \frac{FW\ (subsample)}{DW\ (subsample)} * FW(sample) \tag{27}$$

The small size crop biomass per area was calculated as:

$$Small\ size\ crop\ biomass(total\ area) = \frac{Field\ area}{Sample\ area} * Small\ size\ crop\ biomass(sample\ area) \tag{28}$$

The carbon present in the small size crops was calculated using the carbon fraction (CF)

$$\text{C(small size crop)} = Small\ size\ crop\ biomass(total\ area) * CF \tag{29}$$

Big size crops carbon

For the banana crops (*Musa sp.*), the following allometric equation was used to estimate the AGB.

$$\text{AGB (Banana)} = -0.0927 + 0.0203 * (\text{DBH})^2 \tag{30}$$

This equation was developed from the measurements and biomass estimations of several banana crops fields in Mexico (Alcudia et al., 2019), the results of this research showed that the AGB in banana plants represented on average 87.6% of the total biomass, and the BGB represented the remaining 12.4%. This last value was used to estimate the banana BGB biomass. Finally, to obtain the carbon present in the biomass (AGB and BGB) the CF (0.5) was used.

To estimate the biomass on coffee crops, the values obtained by a study conducted in a mature coffee plantation in Southwestern Togo were used (Dossa et al., 2008). This study determined the biomass of different species of coffee in agroforestry systems. The results showed that on average, a mature coffee plant (*Coffea robusta*), under shaded conditions had 15.4 kg and 3.3 kg of AGB and BGB, respectively. With these values and the number of coffee plants per field, the coffee biomass stock was estimated. Finally, to obtain the carbon present in the biomass, the CF (0.5) was used.

3.2.1.3 Dead organic matter Biomass (DOMB) carbon

The dead organic matter biomass (DOMB) was calculated as the sum of the carbon of the litter biomass (CLB) plus the carbon present in the biomass of the standing dead trees (CSDTB).

$$C(DOMB) = CLB + CSTDB \tag{31}$$

Litter biomass carbon (CLB)

The process to estimate CLB according to Rügnitz et al. (2009) was used. It follows the next steps:

- ✓ Throw a square frame of 0.25 m^2 (50cm x 50cm)
- ✓ Cut and weigh all the live matter above the soil to obtain the fresh weight (FW sample)
- ✓ Take a sub-sample of 200g (FW sub-sample = 200g)
- ✓ Dry the sub-sample in the oven at 60^o Celsius until the weight is constant
- ✓ Obtain the dry weight (DW sub-sample)

To obtain the biomass of the litter, the following equation was applied.

$$Litter\ biomass(sample\ area) = \frac{FW\ (subsample)}{DW\ (subsample)} * FW(sample) \tag{32}$$

The litter biomass per area was calculated as:

$$Litter\ biomass(total\ area) = \frac{Field\ area}{Sample\ area} * Litter\ biomass(sample\ area) \tag{33}$$

The carbon present in the litter was calculated using the carbon fraction (CF)

$$\mathrm{C(litter)} = litter\ biomass(total\ area) * CF \tag{34}$$

Standing death trees biomass carbon (C_{STDB}; MgC ha^{-1})

For the standing dead trees that still have branches and leaves the same allometric equations were applied to estimate the arboreal biomass (Chave et al., 2005; Cairns et al., 1997) were used in this case to obtain a reference biomass value for each dead tree. Then, a reduction of 3% from the reference biomass value was applied to estimate the actual biomass of the dead tree. If the standing dead trees did not have branches, the biomass was estimated using the volume of each tree (DBH * H) times the density. Finally, to obtain the carbon of the standing dead trees, the biomass was multiplied by the CF (0.5) (Rügnitz et al., 2009).

3.2.2 Estimation of soil organic carbon (SOC)

To determine the soil organic carbon of the fields, the Walkley and Black method (Walkley, 1947) was used. This method determines the percentage of C present in the soil using chemical reactions and oxidation techniques.

The soil sampling method used by Rügnitz et al. (2009) was applied in the nine experimental fields. Three profiles were established per field, each of them was divided into three horizons of 10 cm depth (0-10, 10-20, 20-30 cm). A soil sample from each of these layers was taken (9 samples per field). Finally, the samples coming from the same depth were put together and homogenized to obtain one sample per depth per field (3 samples per field).

The soil samples were tested using the Walkley and Black method in the laboratory to obtain the percentage of carbon per depth (SOC_i). The estimation of soil carbon stocks per unit area on a plot (full profile) was calculated using the following equation (Rügnitz et al., 2009):

$$SOC = \sum_{horizon=i}^{n} ([(BD_i\ x\ TH_i\ x\ [1 - Fr_i\ ]\ x\ SOC_i)\ x\ 10) \tag{35}$$

Where, SOC is the organic carbon per profile (Mg ha^{-1}), BD_i is the bulk density of horizon *i* (Mg m^{-3}), TH_i is the thickness of horizon *i* (m), FR_i is the thick fragments fraction of the horizon *i* (0-1), and SOC_i is the percentage of organic carbon in *i* horizon (0-1).

3.3 Net economic profit

Socioeconomic information from the nine experimental fields was collected to characterize the influence of the socioeconomic condition of the families in the management of the fields (SWC measure) and to estimate their actual net operating profit. The study first started with physical observations and informal interviews to obtain primary data (qualitative). Then, a technique based on semi-structured interviews and guided field walks was applied to collect 8 socioeconomic aspects and 13 economic variables that can be grouped in 4 main categories (Table 1).

Table 1. Socioeconomic aspects and economic variables included in the estimation of the net economic profit of the 9 experimental fields located in Shashui village, close to Soni town, in Lushoto district, Tanzania.

Socioeconomic aspects of the household	**Economic variables**	
	Main category	**Sub-category***
Age	Income	(I) Food crops
Family size	Cost of production	(I) Cash crops
Land size	Other costs	(I) Livestock products
Land tenure status	Market characterization	(I) Local poultry production
Level of education		(I) Forest products
Marital status		(I) Off-farm activities
Occupation		(CP) Seeds
Extension services		(CP) Labor
		(CP) Manure/Fertilizing
		(OC) Living expenses
		(OC)Taxes and fees
		(MC) Market prices
		(MC) Market Location

*The sub-category is related with the main category by the prefix: (I) income, (CP) cost of production, (OC) other cost, (MC) market characterization.

Field management is influenced by the socioeconomic condition of the households. Consequently, the revenues generated from different fields are usually related to the aspects that determine these conditions (Bullock et al., 2014). For example, the adaptation of a particular SWC measure like AF systems or bench terraces in a field is generally based on the labor intensity required to install and maintain these measures and in the labor capacity of the households. In this study, semi-structured interviews were applied to the landowners to collect information about the socioeconomic situation of their families.

The annual gross income was quantified by multiplying the yield production of cash and food crops times their respective price in the market, plus an estimation of the income of the timber, which was calculated as the number of trees per year that would be sold in the market, times the price of an individual tree of 10 m height and 100 cm of DBH (30 000 TZS).

To calculate the production cost, 4 variables were taken into consideration, i) costs of the seeds; ii) labor costs, which was calculated based on the price of one person working day (7000 TZS for October 2019); iii) fertilizing costs, and iv) manure costs.

4. Results

4.1 Data collection

Field data were collected from October to December 2019. In total, 9 agricultural fields were selected, 3 with traditional AF system, 3 with bench terraces and 3 without any SWC measure (control fields) (Figure 4). The 9 fields are located in the Lushoto district, around "Shashui" village, which is one of the small settlements that conformed this district. The closest market is in Soni town, around 5 km from the fields.

4.1.1 Field description

The experimental fields are located within a radius of 700 m, which means relative equal weather conditions for the 9 fields. The area of the fields varies from 600 to 2000 m^2, and they all have a steep slope, which ranges from 15° to 29° (Table 2).

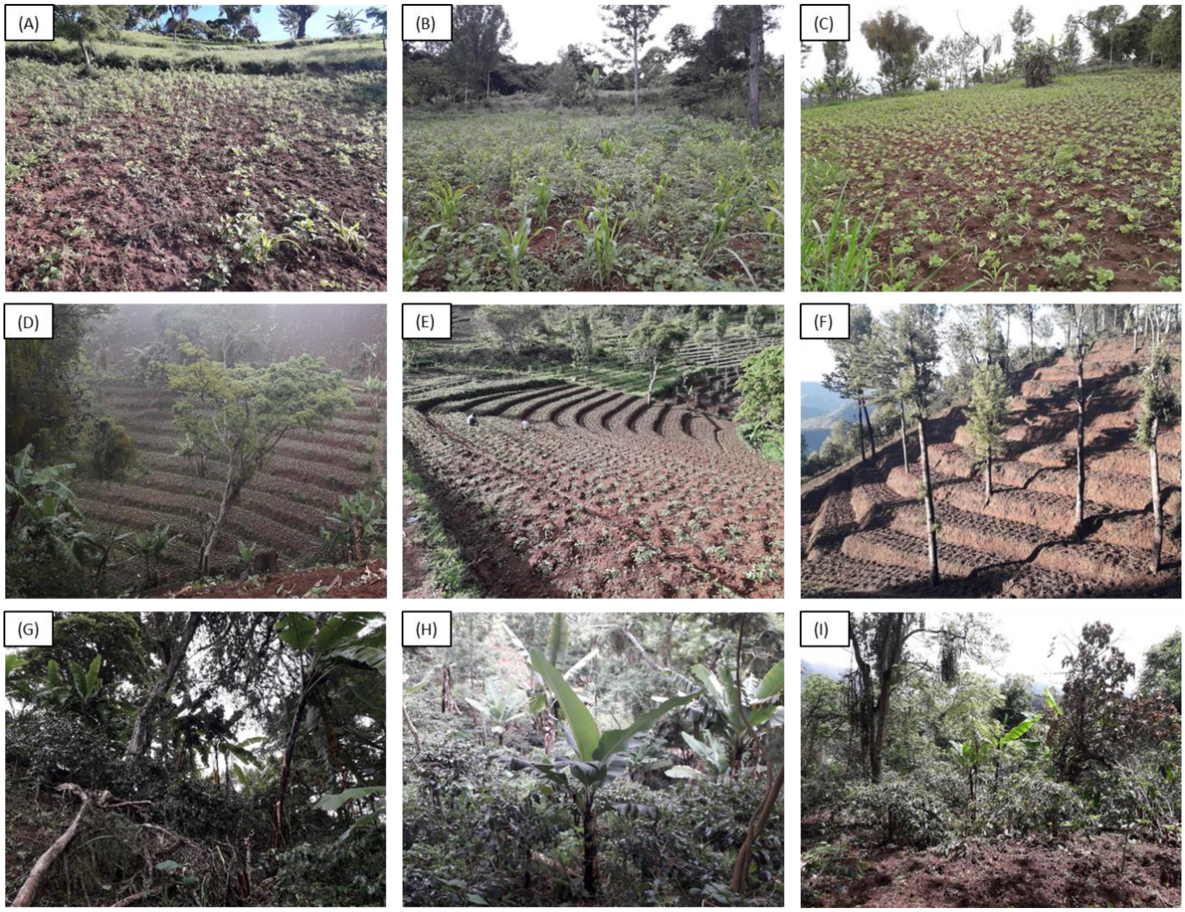

Figure 4.The nine experimental fields used in the study. The fields are located near to Soni town. West Usambara Mountains, Tanzania. (A) Control 1, (B) Control 2, (C) Control 3, (D) Terraces 1, (E) Terraces 2, (F) Terraces 3, (G) Agroforestry 1, (H) Agroforestry 2, (I) Agroforestry 3.

The soil texture of the fields is dominated by a high clay content (around 45%) and a moderate sand percentage of approximately 38%. The roughness and the infiltration capacity of the soil in the fields vary depending on the kind of crop cultivated. Fields with small crops such as maize, potato, and beans show more soil roughness and better drainage than fields with bigger crops like banana and coffee. In terms of labor, bench terraces are the most time demanding SWC measure, due to their construction and maintenance. In the case of traditional AF systems, labor is required for the implementation of the measure, but after the field is mature enough to produce, the demand for labor decreases. The labor demand of control fields is the same year after year during the growing seasons, and it is lower than the labor required by terraced fields and higher than the labor demand of AF fields.

Individual small crops or a combination of crops (e.g. maize-beans) were present in all the control and terraced fields. While in the traditional agroforestry fields, a combination of coffee (*Coffea arabica*), banana (*Musa sp.*), plus a considerable number of trees was the most common. The only exception was AF3, where maize (*Zea maize*) was cultivated together with banana, coffee and trees. Four species of trees were identified in the fields, 1) Albizia (*Falcataria moluccana*) was present in the three AF fields, T1, and T3. 2) *Rauvolfia caffra was just present in AF1*. 3) *Grevillea robusta was present in AF2, AF3, and T3*. And Avocado (*Persea americana*) was present in AF2, AF3, and T1.

At the beginning of October, all the terraced and control fields were seeded, waiting for the short rainy season. It means that the canopy cover, interception factor, and ground cover factor had low values at that time, which increased the splash erosion and consequently the soil loss in this early stage. These factors were changing during the growing season. Contrary to AF fields, where the canopy cover and the interception factor were high and constant during the whole season. The characteristics of the 9 fields are listed in Table 2 and Table 3. Sheets with individual descriptions and complete information about the fields can be found in appendix A.

Table 2. General characteristics (Static variables) of the nine experimental fields used in the study. The fields are located near to Soni town. West Usambara Mountains, Tanzania.

Field code	Slope (°)	Gravimetric soil moisture content at field capacity (kg/kg)	Bulk density (mg/m3)	Length (m)	Drainage	Texture
C1	22.0	0.25	1.24	35.0	Good	Clay
C2	17.0	0.23	1.18	40.0	Good	Clay
C3	15.0	0.31	1.03	36.0	Good	Clay
AF1	27.0	0.21	0.95	20.0	medium	Clay
AF2	23.5	0.26	1.06	70.0	medium	Clay
AF3	18.0	0.18	0.79	40.0	Good	Clay
T1	21.5	0.26	1.07	34.0	Good	Clay loam
T2	15.0	0.22	0.92	38.2	Good	Clay
T3	29.0	0.30	1.14	32.7	medium	Clay loam

The data corresponds to the period October-December 2019

Table 3. General characteristics (dynamic variables) of the nine experimental fields used in the study. The fields are located near to Soni town. West Usambara Mountains, Tanzania.

Field code	Interception factor (0-1)	Canopy cover (0-1)	Plant height (m)	Fraction of vegetation ground cover (0-1)	Surface roughness
C1	0.15-0.25	0.20-0.25	0.15-0.35	0.15-0.25	Very rough
C2	0.15-0.25	0.20-0.30	0.15-0.40	0.15-0.30	Rough
C3	0.20-0.25	0.20-0.30	0.15-0.40	0.15-0.65	Very rough
AF1	0.30	0.90	0.05	0.80	medium
AF2	0.30	0.80	0.05	0.80	medium
AF3	0.30	0.90	0.05	0.85	Rough
T1	0.20-0.25	0.35-0.50	0.15-0.40	0.15-0.60	Very rough
T2	0.20-0.25	0.25-0.30	0.15-0.70	0.15-0.25	Very rough
T3	0.19-0.25	0.20-0.40	0.15-0.60	0.15-0.40	Rough

The data corresponds to the period October-December 2019

4.1.2 Rainfall

The annual rainfall in the region for the Sakharani mission station in 2019 was 1463 mm, which exceeds the mean annual range of 800 to 1300 mm given by Mascarenhas (2000). Although, this value is lower than the highest historical values reported during "El Niño" years of 1997 (1862 mm) and 2006 (1754 mm) (Mahoo et al., 2015).

The high annual rainfall value in 2019 can be explained by the extraordinary rainfall during October (524 mm), a very unusual value for this month if it is compared with the mean monthly rainfall of 50 mm (period of 1971-2000; Mahoo et al., 2015). Nevertheless, in 2019, the months of September, November, and December also showed rainfall values that differ from the mean (Figure 5). This behavior of the rains shows an early start of the short rainy season (Vuli) with a peak in October. The total precipitation during the short rainy season (October-December) in 2019 was 699 mm, more similar to the precipitation expected for the long rainy season (Masika) than the expected during the short rains. The mean rainfall during Masika is 527.8 mm, and during Vuli is 272.4 mm (period of 1971-2000; Mahoo et al., 2015).

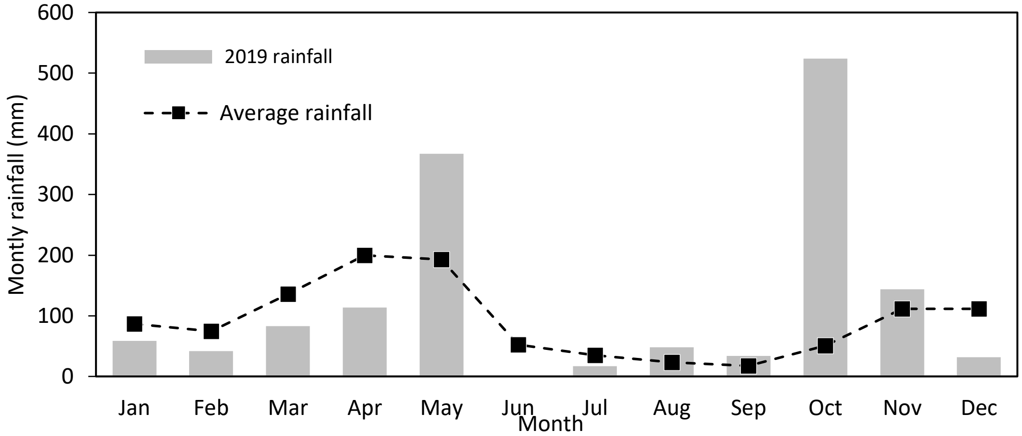

Figure 5. Bar graph of the 2019 monthly rainfall values for the Sakharani mission station, located 5 km from the fields in Lushoto district, West Usambara Mountains, Tanzania. The dotted line represents the mean monthly rainfall values for the Lushoto district from 1971 to 2000 (Mahoo et al., 2015).

The excessive rainfall during October 2019 led to destructive floods in the country. According to media reports and the emergency response coordination center (ERCC) of the European Commission, 44 people were killed during October by flooding caused by heavy rainfall across Tanzania, especially in the north-east of the country. Besides, some houses, roads, bridges and crop farms were damaged.

The first events of the short rainy season started at the beginning of October, and lasted until the 24th of the same month. During this time, 12 days with small rainfall amounts and 7 major events with daily rainfall data varying from 30 to 87 mm were register. This wet period was followed by an interval of 12 dry days. After this period, and until the end of December, just one more wet period of 6 rainy days was recorded. It was assumed that these later 6 days with rainfall did not cause much erosion. Therefore, just the rainfall for the period between the 30th of September and 24th October was considered for the estimation of the soil loss values (Figure 6).

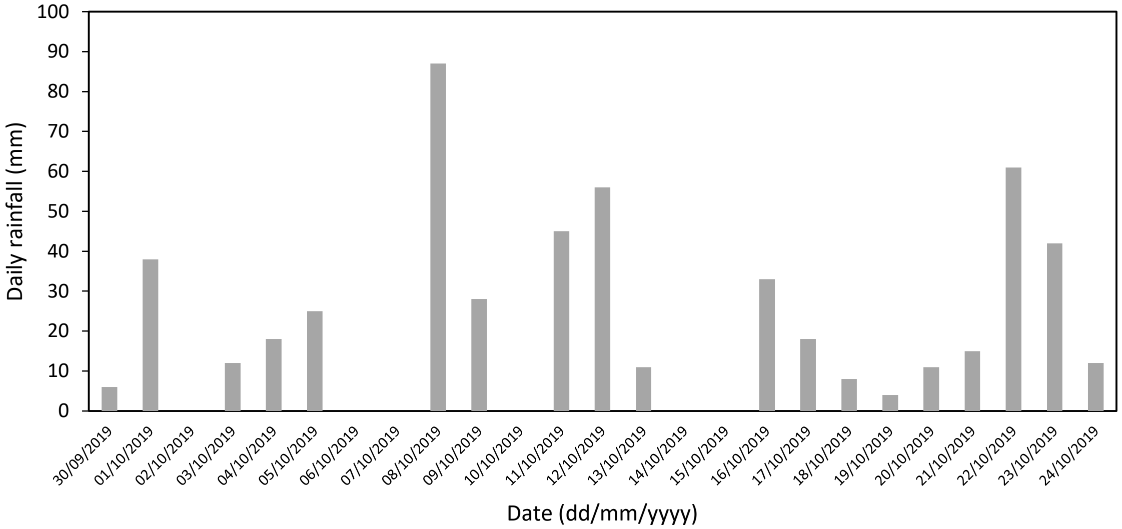

Figure 6. Daily rainfall values (mm) for the Sakharani mission station, located 5 km from the fields in Lushoto district, West Usambara Mountains, Tanzania. For the period from 30th September to 24th October 2019.

4.1.3 Soil loss

The first soil loss quantification with the ACED method was carried out at the end of October, and it was replicated after 12, 42, and 52 days. In the first campaign, several erosion features were identified in most of the fields. It was assumed that these erosion features were caused exclusively by the rainfall events of October due to 1) the low rainfall values of the previous months, and 2) the initial dates of the growing season, which for control and terraced fields coincide with the beginning of October. The terraced and control fields received tillage before the new growing season, which was not the case for the AF fields. The crops (banana-coffee) and the trees in the AF fields were not planted at that time, which means that the soil was not tilled before October and previous erosion features in AF fields were not necessarily removed from the soil.

Two values of soil loss were obtained from the ACED method. The gross soil erosion, which is referred to the quantity of the soil loss from all the erosion features present in the fields, and the net soil erosion, which represents the quantity of soil that is transported out of the fields by water erosion. For example, in the case of terraced fields, the soil loss of one terrace in the upper part of the field is transported to the terrace immediately below. Consequently, the sediment is transported from terrace to terrace, but not out of the field. Thus, to obtain the "net soil loss", only the soil loss values of those terraces located at the lower boundaries of the fields should be quantified. The values of the net soil loss for the nine fields are given in Figure 7.

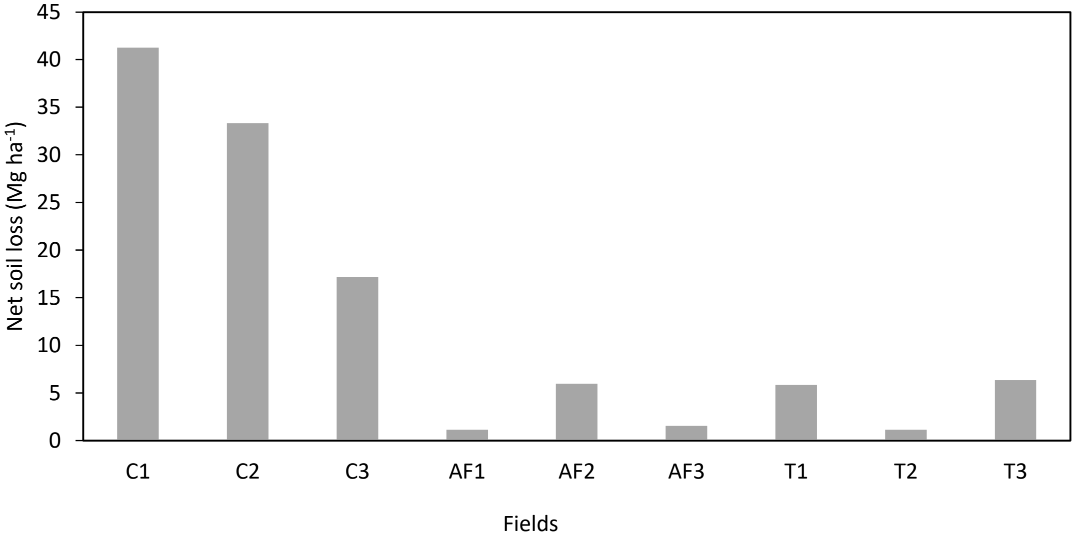

Figure 7. Net soil erosion (Mg ha^{-1}) of the nine experimental fields for the short rainy season of 2019, the fields are located at Shashui village, in Lushoto district, West Usambara Mountains, Tanzania

For the short rainy season, C1 was the field with the highest net soil loss value (41.3 Mg ha^{-1}). This field has a slope of 22°, and a low ground cover factor estimated around 15% at the end of October. However, vegetation and soil characteristics were similar for the three control fields. Therefore, the net soil loss values differences between control fields were mainly explained by the difference in slope between them. For instance, C2 has a slope of 17° and the net soil loss value was estimated in 33.3 Mg ha^{-1}, while C3 has a slope of 15° and the net soil loss value was estimated in 17.2 Mg ha^{-1}.

The low values of net soil loss in agroforestry systems can be explained by the small quantity of water that reaches the soil directly during a rainfall event. Most raindrops are intercepted by the canopy cover, the groundcover, and the litter. As a consequence, the splash erosion is reduced and the system becomes sediment supply-limited. Nevertheless, the length of the hillslope and the presence of depressions in the slope shape can lead to the formation of some rills, increasing the soil loss values. For example, AF2 has the longest slope length (70m) and the net soil loss for this field was estimated at 6 Mg ha-1, while for AF1 (20m) and AF3 (40m), the values of soil losses were 1.1 and 1.6 Mg ha^{-1}, respectively.

In the case of terraced fields, the net soil loss was estimated at 5.9 Mg ha^{-1} for T1 and 6.3 Mg ha^{-1} for T3, which means a small variation of 6% in soil loss, despite the difference of 8° in slope between these two fields. Contrary to control fields, where a similar difference in slope (7°) between T1 and T3, had a reduction of 19% of soil loss between these fields. It shows the efficiency of the terraces in decreasing the influence of slope on soil erosion. Furthermore, the small soil loss value of T2 (1.2 Mg ha^{-1}) can be attributed to the larger width of the terraces in this field with respect to the width of the terraces in T1 and T3.

4.1.4 Effectiveness of soil erosion control

On average, the net soil loss for the three control fields was estimated at 30 Mg ha^{-1} for the short rainy season. For the same period, the average net soil lost in terraced fields was estimated at 4.5 Mg ha^{-1} and, for AF fields it was 2.9 Mg ha^{-1}.

The soil erosion reduction effectiveness was estimated using equation 1. Terraced fields showed a soil loss reduction of 85% ± 7%, compared with the average soil loss of control fields, and a slightly higher reduction rate (91% ± 7%) was obtained for the AF fields.

4.1.5 Carbon sequestration

The total carbon sequestrated during the period of 38 days was quantified as the difference between the final and the initial carbon stock. To obtain the carbon stock in the biomass, first the biomass present in the fields was estimated at the start and the end of the 38 days. Then, these values were multiplied by the carbon fraction value of 0.5 (IPCC, 1997).

4.1.5.1 **Arboreal biomass (AB) Carbon**

Arboreal biomass was present in five out of the nine experimental fields, 3 fields with agroforestry systems and 2 terraced fields. The highest values of initial biomass corresponded to the AF fields, on average these three fields had 499.6 Mg ha^{-1} of initial arboreal biomass, while T3 had almost half of this value (241 Mg ha^{-1}), and T1 had 35.5 Mg ha^{-1}. On average, 89% of the initial arboreal biomass of the 5 fields corresponded to the above ground biomass (AGB) and 11% to the below ground biomass (BGB) (Figure 8).

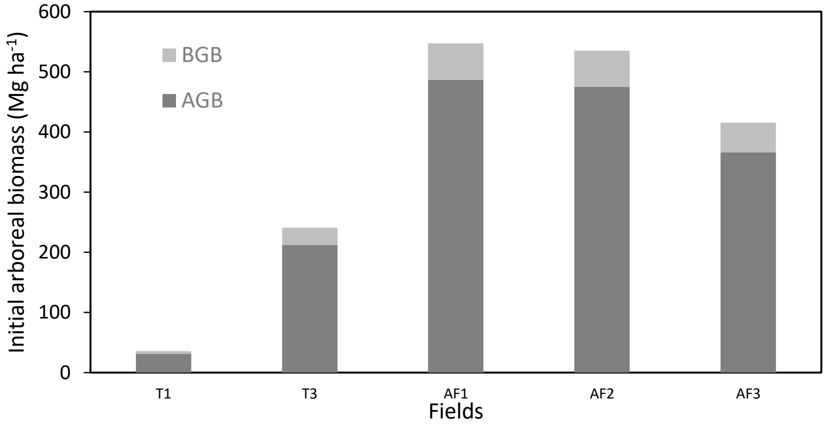

Figure 8. Initial arboreal biomass (Mg ha^{-1}) of five out of the nine experimental fields, located at Shashui village, in Lushoto district, West Usambara Mountains, Tanzania. (AGB): Aboveground biomass, (BGB): Belowground biomass.

Specific mean annual growth rates for each tree species (Table 4) were used to estimate the final arboreal biomass stock (Mg ha^{-1}) after 38 days of the initial estimations.

Table 4. Mean annual growth rates for arboreal species, in terms of diameter at breast height (DBH) and height.

Species	DBH	Height	Source
Grevillea robusta	3.46 cm/year	1.34 m/year	(Baggio et al., 1997)
Albizia sp.	1.54 cm/year	1.72 m/year	(Debell et al., 2019)
Rauvolfia caffra	3.75 cm/year	1.50 m/year	(CABI, 2019)
Persea americana	3.00 cm/year	1.00 m/year	(Samaniego and Russo, 1999)

After 38 days, the carbon sequestrated by the arboreal biomass (C Mg ha^{-1}) of the five fields was calculated. This value was mainly influenced by the initial biomass stock of the fields and the growth rates for the individual species of trees. AF2 had the highest value of carbon sequestered per hectare (57.06 C Mg ha^{-1}), followed by AF1 (49.17 C Mg ha^{-1}) and AF3 (39.37 C Mg ha^{-1}), while terraced fields had the lowest values, T1 with 0.57 C Mg ha^{-1} and T3 with 23.67 C Mg ha^{-1} (Figure 9).

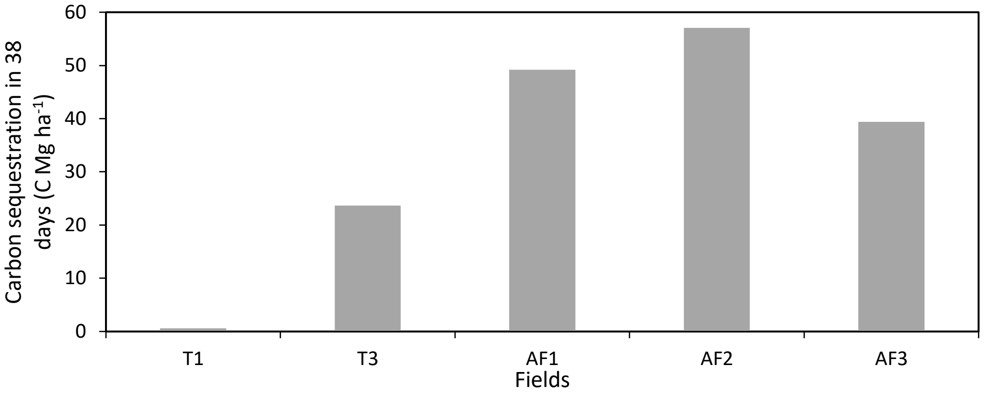

Figure 9. Carbon sequestrated (C Mg ha^{-1}) by the arboreal biomass in 38 days for five out of the nine experimental fields, located at Shashui village, in Lushoto district, West Usambara Mountains, Tanzania.

4.1.5.2 **Non-arboreal biomass (NAB) carbon**

Small size crops carbon

Seven out of the nine experimental fields had small size crops such as beans, maize, potato, and tomato. The initial biomass values for four fields (C1, C2, T1, T2) were between 0.09 Mg ha^{-1}and 0.12 Mg ha^{-1}. C3 and T3 had the highest initial values around 0.8 Mg ha^{-1}, and AF had the lowest value (0.01 Mg ha^{-1}) (Figure 10). Two fields did not have small crops (AF1 and AF2).

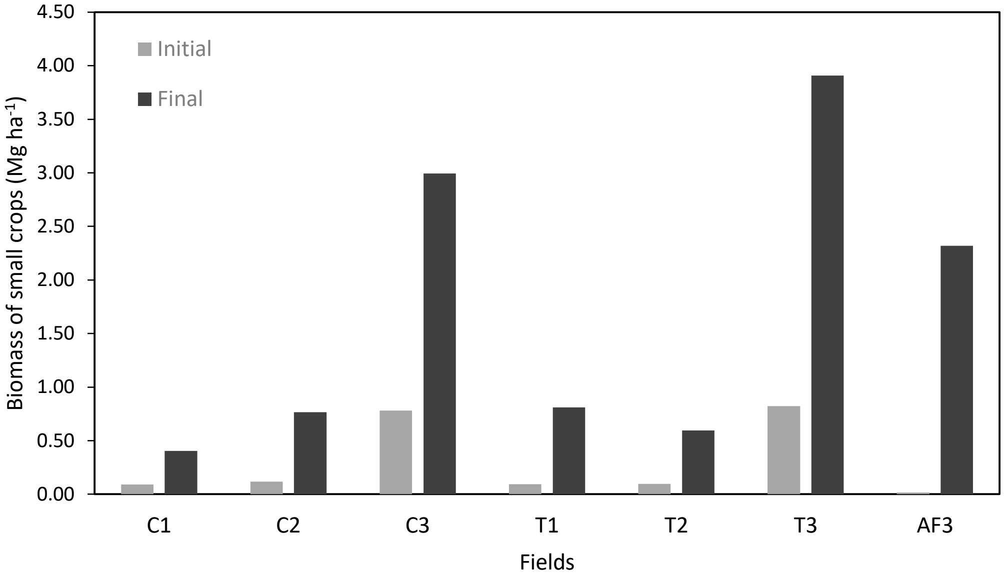

Figure 10. Initial and final (after 38 days) small size crops biomass (Mg ha^{-1}) of seven out of the nine experimental fields, located at Shashui village, in Lushoto district, West Usambara Mountains, Tanzania.

For the estimation of the final biomass at the end of the period, new samples of small crops were collected, dried, and weighed. As a result, T3 (3.9 Mg ha^{-1}), C3 (2.9 Mg ha^{-1}) and AF3 (2.3 Mg ha^{-1}) presented the three highest biomass values (Figure 10), as well as the three highest carbon sequestration rates 1.54, 1.15, 1.11 C Mg ha^{-1} (Figure 11). However, there was no evidence that a specific SWC measure caused faster biomass growth in small crops than others. Because many other factors are involved in biomass growth. For example, the quantity and quality of manure applied, and type of crop grown.

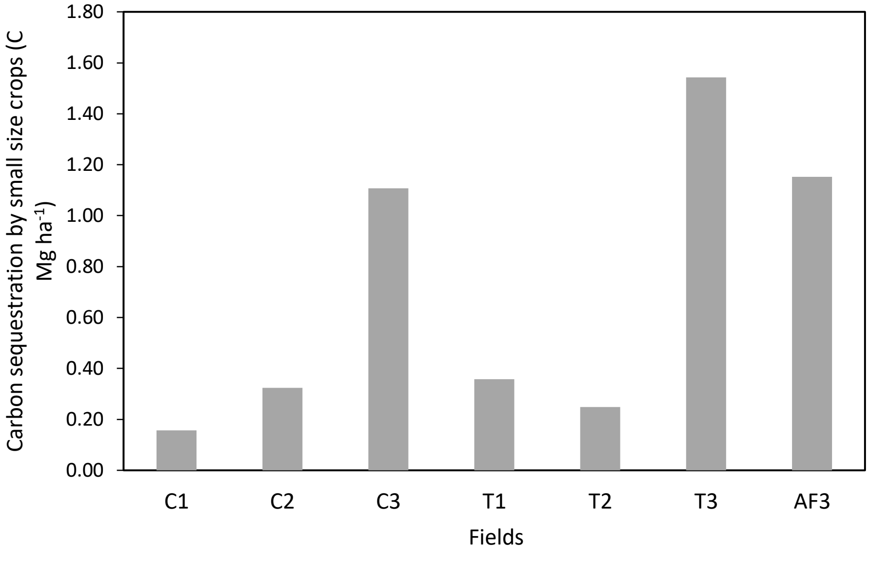

Figure 11. Carbon sequestrated (C Mg ha^{-1}) by small size crops in 38 days for seven out of the nine experimental fields, located at Shashui village, in Lushoto district, West Usambara Mountains, Tanzania.

Big size crops carbon

Big size crops such as banana and coffee were present just in the three fields with AF systems. In general, coffee is the crop that contributed most to the total big size crops biomass (82%). The differences in the initial big size crops biomass estimations between the three fields are mainly explained by the density of the crops (number of plants per m^2). For example, AF1 and AF3 had the highest density for coffee, around 1 plant every 3 m^2 and initial biomass values of 83.87 Mg ha^{-1}and 75.03 Mg ha^{-1}, respectively, while coffee density in AF2 was just 1 plant every 4.9 m^2 and it biomass was 40.07 Mg ha^{-1}. In the case of banana, density in AF1 was 1 plant every 7.9 m^2, in AF2 the density was 1 plant every 16.7m^2, and density in AF3 was 1 plant every 86 m^2. The values of the initial big crops biomass are shown in Figure 12.

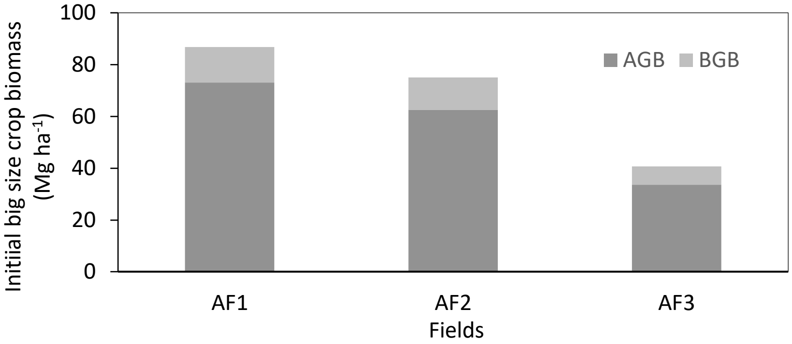

Figure 12. Initial big size crops biomass (Mg ha^{-1}) of three out of the nine experimental fields, located at Shashui village, in Lushoto district, West Usambara Mountains, Tanzania. AGB: Aboveground biomass, BGB: Belowground biomass

Specific mean annual growth rates for banana and coffee were used to estimate the final biomass of the fields. Rodríguez et al. (2006) proposed an average DBH growth of 0.154 cm per day for Banana, and according to Dossa et al. (2008), Coffee (*Coffea Arabica*) plants have a biomass increment of 0.36 kg per year.

The carbon sequestration rates for the big size crops biomass in the three fields were mainly dominated by the values of the initial biomass stock. Therefore, big-size crop biomass from AF1 sequestered around 2 Mg of carbon per hectare, followed by AF2 with 1.3 C Mg ha^{-1}, and AF3 with just 0.5 Mg ha^{-1} (Figure 15).

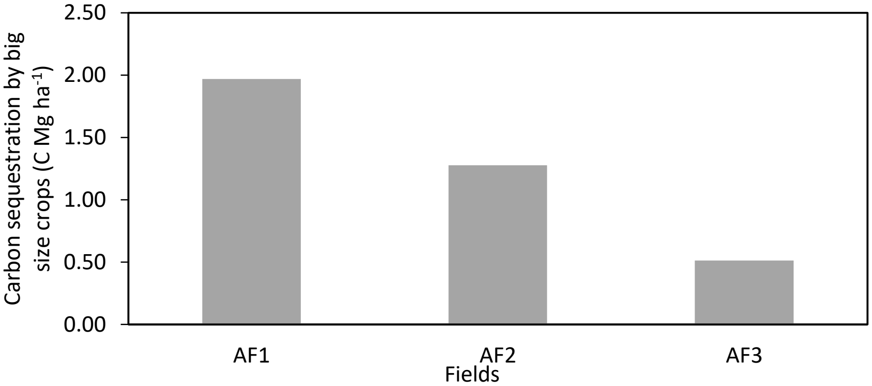

Figure 13. Carbon sequestrated (C Mg ha^{-1}) by big size crops in 38 days for three out of the nine experimental fields, located at Shashui village, in Lushoto district, West Usambara Mountains, Tanzania.

4.1.5.3 **Dead organic matter biomass (DOMB) carbon**

The biomass of dead standing trees decreases over time due to the reduction in wood density. Rügnitz (2009) used a constant reduction value of 3% from live tree biomass to estimate the biomass of dead standing trees. In this study, the same value was used to estimate the initial biomass of the dead trees. Subsequently, the biomass of the dead organic matter was calculated as the sum of the biomass of the dead standing trees plus the biomass of the litter.

AF3 had the highest value of dead organic matter biomass (16.72 Mg ha^{-1}), followed by T1 (10.54 Mg ha^{-1}), and AF1 (6.98 Mg ha^{-1}). AF2 (3.71 Mg ha^{-1}) and T3 (2.56 Mg ha^{-1}) showed intermediate values, while C1, C2, T2, and C3 had values of dead organic matter biomass close to 0 (Figure 14). The presence of dead standing trees in the fields was not related with the type of SWC measure applied. On the other hand, litter biomass values are higher in those fields with arboreal vegetation, which includes the 3 AF fields, T1 and T3.

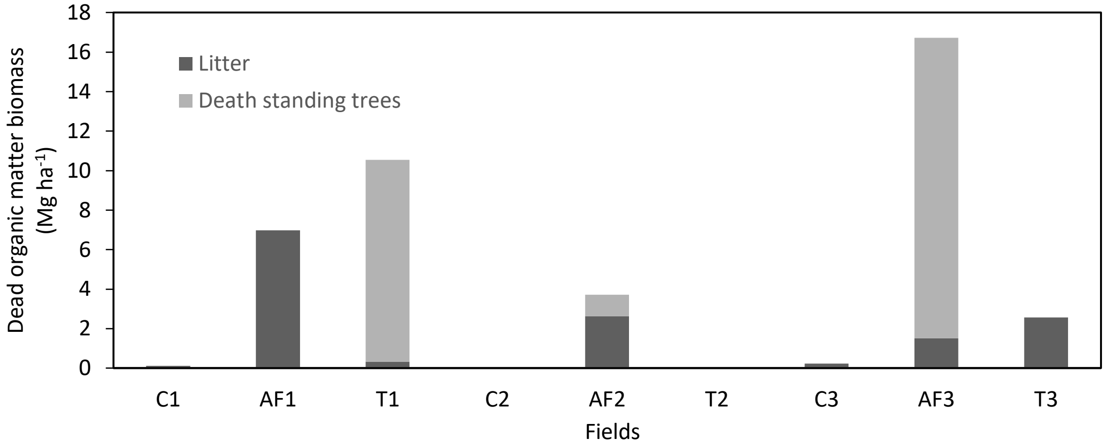

Figure 14. Dead organic matter biomass (Mg ha^{-1}) of the nine experimental fields, located at Shashui village, in Lushoto district, West Usambara Mountains, Tanzania. AGB: Aboveground biomass, BGB: Belowground biomass

It was assumed that the density of dead standing trees and the amount of litter did not change significantly in the 38 days. It means, that the final biomass was the same as the initial biomass. Therefore, the dead organic matter biomass of the fields was not considered for the estimation of the carbon sequestration in that period.

4.1.5.4 **Biomass carbon stock**

Assuming that all the fields have the same extension (1 hectare), the initial biomass stock quantified for the 9 fields would be 2016 Mg. The highest contribution corresponded to the arboreal biomass (88%), followed by the biomass of the big crops (banana and coffee) with 10%. Then, the biomass of the dead organic matter (1.8%), and finally, the small crop's biomass (0.2%).

The fields with AF systems had on average an initial biomass stock of 287.9 C Mg ha^{-1}, followed by terraced fields (48.0 Mg ha^{-1}), and control fields with just 0.23 Mg ha^{-1}. The rates of carbon sequestered by biomass in 38 days for the nine experimental fields are shown in Figure 15.

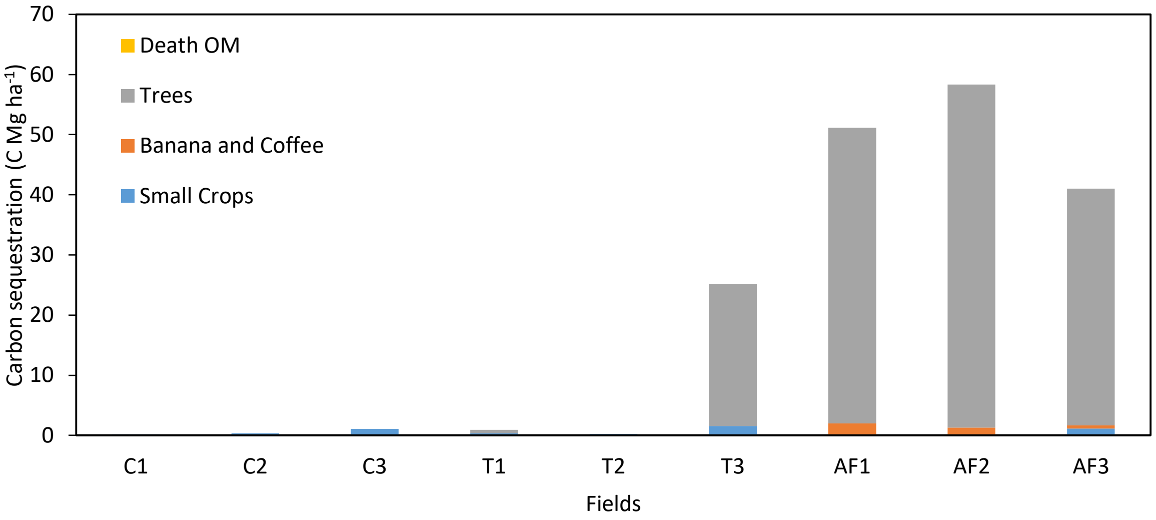

Figure 15. Total carbon sequestrated (tC/ha) by biomass in 38 days for the nine experimental fields, located at Shashui village, in Lushoto district, West Usambara Mountains, Tanzania.

The big difference between the biomass present in terraced and control fields with fields with AF systems produced also a big difference in the carbon sequestration rates. These differences are mainly caused by the presence of trees (arboreal biomass). For example, despite T3 was a field with small crops (potato, maize, and beans), similar to the control and terraced fields, several trees were present within T3, which increased the total biomass of this field. On the other hand, big crops such as banana and coffee, which have the second highest value of biomass, were planted together with trees in the 3 AF fields, which increased even more the difference in biomass and carbon sequestration between the AF fields and the rest of them.

4.1.5.5 **Soil organic carbon (SOC)**

Soil organic carbon (SOC) was determined for each field twice. The first time at the beginning of November, and the second time after 38 days. The results from the second sampling showed an average decrease in soil organic absolute values of 1.37 % as compared with the first sampling for all the fields in the first 10 cm, except for T3, which showed an increment of 1.98 %. The results for the other two depths (10-20 and 20-30cm) showed an increase of SOC percentages for three fields (T3, T1, AF1), while for the other six fields, their final percentages of SOC were lower than their initial values.

Few studies have been published about changes in SOC % in less than one year. Generally, such variations were measured after 10 years (e.g. Wang et al., 2012; Turner et al., 2015) or in slightly shorter periods (8 years) (e.g. Liu et al., 2007). Although, Turner et al. (2015) found seasonal variations in a lowland tropical forest of up to 20% in SOC values which were attributed to the changes in rainfall amounts. SOC values were lower after dry periods than during wet periods. Also Leinweber et al. (1994) described intra-annual changes in SOC % in agricultural fields with one peak in spring and another in autumn. Therefore, the decrease in SOC percentages in most of the fields of this study could be influenced by the rainfall distribution during the 38 days, heavy rainfalls during the previous month before the first sampling (wet conditions), followed by a dry period with sporadic rains that lasted until the second sampling.

Nevertheless, there are more factors that influenced the SOC % variations, especially in short periods of time. For example, T3 was the only field in which abundant manure was applied during the 38 days. Consequently, the organic matter in this field increased and thus the values of SOC were higher. Therefore, the average values of the two sampling moments were assumed the best SOC values for the nine fields in this study, and are shown in Figure 16.

The average SOC % on the topsoil (0-10 cm) for seven out of the nine fields was 2.26 ± 0.18 %. Consequently, it was not possible to establish a relation between the SWC measures and the soil organic carbon percentages of the fields. Two fields had topsoil SOC values that were much lower (AF3 1.44%), or much higher than the mean (T3 3.21%). The reason of these extreme values are probably related to the variable local conditions, instead of the presence of SWC measures.

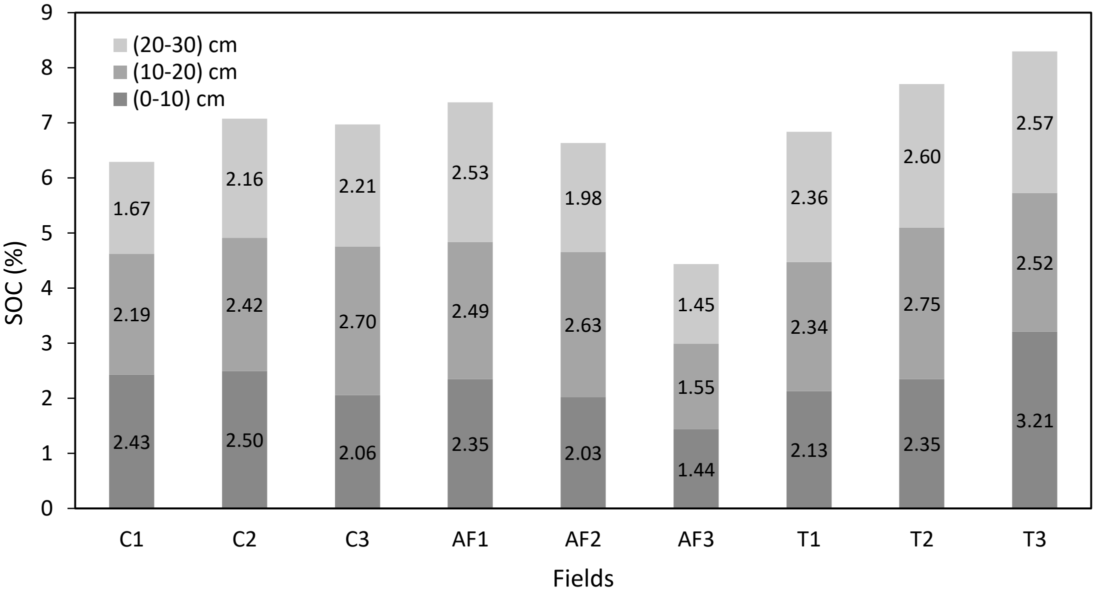

Figure 16. Average soil organic carbon (%) for 3 depths (0-10, 10-20, 20-30 cm) of the nine experimental fields, located at Shashui village, in Lushoto district, West Usambara Mountains, Tanzania.

The SOC percentages of the three depths were transformed into megagrams of carbon per hectare (Mg ha^{-1}) using the values of bulk density, coarse fragments, and soil thickness layer. The bulk density was determined using the volume and the dry weight of the soil core samples of 100 cm^3, and the coarse fragment fraction was estimated during the fieldwork. The average SOC content until 30 cm depth for control fields was 71.1 Mg ha^{-1}, for traditional agroforestry was 56.1 Mg ha^{-1}, and for terraced fields was 75.2 Mg ha^{-1}. Considering that a relationship could not be established between the SOC % and the SWC measures, the differences between the average values of SOC (Mg ha^{-1}) of AF fields with control and terraced fields can be also attributed to local conditions of the fields and not to the application of a particular SWC measure, and the mean value of SOC (0-30cm) for the nine fields is 67.5±11.5 Mg ha^{-1}

4.1.5.6 **Total carbon sequestration rates**

The C sequestration was estimated for a period of 38 days during the short rainy season of 2019. Soil organic carbon and biomass carbon were considered for the determination of the total carbon stocks of the nine fields at the beginning and the end of the period. It was assumed that SOC values for all the fields were the same during the 38 days, Thus, these values did not affect the carbon sequestration estimations, and the carbon sequestration rates were based just on the carbon sequestered by the living and dead biomass.

Fields with AF systems sequestered on average 50.17 C Mg ha^{-1} in 38 days. AF2 (58.34 C Mg ha^{-1}) had the highest value of the 3 AF fields, followed by AF1 (51.14 C Mg ha^{-1}) and AF3 (41.04 C Mg ha^{-1}). On the other hand, control and terraced fields had values that ranged from 0.16 to 1.11 C Mg ha^{-1} with a mean of 0.55 C Mg ha^{-1}, which represents 1% of the carbon sequestered by the AF fields, except for T3, that sequestered 25.21 C Mg ha^{-1}, which was considered as extreme value for terraced fields.

The reason why the carbon sequestered by AF fields is much higher than the carbon sequestered by control and terraced fields is the type of vegetation present in the AF fields. As indicated above, 98 % of the total biomass from the nine fields, corresponded to the sum of the arboreal biomass (88%) plus the biomass of the big size crops (10%), which is characteristic combination of AF fields.

4.1.6 Socioeconomic

The results of the interviews showed that 77.8 % of the landowners are older than 46 years. All of the landowners have received formal primary education, and all of them were married at the moment of the interviews. Generally, two adults and several young children between 6 and 17 years old live in the same house. Thus, to determine the family size, it was assumed that the family was comprised by the people who were currently living in the same house at the moment of the interview. The results showed that the smallest families had 6 members (56%), and 22% of the families had 9 or more members. Only 22 % of the landowners mentioned an off-farm economic activity as the main financial source of the family. The other 88 % considered farming as the main economic activity. Finally, just 11.1% of the landowners reported receiving assistance from the local extension services. The results are shown in Table 5.

Table 5. Results of the semi-structured interviews applied to the landowners, it contains socioeconomic information about the condition of the families of the 9 experimental fields located in Shashui village, close to Soni town, in Lushoto district, Tanzania.

Socioeconomic aspects of the landowner	SWC measure				Socioeconomic aspects of the landowner	SWC measure			
	Control	AF	Terraces	Average		Control	AF	Terraces	Average
Sex					**Extension services**				
Male (%)	66.7	100.0	66.7	77.8	Yes (%)	33.3	00.0	00.0	11.1
Female (%)	33.3	00.0	33.3	22.2	No (%)	66.7	100.0	100.0	88.9
Age					**Land tenure status**				
18-35 (%)	00.0	00.0	00.0	00.0	Family-owned land (%)	33.3	100.0	00.0	44.4
36-45 (%)	00.0	00.0	66.7	22.2	Leased (%)	33.3	00.0	00.0	11.1
46-55 (%)	33.3	100.0	0.0	44.4	Bought (%)	33.3	00.0	100.0	44.4
>55 (%)	66.7	0.0	33.3	33.3	Governmental (%)	0.0	00.0	00.0	00.0
Education level					**Occupation**				
None (%)	00.0	00.0	00.0	00.0	Farming (%)	66.7	66.7	100.0	77.8
Primary (%)	100.0	100.0	100.0	100.0	Government (%)	0.0	00.0	00.0	00.0
Secondary (%)	00.0	00.0	00.0	00.0	Private (%)	33.3	33.3	00.0	22.2
Diploma (%)	00.0	00.0	00.0	00.0	Other (%)	00.0	00.0	00.0	0.00
Marital status					**Family size**				
Single (%)	00.0	00.0	00.0	00.0	6 (%)	33.3	33.3	100.0	56.0
Married (%)	100.0	100.0	100.0	100.0	7 (%)	00.0	33.3	00.0	11.0
Divorced (%)	00.0	00.0	00.0	00.0	8 (%)	33.3	00.0	00.0	11.0
Widowed (%)	00.0	00.0	00.0	00.0	9 or more (%)	33.3	33.3	00.0	22.0

In general, terraced fields show a higher net income than control and AF fields. On average, terraced fields have an annual net income of 514.7 USD, followed by control fields (219.5 USD), and fields with AF systems (196.4 USD). Two fields exceed the average net income for their SWC measure category. T2 showed a net income value of 68% higher than the other terraced fields. One explanation for this difference can be the type of crop (tomato) cultivated in T2, which has a higher price in the market than the crops (beans, maize, and potato) cultivated in the other terraced fields. Other reasons are better agricultural practices and the availability of water for irrigation in this field, which is a clear advantage to the other fields because the farmer of the field T2 do not need to pay for this service. C3 also showed a net income value of 65% higher than the other control fields. Nevertheless, unlike T2, C3 had the same type of crops and similar biophysical characteristics (length, slope, area) than the other control fields. In this case, the net income is affected by the faster growth rate of the crops in C3 than in the other control fields, which can be attributed to the fertility of the soils.

The annual investment required to cultivate the different crops is higher in terraced fields (100 USD) than in control and AF fields. For control fields, this value is on average 50% smaller than the investment in terraced fields, while for AF fields it is around 7 times smaller. These low investment values in AF fields (13.7 USD) can be considered an advantage of this measure. Nevertheless, in the three AF fields, the lack of renewal in coffee crops also produced low profit values.

Generally, most of the economic advantages attributed to AF systems are more related to the reduction of costs than to the increase in productivity. For example, the shade provided by trees in many cases extends the harvesting periods, which increases labor efficiency and reduces labor costs (Hoekstra, 1987). However, as it was shown above, AF fields had really low production costs. Consequently, reducing the production cost even more in AF fields does not provide a significant increase in the net income. The results of the annual gross income and production costs of the fields are shown in (Figure 17)

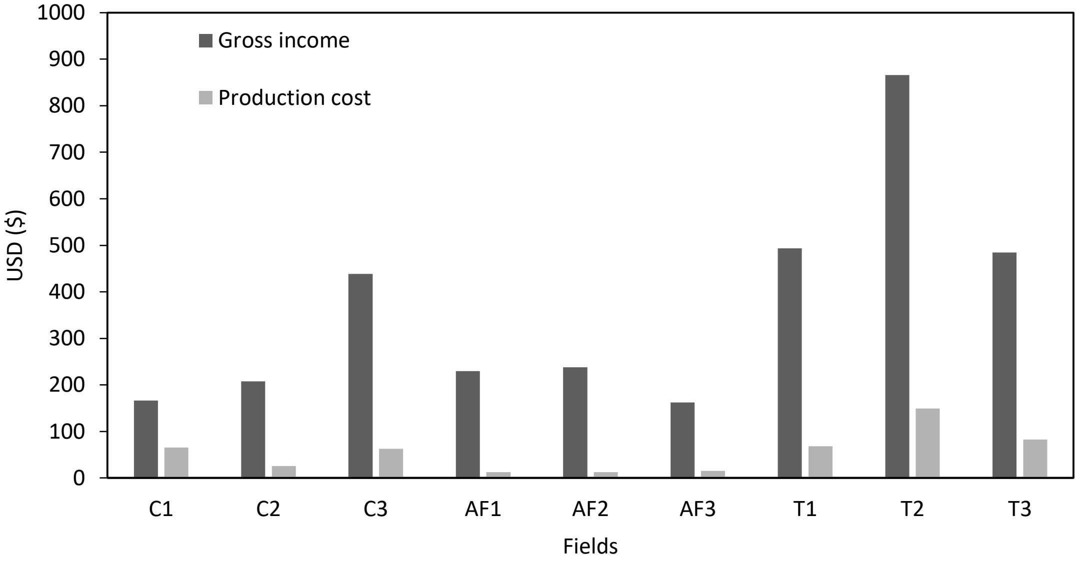

Figure 17. Annual gross income and production cost values expressed in US dollars of the 9 experimental fields located in Shashui village, close to Soni town, in Lushoto district, Tanzania.

According to the results of the nine fields, the annual net income of T2 (716.5 USD) is the only value that is above the national annual gross income per capita of Tanzania (639 USD). If instead, the monthly income of T2 is compared with the minimum wage of Tanzania in 2019 (143.9 USD), it just represents around 30% of this value. Nevertheless, it is important to remark that for all the nine families, these fields do not represent the totality of the land owned by them. For instance, AF1 represents just 10%, T1 represents 13%, T3 represents 50%, and the rest of the fields represent around 27% of the total area owned by the families.

The annual net income is directly influenced by the area of the fields. Generally, bigger fields represent higher profits. Thus, to analyze the relationship between the economic benefits and the type of SWC measure applied in the fields, the annual values of gross income and production cost were normalized using the area of the fields. Therefore, the results were transformed from USD to USD per hectare (Figure 19). As a result, terraced fields showed higher net income per hectare than control and AF fields. However, these differences are smaller than the results obtained using the absolute values.

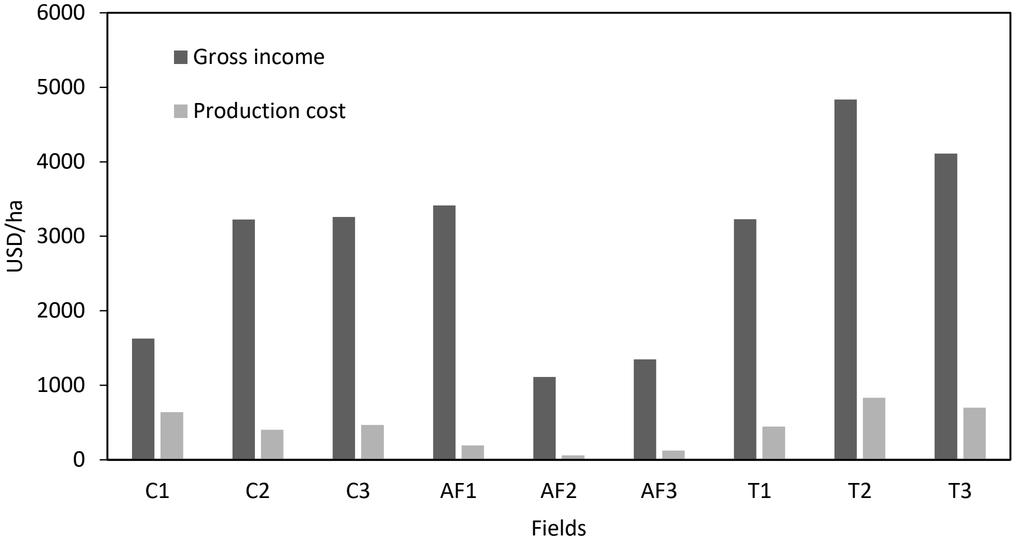

Figure 18. Annual gross income and production cost values expressed in US dollars per hectare of the 9 experimental fields located in Shashui village, close to Soni town, in Lushoto district, Tanzania.

4.2 hMMF model application

The hillslope version of the revised Morgan, Morgan and Finney water erosion model (hMMF; Sterk, 2020) was used to establish the water erosion patterns of the nine experimental fields. Input values were obtained from specific (literature) information of the study area, field measurements, and guide values from Morgan (2005). The parameter values used in the model are listed in Table 6, and the characteristics of the nine fields are listed in Table 7.

Table 6. Parameter values used for the hMMF modelling of nine experimental fields located at Shashui village, near to Soni town in the West Usambara Mountains, Tanzania.

Field	A	CC	PH	*MS	*BD	EHD	Et/Eo	K	COH	GC	C	°SR$_{inf}$	°ß
			m	wt.%	Mg m^{-3}	m		g J^{-1}	kPa				
C1	0.15	0.20	0.15	0.25	1.24	0.09	0.60	0.4	11	0.15	0.45	0.00	3.5
C2	0.15	0.20	0.15	0.23	1.18	0.10	0.60	0.4	11	0.15	0.45	0.00	3.5
C3	0.20	0.20	0.15	0.31	1.04	0.11	0.67	0.4	11	0.15	0.40	0.00	3.3
AF1	0.30	0.90	0.05	0.21	0.95	0.19	0.90	0.6	11	0.80	0.10	0.00	4.0
AF2	0.30	0.80	0.05	0.26	1.06	0.19	0.90	0.6	11	0.80	0.10	0.00	4.0
AF3	0.30	0.90	0.05	0.18	0.79	0.19	0.90	0.6	11	0.85	0.10	0.00	2.5
T1	0.20	0.35	0.15	0.26	1.07	0.09	0.60	0.6	10	0.15	0.40	0.21	8.7
T2	0.20	0.25	0.15	0.22	0.92	0.09	0.60	0.4	11	0.15	0.50	0.37	8.7
T3	0.19	0.20	0.15	0.30	1.14	0.09	0.62	0.6	11	0.15	0.50	0.26	8.7

Note: The parameters correspond to the state of the fields at the end of October 2019, after the rainfall events considered for the ACED measurements of soil loss. * indicates measure parameter values, ° indicates calibration values, the rest of the parameters are recommended values based on vegetation characteristics and soil properties.

Table 7. Characteristics and measured soil losses of nine experimental fields at Shashui village, near to Soni town in the West Usambara Mountains, Tanzania. Including the rainfall values considered for the field observations.

Field	Length m	Slope °	Rain mm	Rain days no.	I mm h^{-1}	Soil loss t ha -1	Soil Texture
C1	35.0	22.0	530	19	50	41.25	Clay
C2	40.0	17.0	530	19	50	33.34	Clay
C3	36.0	15.0	530	19	50	17.16	Clay
AF1	20.0	27.0	530	19	50	1.14	Clay
AF2	70.0	23.5	530	19	50	5.99	Clay
AF3	40.0	18.0	530	19	50	1.57	Clay
T1	34.0	21.5	530	19	50	5.86	Clay loam
T2	38.2	15.0	530	19	50	1.16	Clay
T3	32.7	29.0	530	19	50	6.35	Clay loam

The rainfall data used in the model corresponds to the rainfall data recorded in October 2019 which was the first month of the short rainy season that year. From the 30th of September until the 25th of October, 19 events occurred with a total rainfall of 530 mm. An average intensity of 50 mm h^{-1} was assumed base on the characteristics of the region.

To simulate the water erosion process of the different fields, these were divided into sections. For control and AF plots, which have a linear slope, the total slope length (L) was divided by 10 to obtain equal sections. In the case of terraced fields, the number of sections used in the modelling corresponds with the number of terraces of the fields, and the length of these sections was the average length of the terraces of each field. Similar water erosion patterns between fields with the same SWC measure were evident in the model. Two parameters (SR_{inf}, ß) were used to calibrate the model according to the soil loss measurements from ACED method. The differences between fields with the same SWC measure was determined by specific parameters in the model. The resultant soil losses and surface runoff are listed in Table 8.

Table 8. Simulated values of soil loss and surface runoff obtained on the hMMF model for the nine experimental fields at Shashui village, near to Soni town in the West Usambara Mountains, Tanzania.

Field	Measured soil loss Mg h^{-1}	Simulated soil loss Mg ha^{-1}	Simulated surface runoff mm
C1	41.25	34.48	244.2
C2	33.34	33.91	299.4
C3	17.16	17.17	187.2
AF1	1.14	1.09	146.0
AF2	5.99	6.95	89.3
AF3	1.57	1.65	211.5
T1	5.86	6.40	45.0
T2	1.16	1.33	49.6
T3	6.35	6.40	63.8

4.2.1 Water erosion patterns

4.2.1.1 Control fields

For control fields, it was assumed that there is no surface runoff infiltration along the slope length ($SR_{inf} = 0$). Therefore, the simulated surface runoff on these plots only depends on the length of the section, the rainfall characteristics, and the soil and vegetation properties that control the soil moisture (bulk density, effective hydrological depth, actual-effective evapotranspiration ratio, and soil moisture at field capacity).

Similar responses in the modeled water erosion processes between the 3 control fields were obtained (Appendix B, C). In the first sections, the transport capacity is always lower than the sum of the soil detached by the surface runoff plus the soil detached by the raindrop impact. Consequently, the limiting factor of the system at these first sections is the transport capacity. The soil detached by the raindrop impact is constant in every section of the hillslope, while the soil detached by the surface runoff increases with the slope length. This situation causes that at some point along the hillslope, the transport capacity, which is influenced by the slope and also by the increment in the runoff, becomes higher than the soil detached in the section. At that point, the system is no longer transport capacity limited and it becomes a sediment supply-limited system.

The sediment transport increment is slow while the system is transport capacity limited. When it turns into a sediment limited system, the increment in the sediment transport increases. The distance at which the system becomes sediment limited is mainly regulated by the "ß" (Equation 18), which regulates the transport capacity magnitude. The ß factor was used to calibrate the model with the values of the soil loss measurements from the fields. For the three control fields, the ß factor ranges between 3.5 and 3.8. The differences in soil loss and surface runoff values between the control fields can be mainly explained by the differences in the hillslope length and the slope between them since the three control fields have similar soil and vegetation properties (Figure 19).

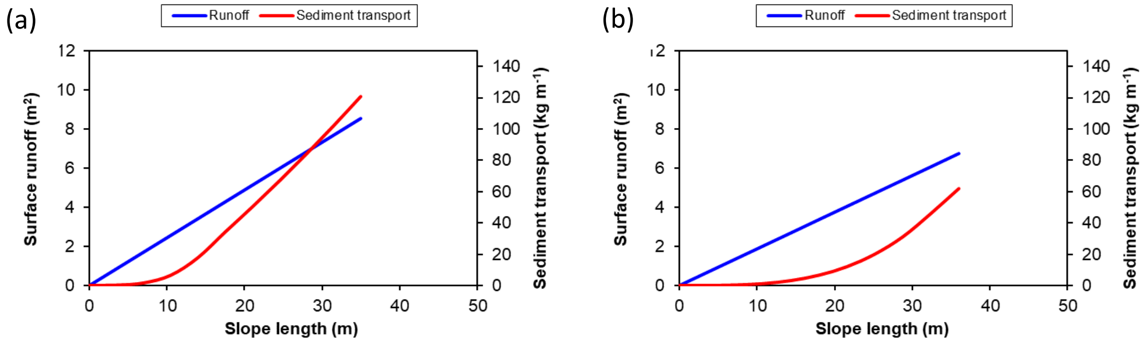

Figure 19. Surface runoff and sediment transport modelled with the hMMF erosion model along 2 control fields at Shashui village, near to Soni town in the West Usambara Mountains, Tanzania. for October 2019. (a): Control 1; (b): Control 3.

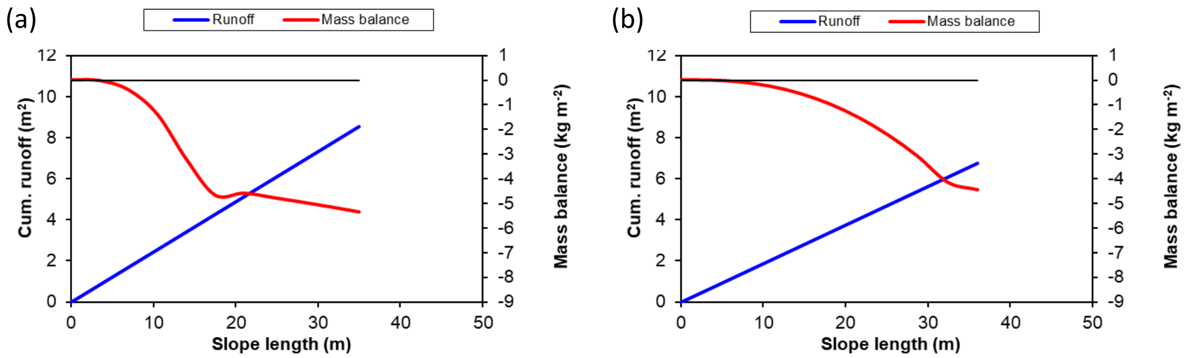

Figure 20. Surface runoff and mass balance modelled with the hMMF erosion model along 2 control fields at Shashui village, near to Soni town in the West Usambara Mountains, Tanzania. for October 2019. (a): Control 1; (b): Control 3.

The initial increment in the sediment transport causes a large difference between the sediment transport of each section with the sediment transport from the section above. This difference is represented by the mass balance value (Figure 20). The variation of this value along the hillslope is divided into two phases. The first one, which shows the increase of the negative mass balance values from the upslope sections to the immediately downslope sections. And the second one, which occurs when the system becomes sediment-supply limited and the mass balance values start to be similar between the sections. As a result of this, the mass balance remains more or less constant in the second part of the hillslope. Although, some small negative differences between sections is still visible in this phase.

4.2.1.2 **Bench terraces**

To simulate water erosion on the terraced fields in the model, two main changes with respect to the control fields were implemented. First, two types of sections along the hillslope were used to reproduce the characteristic profile of the bench terraces; the “bed”, which is the flat section where crops are grown, and the “riser”, which is the vertical section between the beds. The second modification on the model with respect to the control fields was to allow surface runoff infiltration on the bed sections of the terraces, changing the value of *SRinf* from 0 to values that range between 0.21 to 0.37. These values depend on the length and the slope of the bed sections. Wider and nearly horizontal terraces have higher surface runoff infiltration values, while more narrow and steeper bed sections have lower surface runoff infiltration values. In the case of the risers, no surface runoff infiltration was allowed.

The general pattern of water erosion on the 3 terraced fields is characterized by low values of the surface runoff along the hillslope (Appendix B, C). It is caused by the incorporation of the infiltration capacity in the bed sections (*SRinf)*, and the small slope length of the risers. The surface runoff increment is constant and equal on the risers, and it decreases progressively on the bed sections. As a consequence, the increment in the surface runoff is high at the beginning of the hillslope. But, it drops fast along the slope until the surface runoff reaches a constant value. This value is around 2.2 m^2 for the terraced fields, and it represents around 30% of the surface runoff generated by the control fields at 30m from the beginning of the hillslope (6.1 m^2) (Figure 21).

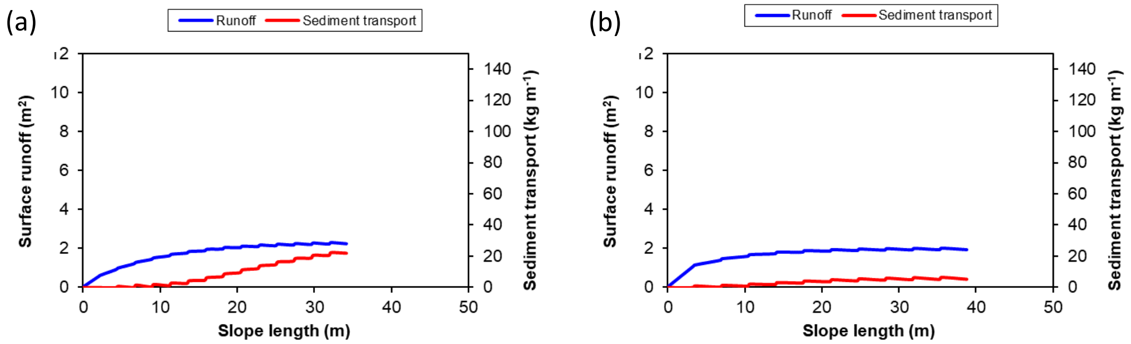

Figure 21. Surface runoff and sediment transport modelled with the hMMF erosion model along 2 fields with bench terraces at Shashui village, near to Soni town in the West Usambara Mountains, Tanzania. for October 2019. (a): T1; (b): T2.

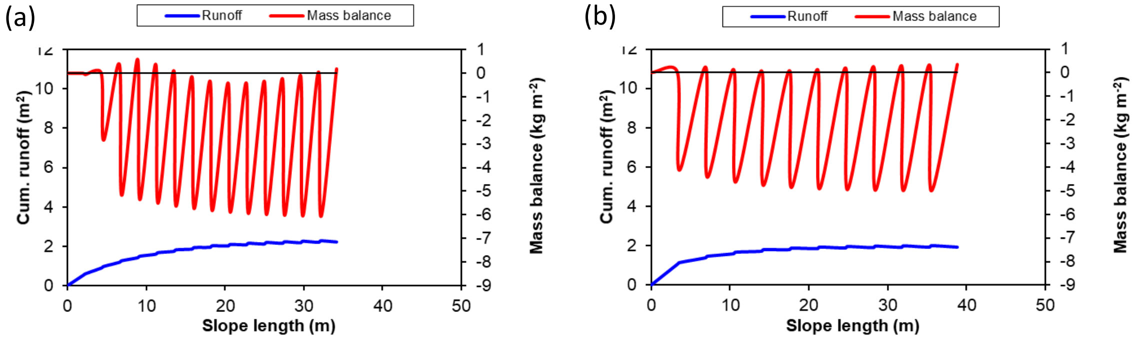

Figure 22. Surface runoff and mass balance modelled with the hMMF erosion model along 2 fields with bench terraces at Shashui village, near to Soni town in the West Usambara Mountains, Tanzania. for October 2019. (a): T1; (b): T2

The system is transport capacity limited in the bed sections and it is sediment supply limited in the riser sections. Consequently, the sediment that is transported from the risers is deposited on the downslope beds. The calibration value of the transport capacity (ß) used for the 3 terraced fields was 8.7. With this value, the mass balance showed a cyclical pattern along the slope length which remains close to 0 on the bed sections and it presents negative values on the risers (Figure 22). Small quantities of sediment are deposited or transported out of the bed sections because the transport capacity of the bed sections is similar to the amount of sediment transported from the risers.

The soil loss differences between the measurements obtained with the ACED method from the 3 terraced fields are theoretically explained by the differences in the structure of their terraces. The main reason is that the other variables that also influenced the soil losses such as rainfall values and the vegetation and soil properties are quite similar between these three fields. For example, T2 is the field that has the widest and the flattest terraces. Consequently, it presented the lowest soil loss values. These structural differences between the fields were represented on the model using four variables. 1) the terrace length, 2) the riser length, 3) the terrace slope angle, and 4) the riser angle.

4.2.1.3 **Traditional AF systems**

For the simulation of water erosion on the agroforestry fields, it was assumed that there is no surface runoff infiltration along the slope (*SRinf* = 0). Therefore, like in the case of the control fields, the simulated surface runoff only depends on the length of the section, the rainfall characteristics, and the soil and vegetation properties that control the soil moisture. In fact, the characteristics of the agroforestry system can be reproduced in the model simply adjusting the values of some of the variables concerning the vegetation properties. For example, the canopy cover percentage for the crops present in the control and terraced fields is around 30%, while for the vegetation in the agroforestry system, these values are between 80 and 90%. A similar situation occurs with others variables such as the effective hydrological depth, which varies from 0.10 m for control and terraced fields to 0.19 m for agroforestry fields, or the ratio between actual and potential evapotranspiration, which increases from 0.45 for the small crops in terraced and control fields to 0.90 for the vegetation in AF systems. Finally, the crop cover factor, which is a value that indicates how similar is the vegetation of one field in comparison with bare soil. In the case of terraced and control fields, this value was around 0.45, whereas for the AF system this value was 0.10. The combination of these variables was used to simulate the conditions of each of the 3 AF fields.

The general pattern of the water erosion processes for the three agroforestry fields is characterized by 1) a linear increment of the surface runoff along the hillslope, and 2) the low values of sediment detached in comparison with the values of the control fields (Figure 23). The surface runoff in AF fields is reduced by the high values of the effective hydrological depth and the high ratio between the actual and potential evapotranspiration. As a consequence of this reduction of the surface runoff, plus the increment in the groundcover factor, the soil detached by surface runoff is diminished. Besides, the soil detached by raindrop impact is reduced by the low plant height values (Morgan, 2005, established plant height values of 0.01 m for forest with understory and litter layer), which reduces the kinetic energy of the leaf drainage. Therefore, the sum of the sediment detachment by surface runoff and by raindrops is low for the three AF fields.

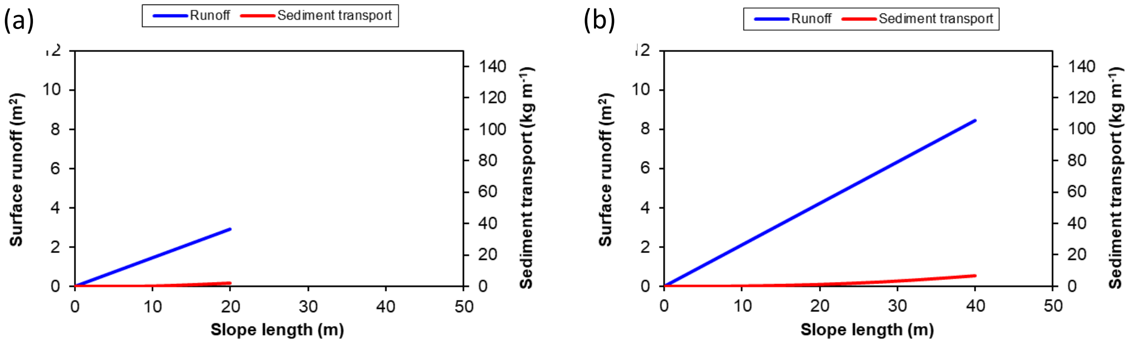

Figure 23. Surface runoff and sediment transport modelled with the hMMF erosion model along 2 fields with agroforestry system at Shashui village, near to Soni town in the West Usambara Mountains, Tanzania. for October 2019. (a): AF1; (b):AF2.

The system is transport capacity limited along the first sections of the hillslope. Then, at some point in the hillslope, it becomes sediment supply limited. The calibration values for the transport capacity (ß) used to match the model results with the soil loss measurements on the AF fields were 4 and 2.5. Unlike control and terraced fields, the transport capacity for AF fields is reduced by the low crop or cover (C) factor characteristic of the forest with undergrowth. The magnitude of the surface runoff varies between the AF fields as a response to the differences in the slope angle and slope length between them.

In conclusion, the modelling of the AF fields shows a considerable increase in surface runoff along the slope length. Nevertheless, it does not generate high values of soil losses because unlike control fields, the variable that controls the soil losses in AF fields is the quantity of sediment detached, which is close to 0 on the upper 30 m of the hillslope, and just after this distance, a slight increment is produced. For example, in the case of AF2, which has a slope length of 70 m, the modelled soil loss is 6.95 t ha^{-1}, which is bigger than AF1 and AF3, which have slope lengths of 20 and 40 m, respectively. The corresponding soil losses are 1.09 t ha^{-1} for AF1 and 1.65 t ha^{-1} for AF3 (Appendix B and C).

The water erosion rates from the nine experimental fields along their hillslope are illustrated in Appendix B, and erosion/deposition patterns along the hillslope in Appendix C.

5. Discussion

The results of this study have demonstrated that traditional agroforestry systems and bench terraces are equally effective to control soil erosion on steep sloping fields in the West Usambara Mountains. These findings are in agreement with the values reported by some previous studies in the area or in regions with similar conditions. For example, the effectiveness in soil erosion control of terraced and AF fields in this study is around 85±7% and 91±7%, respectively. This is similar to the values reported by Wickama et al. (2014) for different kinds of terraced fields in the West Usambara Mountains. They obtained erosion reductions equal to 85 % for fields with poor quality terraces and 96% for high-quality terraces. In the case of AF fields, Lal (1989) reported slightly lower percentages (85-73%) of soil erosion control effectiveness for several AF fields located in Nigeria. On the other hand, a research conducted in Nicaragua in AF fields with the same crop composition of the AF fields in this study (banana-coffee-trees) did not find any evidence of rill erosion in the fields, and thus a nearly 100% soil erosion control. The only erosion observed in those AF systems was caused by splash and sheet erosion (Sepúlveda and Carrillo, 2015). Furthermore, Kaswamila (2013) ranked AF system, over bench terraces and grass strips, as the best SWC measure considering its performance for soil erosion control in several fields located in the West Usambara Mountains.

Different water erosion patterns and distinctive sensitive variables can be identified for each SWC measure. Control and AF fields show the same magnitude in simulated surface runoff values along the hillslope, as well as the same pattern on the water erosion process, transport capacity limited at the begging of the hillslope and sediment-supply limited system at the end of it. Nevertheless, the values of sediment detachment on AF fields represent just a fraction of the sediment detached in control fields. Besides, the results showed that the most sensitive variable in control fields is the slope, which is similar to the results of Vigiak et al. (2005) who modelled erosion on fields without SWC measures in the same region. On the other hand, the length of the field is the most sensitive factor for AF fields, which is different from the reported results by Sepúlveda and Carrillo (2015), who identified the amount of litter as the factor which contributed more (66%) to the variability of soil losses in AF fields. In the case of bench terraced fields, unlike control and AF fields, the surface runoff reaches only low values along the hillslope, similar to the values reported by Wickama et al. (2014). The system is transport capacity limited for all the terraces and sediment-supply limited for all the risers along the hillslope. The most sensitive variable in the hMMF model is the width of the terraces.

Carbon sequestration rates showed that fields with traditional AF systems sequestered around six times more carbon than terraced fields. This difference is higher than the values reported by Pandey (2007), in which agroforestry systems sequestered 3.5 times more carbon than degrades forest lands in Central Himalaya. These results are directly related to the huge differences in biomass stock and growth rates between the vegetation present in AF fields and the vegetation present in control and terraced fields. Trees and big crops (coffee and banana), that represent 88% and 10% of the total initial biomass stock of the 9 experimental fields, are the main vegetation present in AF fields. Small crops, which just represent 0.2% in AF fields, is the main vegetation present in control and terraced fields. These percentages are similar to the ones reported by Negash and Starr (2015), who estimated that trees account for up to 93% of the total biomass C stocks, while herbs covered less than the 4% of fields with indigenous traditional agroforestry systems in Ethiopia.

The average biomass C stock of the AF fields in the West Usambara Mountains (287.9 t ha^{-1}) is higher than the range reported for agroforestry systems globally, which is between 12 and 228 t ha^{-1}, (Pandey, 2007; Albrecht and Kandji, 2003). But, it is between the values reported by Henry et al. (2009) for forest and traditional agroforestry fields in Panama, and similar to the values from primary forest in Mekoe, southern Cameroon (Duguma et al., 2001). The high values of biomass stock in the experimental AF fields are attribute to 1) the size, age and high density of trees in the fields, similar to the conditions of natural forest, and 2) to a possible overestimation of the arboreal biomass due to the use of allometric equations. During the validation procedure of the equation used in this study, Chave et al. (2005) found that in most of the sites the models tend to overestimate the AGB. Especially in fields with less than 30 trees, where only a few trees may bias the overall prediction. However, he concluded that the inclusion of forest type and height in the model reduces this overestimation, and the final model tends to overestimate the AGB by 0-5%. Nevertheless, even taking into account a possible overestimation of arboreal biomass in this study, the values of biomass from the small crops in control and terraced fields would remain low, and the relation between the carbon sequestration capacity of AF fields and the carbon sequestration capacity of control and terraced fields would not have a significant variation.

The SOC values measured in the terraced, control, and AF fields were similar. The average SOC concentration (2.26 ± 0.18 %) for the experimental fields in the first 10 cm depth is similar to the SOC values obtained by Wickama et al. (2014) from several agricultural fields located around the same village (Shashui). The results of the current study show that the use of a specific SWC measure and SOC were unrelated. This results were unexpected because higher SOC's values in AF fields were presumed in the initial hypothesis. Although, different variables that modified the SOC in agricultural fields have been proposed by many authors. For example, Soto-Pinto et al. (2010) attributed the differences in SOC between AF fields to the agro-climatic zone and the elevation of the fields. Similar to Lal (2014), who stated that well-drained soils and cooler temperatures sequestered more carbon than poorly drained soils (clays) and warm temperatures, while Kirsten et al. (2016) associated the differences in SOC between tropical forests to the variations in concentrations of Fe- and Al-oxides in the soils. Meanwhile, Zhang et al. (2006) determined that the SOC concentrations in hillslope fields can vary depending on the location where the samples are taken. Lower parts generally show more SOC than upper sections. Nevertheless, no study that demonstrates a direct relationship between the application of a particular SWC measure and the concentration of SOC for fields located in the same agro-climatic area was found.

The SOC results are similar to the values reported by Zhang et al. (2006), where the same concentrations of SOC between terraced and non-terraced fields were obtained for several fields located in the hilly area of the Sichuan basin in China. However, the values of SOC in the first 30 cm depth layer of the soil (67.5±11.5 Mg ha^{-1}) are lower than the values reported by Negash and Starr (2015). They obtained ranges of SOC values between 114 to 121 Mg ha^{-1} for AF fields in Ethiopia. On the other hand, Soto-Pinto et al. (2010) measured similar SOC values

(77-120 Mg ha^{-1}) in agroforestry systems in Chiapas, Mexico. Nevertheless, the average SOC in the first 30 cm depth for the experimental fields is higher than global values, which are 51 Mg ha^{-1} for Acrisols and 31 Mg ha^{-1} for Luvisols (Batjes, 1996).

Bench terraces applied on sloping fields in the West Usambara Mountains demonstrated to be more economically profitable than traditional agroforestry practices. In this study, the net income estimation of terraced fields was 2.6 times higher than the estimation of AF fields and 2.3 higher than the estimated values for control fields. These findings are in agreement with the values obtained by Antle et al. (2007), who estimated that fields with AF system were 40 % less profitable than terraced fields. However, the mean net income for terraced fields in this study is higher than the values reported by Tenge and Hella (2005) for terraced fields in the same area. One of the variables that influenced these results is the type of crop present in the fields. Small cash crops such as beans, maize, potato, and tomato are generally cultivated in control and terraced fields, while banana and not well-managed coffee are present in AF fields. Another reason for the high net income of terraced fields is the availability of irrigation water, it was evident in the case of T2 that is the only filed of the nine with the access to this service and it is also the field with the highest net income.

In general, fields with traditional AF in this study seemed to have low productivity due to the similar values of net income between them and control fields, even though the investment required for AF fields was 3.5 times lower than the investment required for control fields. Reyes et al. (2005) stated that fields with traditional AF systems with low costs of production generate low gross income values (just 7% higher than the production costs), and improved AF systems, which require 20% more investment than traditional practices, produce a gross income 50 % higher than the investment. Therefore, productivity and net income of the AF fields could increase substantially by the application of some characteristics of the improved AF systems. Technical and market assistance plus general preconditions such as underutilized areas, accessible markets, and household interest in tree farming are required to assure productivity and profitably of AF fields (Roshetko et al., 2009; Franz and Scherr, 2002). According to the socio-economic results, it can be stated that the AF fields in the study fulfill these conditions, except for the technical assistance. During the interviews, only 11.1 % of the landowners mentioned that they had received advice from extension services. All of them reported to have primary education level, which means that they could receive and understand such advices. Apart from these conditions, several studies mentioned inadequate access to capital and costs as one of the main constrains to increase the net income in AF fields (Reyes et al., 2005; Bullock et al., 2014)

The erosion control effect showed by AF systems has the potential to increase the net income of the households. However, these benefits can only be quantified in well-planned AF fields, where the crops receive appropriate maintenance work, similar to the maintenance applied to the crops in terraced fields. Besides, the high carbon sequestration capacity of AF fields can become another source of income to the families, if the landowners of the small AF fields unite and share the cost that involves receiving the benefits from the emerging carbon market. (Flugge & Abadi, 2006). Apart from these, some extra benefits, that were not quantified in this study, have been attributed to AF systems by several authors. For example, Bullock et al. (2014) concluded that AF fields, apart from being financially competitive with other SWC practices, they raise the labor opportunity due to the less labor-demanding methods used in AF systems, while Franz and Scherr (2002) stated that the multi-seasonal character of AF systems reduces the risk and uncertainty in the revenues diversifying the products in the fields. Although, Reyes et al., (2005) concluded that well planned land-use in addition to well-managed crops in AF systems produce higher net income than inefficiently AF fields, which are generally planted with annual crops in monoculture or with banana and no/few poorly managed cash crops. Therefore, several and different benefits can be obtained from AF fields. Nevertheless, the determinant factor to take advantage of these is a well-planned AF strategy that is currently lacking.

6. Conclusions

Traditional AF fields and terraced fields are equally effective to control soil erosion in the West Usambara Mountains, but important differences in terms of carbon sequestration and economic benefits are evident between these two types of SWC measures. Terraced fields decrease soil erosion by reducing the amount of surface runoff, while AF fields decrease erosion by preventing sediment detachment. Based on the carbon stock in the biomass, AF fields sequester six times more carbon than terraced fields. The arboreal biomass is the most determining component in the estimations of the C-sequestration, and is much higher in AF fields than on terraced fields. On the other hand, terraced fields generate net incomes 2.6 higher than AF fields due to the differences in crop market prices and the inadequate management of AF fields. Traditional AF systems have the potential to become more profitable if better crop management would be implemented. In the case of the AF fields in this study, it would mean a constant renewal of the actual cash crop (coffee) present in the fields. In the case of terraced fields, they could increase the rates of biomass stock and carbon sequestration by incorporating trees.

The decision to adopt one of these SWC measures in a specific field or area depends on the initial conditions. For example, in the West Usambara Mountains, for steep-sloping fields without trees and without any SWC measure (e.g., C1, C2, and C3), the best alternative in the short-time would be the adoption of bench terraces or similar practices that reduce the surface runoff and soil erosion like grass strips or cut-off drains. Bench terraces reach the peak of positive economic flux after 2 years of being installed (Tenge and Hella, 2005). The adoption of AF systems in such fields would require higher investment in terms of time, capital and technical assistance. Nevertheless, AF systems would become a viable option to implement in steep-sloping fields if it is part of a long-term participative project, which provides technical, market, and economic support to the landowners. AF systems are the best alternative when private fields with secondary forest characteristics or degraded forest lands start becoming agricultural fields.

7. Literature

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Appendices

Appendix A: Individuals field description sheets

FIELD DESCRIPTION SHEET

Universiteit Utrecht
Faculty of Geosciences

Landowner: Hassan Athuman	**Date:** November 2019
Author: Guillermo Molina	**SWC:** Control
Slope: 22°	**Cod:** C1
Area: 102180 m2	**Perimeter:** 127.11m

Location

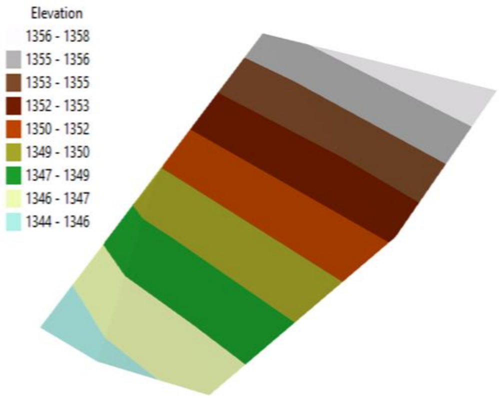
Country	Region	District	Ward	Village
Tanzania	Tanga	Lushoto	Soni	Shashui Vangui

Coordinates

Geographic Coordinates		Projected Coordinates		Elevation range
Latitude (°´ ´´):	S 4°52.22'13.16''	**North (m):**	9461636.67	1344-1358
Longitude (°´ ´´):	E 38°2168'4136''	**Est (m):**	429203.05	
Coordinate System:	GCS_WGS_1984	**Coordinate System:**	WGS_1984_UTM_Zone_37S	

Location

Digital elevation model



Field pictures

Crops Description	Forestry Description
Beans (5 units per m2)	No trees
Maize (5 units per m2)	

Soil Properties	SWC Description
Texture: Clay	The field is divided by a grass strip in two sections, the upper part has a steeper slope than the lower section. Thus, some deposition is visible before this division. But, several rills pass trough this barrier and they are presented all along the field. Non-effective manual tillage is used during the growing season.
Surface roughness: Very rough	
Drainage: Good	

General Observations

During the 38 days of observation, the crops slightly increased their biomass in comparison with the other fields.

A non-effective tillage (no re-hoeing and late weeding) is evident in the field

mparison Between Agroforestry Systems and Bench Terraces for Soil Erosion Control and Carbon Sequestration, West Usambara Mountains, Tanza

FIELD DESCRIPTION SHEET

Universiteit Utrecht *Faculty of Geosciences*	**Landowner:** Zubeda Ayubu	**Date:** November 2019
	Author: Guillermo Molina	**SWC:** Control
	Slope: 17°	**Cod:** C2
	Area: 644.42 m2	**Perimeter:** 112.29 m

Location

Country	Region	District	Ward	Village
Tanzania	Tanga	Lushoto	Soni	Shashui Vangui

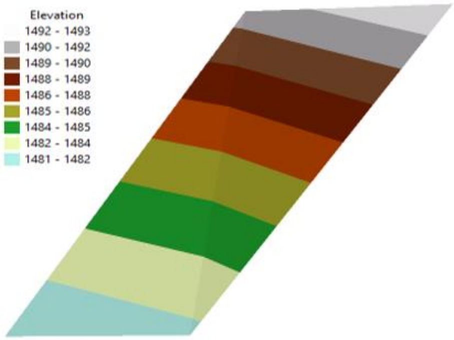
Coordinates

Geographic Coordinates		Projected Coordinates		Elevation range
Latitude (°´ ´´):	S 4°52.79'47.35''	**North (m):**	9460587.46	1481-1493
Longitude (°´ ´´):	E 38°22.15'9.3''	**Est (m):**	430064.64	
Coordinate System:	GCS_WGS_1984	**Coordinate System:**	WGS_1984_UTM_Zone_37S	

Location

Field pictures

Digital elevation model



Crops Description	Forestry Description
Maize (4 units per m2)	No trees
Potato (2.5 units per m2)	
Beans (2.5 units per m2)	

Soil Properties	SWC Description
Texture: Clay	No SWC measure is applied in the field. Some trees are located at the borders of the field area. A diagonal big rill pass trough the middle part of the field. The tillage labor is manual.
Surface roughness: Rough	
Drainage: Good	

General Observations

In the upper part a predominance of beans over potato is evident. While, in the lower part the opposite happens.

The maize is constant and homogenous in all the field

mparison Between Agroforestry Systems and Bench Terraces for Soil Erosion Control and Carbon Sequestration, West Usambara Mountains, Tanza

FIELD DESCRIPTION SHEET

Universiteit Utrecht *Faculty of Geosciences*	**Landowner:** Omari Shauvi	**Date:** November 2019
	Author: Guillermo Molina	**SWC:** Control
	Slope: 15°	**Cod:** C3
	Area: 1345.48 m2	**Perimeter:** 159.45 m

Location

Country	Region	District	Ward	Village
Tanzania	Tanga	Lushoto	Soni	Shashui Vangui

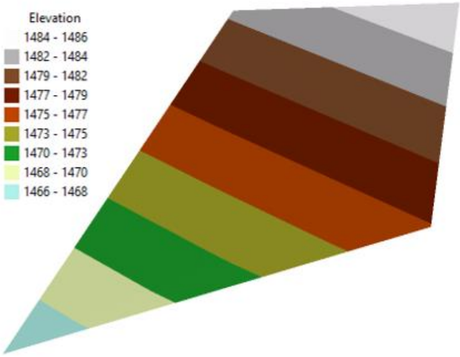
Coordinates

Geographic Coordinates		Projected Coordinates		Elevation range
Latitude (° ´ ´´):	S 4°52.73'44.07''	**North (m):**	9460688.34	1466-1486
Longitude (° ´ ´´):	E 38°22.15'9.46''	**Est (m):**	430069.37	
Coordinate System:	GCS_WGS_1984	**Coordinate System:**	WGS_1984_UTM_Zone_37S	

Location

Field pictures

Digital elevation model



Crops Description	Forestry Description
Maize (4.5 units per m2)	No trees
Potato (2.8 units per m2)	
Beans (3.25 units per m2)	

Soil Properties	SWC Description
Texture: Clay	No SWC measure is visible. The runon from the upper fields creates different sizes rills all along the area. Nevertheless, the crops had a faster growing in comparison with the other control fields. The tillage labor is manual.
Surface roughness: Rough	
Drainage: Medium	

General Observations

Few death banana trees are present in the area, but they were not considering in the biomass analysis

The upper part of the field is mainly formed by other agricultural fields. It means, a constant transit and deposition of soil during rainfall events

mparison Between Agroforestry Systems and Bench Terraces for Soil Erosion Control and Carbon Sequestration, West Usambara Mountains, Tanza

FIELD DESCRIPTION SHEET

Universiteit Utrecht
Faculty of Geosciences

Landowner: Zabia Ahabani	**Date:** November 2019
Author: Guillermo Molina	**SWC:** Bench Terraces
Slope: 21.5°	**Cod:** T1
Area: 1529.92 m2	**Perimeter:** 155.09 m

Location

Country	Region	District	Ward	Village
Tanzania	Tanga	Lushoto	Soni	Shashui Vangui

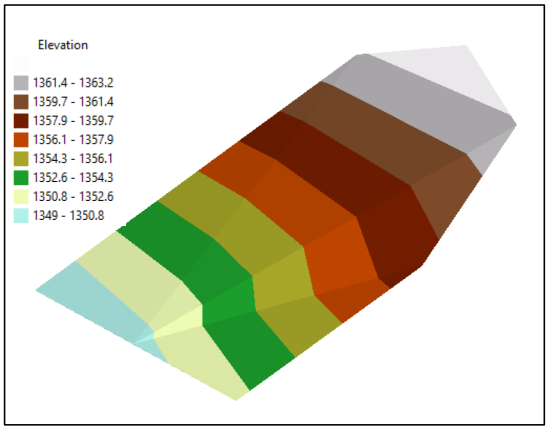
Coordinates

Geographic Coordinates		Projected Coordinates		Elevation range
Latitude (°´ ´´):	S 4°52.28'16.66''	**North (m):**	9461529.05	1349-1363
Longitude (°´ ´´):	E 38°2172'43.47''	**Est (m):**	429268.32	
Coordinate System:	GCS_WGS_1984	**Coordinate System:**	WGS_1984_UTM_Zone_37S	

Location

Field pictures

Digital elevation model



Crops Description	Forestry Description
Beans (6.5 units per m2)	1 Avocado tree
Banana (5 units in the hole area)	3 Albizias

Soil Properties	SWC Description
Texture: Clay loam	Well maintain terraces (average width of 1.8 m). No irrigation system is available in the property. The tillage labor is manual.
Surface roughness: Very rough	
Drainage: Good	

General Observations

2 harvest per year, in the long rainy season maize is the common crop to cultivate in this field.

mparison Between Agroforestry Systems and Bench Terraces for Soil Erosion Control and Carbon Sequestration, West Usambara Mountains, Tanza

FIELD DESCRIPTION SHEET

Universiteit Utrecht
Faculty of Geosciences

Landowner: Mussa Rashidi	**Date:** November 2019
Author: Guillermo Molina	**SWC:** Bench Terraces
Slope: 15°	**Cod:** T2
Area: 17915 m2	**Perimeter:** 1811m

Location

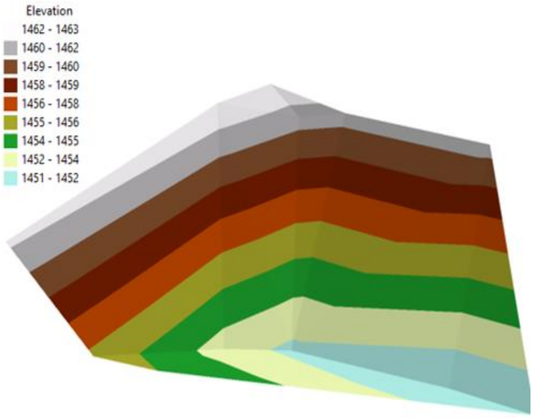
Country	Region	District	Ward	Village
Tanzania	Tanga	Lushoto	Soni	Shashui Vangui

Coordinates

Geographic Coordinates		Projected Coordinates		Elevation range
Latitude (° ´ ´´):	S 4°52.71'42.39''	**North (m):**	9460739.75	1451-1463
Longitude (° ´ ´´):	E 38°22.18'11.23''	**Est (m):**	430123.87	
Coordinate System:	GCS_WGS_1984	**Coordinate System:**	WGS_1984_UTM_Zone_37S	

Location

Digital elevation model



Field pictures

Crops Description	Forestry Description
Tomato (3 units per square meter)	No trees

Soil Properties	SWC Description
Texture: Clay **Surface roughness:** Very rough **Drainage:** Good	Well maintain terraces (average width of 2.5 m). A flood irrigation system is available in the property. Small erosion features are just visible after heavy rainfall, and after watering. The tillage is manual, but intensive during all the growing season.

General Observations

Soil fertilization is just done with chemical products.

The landowner did not report soil erosion problems

mparison Between Agroforestry Systems and Bench Terraces for Soil Erosion Control and Carbon Sequestration, West Usambara Mountains, Tanza

FIELD DESCRIPTION SHEET

Universiteit Utrecht
Faculty of Geosciences

Landowner: Habina Hazar	**Date:** November 2019
Author: Guillermo Molina	**SWC:** Bench Terraces
Slope: 29°	**Cod:** T3
Area: 1180.2 m2	**Perimeter:** 136.3 m

Location

Country	Region	District	Ward	Village
Tanzania	Tanga	Lushoto	Soni	Shashui Vangui

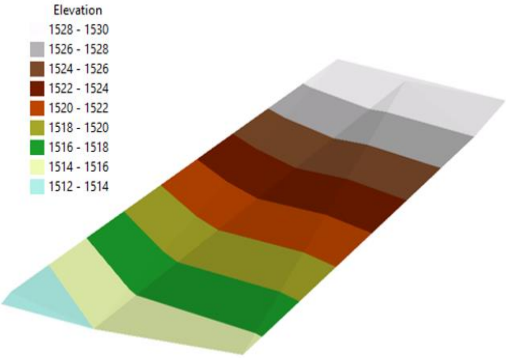
Coordinates

Geographic Coordinates		Projected Coordinates		Elevation range
Latitude (° ´ ´´):	S 4°52.71'42.44''	**North (m):**	9460737.94	1512-1530
Longitude (° ´ ´´):	E 38°22.01'0.69''	**Est (m):**	429799.28	
Coordinate System:	GCS_WGS_1984	**Coordinate System:**	WGS_1984_UTM_Zone_37S	

Location

Field pictures

Digital elevation model



Crops Description	Forestry Description
Beans (few plants, no homogenous distribution)	6 Grevillea
Potato (3 plants per m2)	3 Albizias
Maize (6 plants per m2)	

Soil Properties	SWC Description
Texture: Clay loam	Well maintain terraces in a steep hillslope (average width of 1.8 m). No irrigation system is available in the property. Manual tillage during all the growing season, several woody trees are distributed within the field.
Surface roughness: Rough	
Drainage: Medium	

General Observations

The main fertilization in this field is done with organic matter from livestock

The reference price in the market for one of the 10m trees according the landowner is 30 000 tzs (12 USD)

mparison Between Agroforestry Systems and Bench Terraces for Soil Erosion Control and Carbon Sequestration, West Usambara Mountains, Tanza

FIELD DESCRIPTION SHEET

Universiteit Utrecht
Faculty of Geosciences

Landowner: Sijali Abbi	**Date:** November 2019
Author: Guillermo Molina	**SWC:** Agroforestry
Slope: 27°	**Cod:** AF1
Area: 670.37 m2	**Perimeter:** 119.66 m

Location

Country	Region	District	Ward	Village
Tanzania	Tanga	Lushoto	Soni	Shashui Vangui

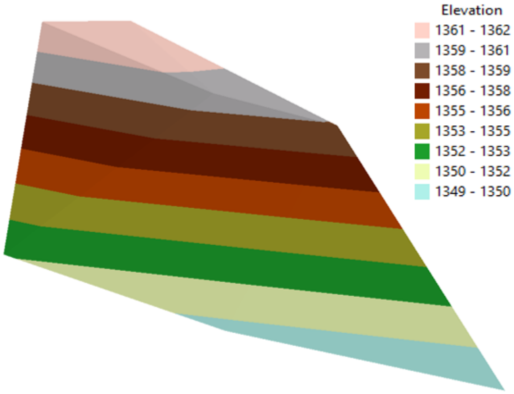
Coordinates

Geographic Coordinates		Projected Coordinates		Elevation range
Latitude (° ´ ´´):	S 4°52.28'17.07''	**North (m):**	9461516.64	1349-1362
Longitude (° ´ ´´):	E 38°2171'42.78''	**Est (m):**	429247.09	
Coordinate System:	GCS_WGS_1984	**Coordinate System:**	WGS_1984_UTM_Zone_37S	

Location

Field pictures

Digital elevation model



Crops Description	Forestry Description
Coffee (1unit each 3 m2)	2 Rauvolfia
Banana (1units each 8 m2)	6 Albizias

Soil Properties	SWC Description
Texture: Clay	Agroforestry system (coffee-banana-trees). The area of this field is smaller than the surrounding ones. Thus, the canopy of the tall trees cover most of the field area (high interception factor). In addition, the presence of banana and coffee canopy increase the interception factor.
Surface roughness: Medium	
Drainage: Medium	

General Observations

Most of the coffee plants are mature and there is not evidence of crop renewal.

mparison Between Agroforestry Systems and Bench Terraces for Soil Erosion Control and Carbon Sequestration, West Usambara Mountains, Tanza

FIELD DESCRIPTION SHEET

Universiteit Utrecht
Faculty of Geosciences

Landowner: Muza Bakari Bendera	**Date:** November 2019
Author: Guillermo Molina	**SWC:** Agroforestry
Slope: 23.5°	**Cod:** AF2
Area: 2161.85 m2	**Perimeter:** 203.76 m

Location

Country	Region	District	Ward	Village
Tanzania	Tanga	Lushoto	Soni	Shashui Vangui

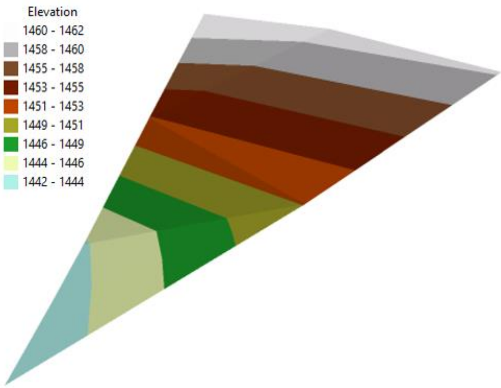
Coordinates

Geographic Coordinates		Projected Coordinates		Elevation range
Latitude (° ´ ´´):	S 4°52.78'46.95''	**North (m):**	430170.92	1442-1462
Longitude (° ´ ´´):	E 38°22.21'12.75''	**Est (m):**	9460599.82	
Coordinate System:	GCS_WGS_1984	**Coordinate System:**	WGS_1984_UTM_Zone_37S	

Location

Field pictures

Digital elevation model



Crops Description	Forestry Description
Coffee (1unit each 3 m2)	2 Avocado tree
Banana (1units each 18 m2)	15 Albizias
	15 Grevillea and 5 Rauvolfia

Soil Properties	SWC Description
Texture: Clay	Agroforestry system (coffee-banana-trees). In general, important erosion features are not visible along the field, except for two 45cm width rills that pass through the middle of the field, formed by a depression in the concave slope of the field.
Surface roughness: Medium	
Drainage: Medium	

General Observations

The distribution of the coffee and banana plants is not completely homogenous.

mparison Between Agroforestry Systems and Bench Terraces for Soil Erosion Control and Carbon Sequestration, West Usambara Mountains, Tanza

FIELD DESCRIPTION SHEET

Universiteit Utrecht
Faculty of Geosciences

Landowner: Mwanaisha Athuman	**Date:** November 2019
Author: Guillermo Molina	**SWC:** Agroforestry
Slope: 18°	**Cod:** AF3
Area: 1204.36 m2	**Perimeter:** 138.94 m

Location

Country	Region	District	Ward	Village
Tanzania	Tanga	Lushoto	Soni	Shashui Vangui

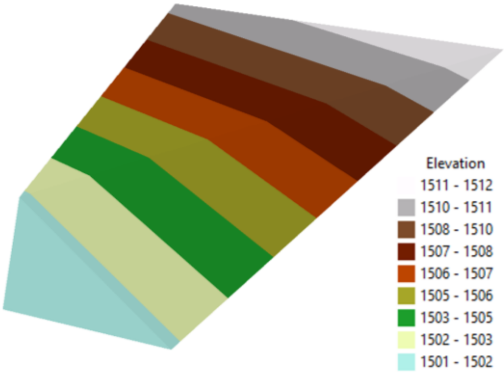
Coordinates

Geographic Coordinates		Projected Coordinates		Elevation range
Latitude (° ´ ´´):	S 4°52.78'46.53''	**North (m):**	9460612.66	1501-1512
Longitude (° ´ ´´):	E 38°22.11'6.69''	**Est (m):**	429984.12	
Coordinate System:	GCS_WGS_1984	**Coordinate System:**	WGS_1984_UTM_Zone_37S	

Location

Field pictures

Digital elevation model



Crops Description	Forestry Description
Coffee (1unit each 5 m2)	2 Avocado tree
Banana (1unit each 85 m2)	15 Albizias
Maize (6 units per m2)	1Grevillea and 1Rauvolfia

Soil Properties	SWC Description
Texture: Clay	Agroforestry system (coffee-banana-trees-maize). Coffee plants are homogeneous distributed all along the field, while banana plants are very dispersed distributed. Trees density is higher in the upper part of the filed than at the lower part, where maize plants are present.
Surface roughness: Rough	
Drainage: Good	

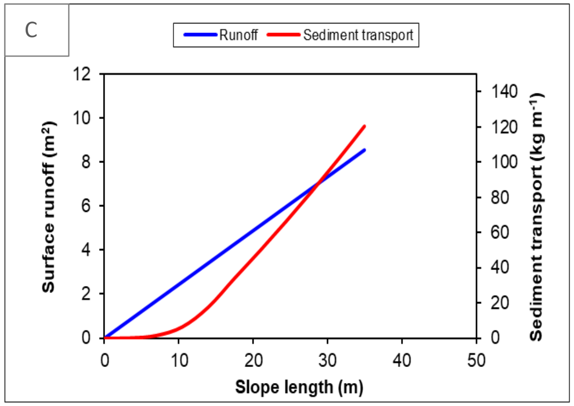
General Observations

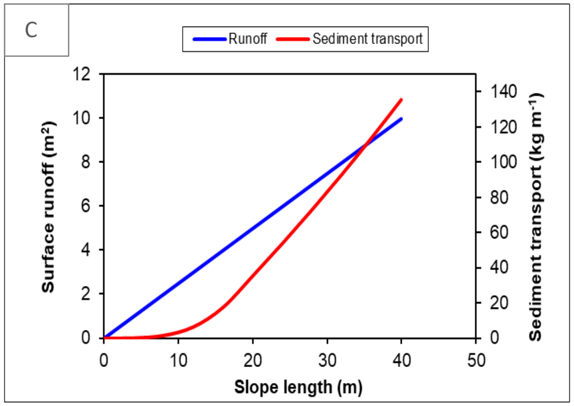
The maize crop is just located in the low part of the field (336 m2)

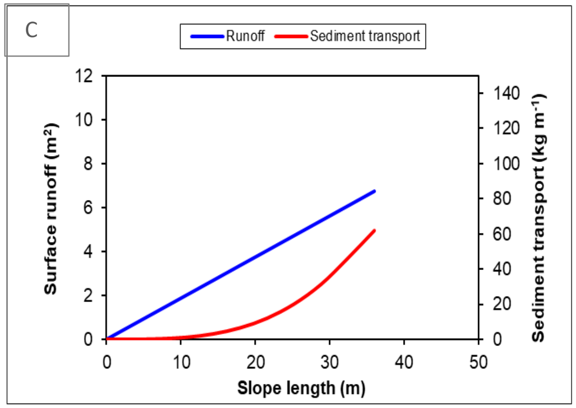
A renewal of coffee plants is evident in the field

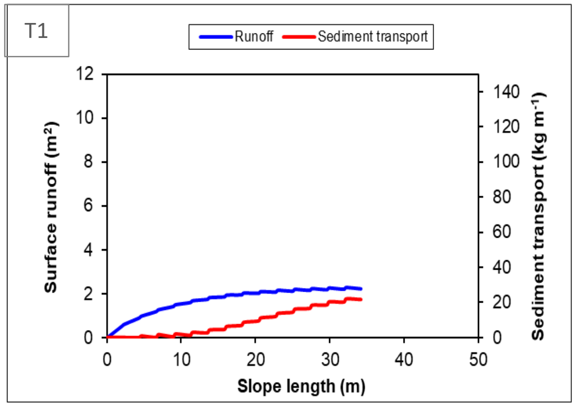
Appendix B: Modelled outcomes (Surface runoff, sediment transport)

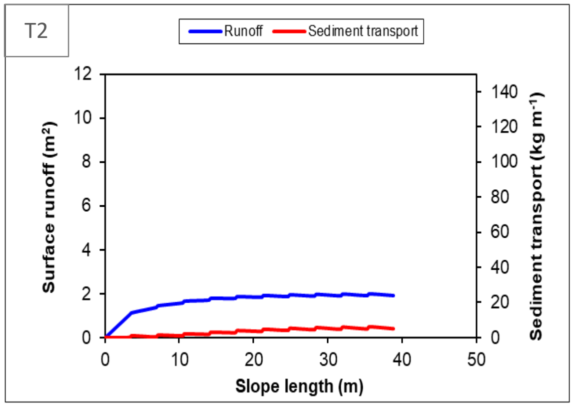
Surface runoff and sediment transport modelled with the hMMF erosion model along the nine experimental fields at Shashui village, near to Soni town in the West Usambara Mountains, Tanzania. for October 2019. C1: Control 1; C2: Control 2 C3; Control 3; T1: Terraces 1; T2 Terraces 2; T3: terraces 3; AF1; Traditional agroforestry 1; AF2: Traditional agroforestry 2; AF3: Traditional agroforestry 3

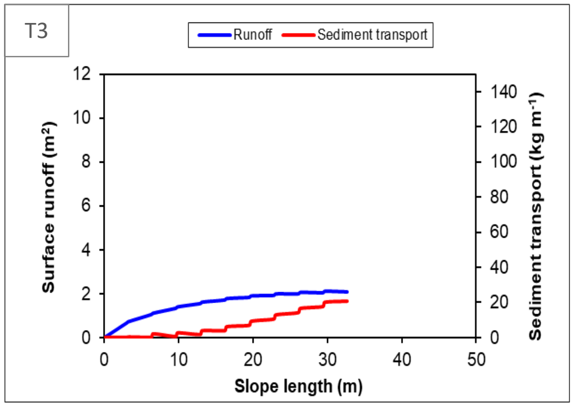

C
Runoff
Sediment transport
Surface runoff (m²)
Sediment transport (kg m⁻¹)
Slope length (m)
0
2
4
6
8
10
12
0
20
40
60
80
100
120
140
0
10
20
30
40
50

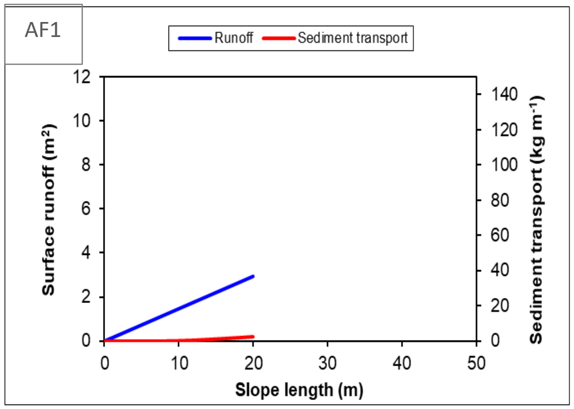

C
Runoff
Sediment transport
Surface runoff (m²)
Sediment transport (kg m⁻¹)
Slope length (m)
0
2
4
6
8
10
12
0
20
40
60
80
100
120
140
0
10
20
30
40
50

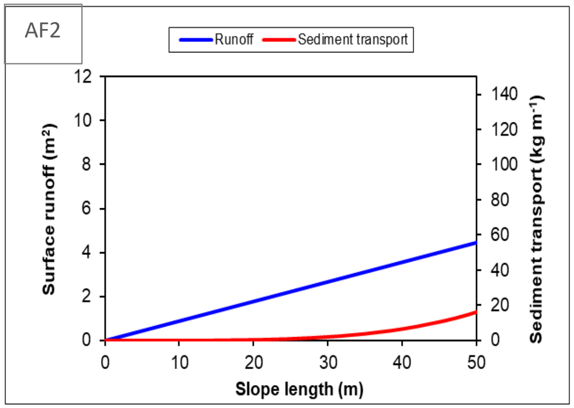

C
Runoff
Sediment transport
Surface runoff (m²)
Sediment transport (kg m⁻¹)
Slope length (m)
0
2
4
6
8
10
12
0
20
40
60
80
100
120
140
0
10
20
30
40
50

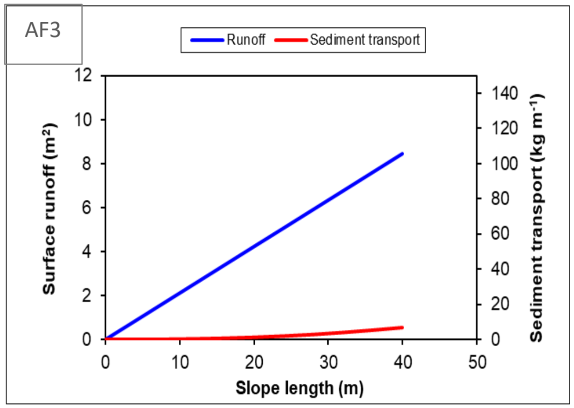

T1
Runoff
Sediment transport
Surface runoff (m²)
Sediment transport (kg m⁻¹)
Slope length (m)
0
2
4
6
8
10
12
0
20
40
60
80
100
120
140
0
10
20
30
40
50


T2
Runoff
Sediment transport
Surface runoff (m²)
Sediment transport (kg m⁻¹)
Slope length (m)
0
2
4
6
8
10
12
0
20
40
60
80
100
120
140
0
10
20
30
40
50


T3
Runoff
Sediment transport
Surface runoff (m²)
Sediment transport (kg m⁻¹)
Slope length (m)
0
2
4
6
8
10
12
0
20
40
60
80
100
120
140
0
10
20
30
40
50

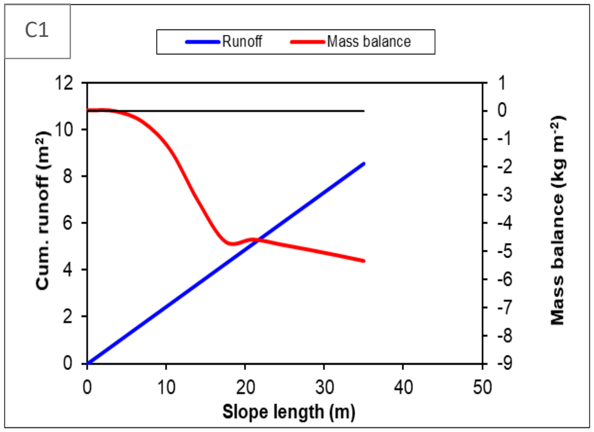

AF1
Runoff
Sediment transport
Surface runoff (m²)
Sediment transport (kg m⁻¹)
Slope length (m)
0
2
4
6
8
10
12
0
20
40
60
80
100
120
140
0
10
20
30
40
50

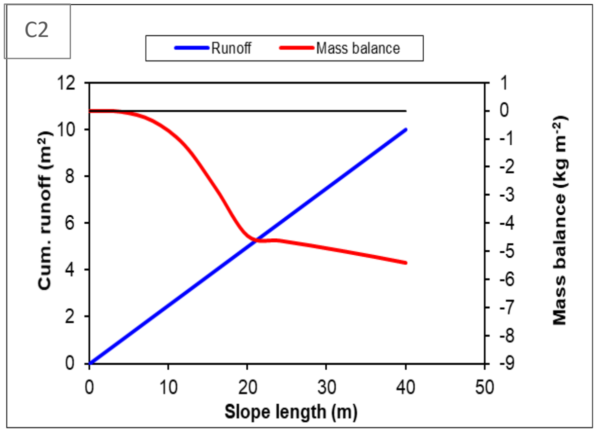

AF2
Runoff
Sediment transport
Surface runoff (m²)
Sediment transport (kg m⁻¹)
Slope length (m)
0
2
4
6
8
10
12
0
20
40
60
80
100
120
140
0
10
20
30
40
50

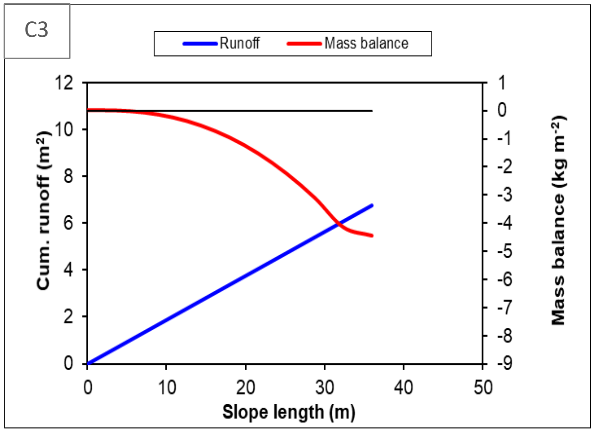

AF3
Runoff
Sediment transport
Surface runoff (m²)
Sediment transport (kg m⁻¹)
Slope length (m)
0
2
4
6
8
10
12
0
20
40
60
80
100
120
140
0
10
20
30
40
50

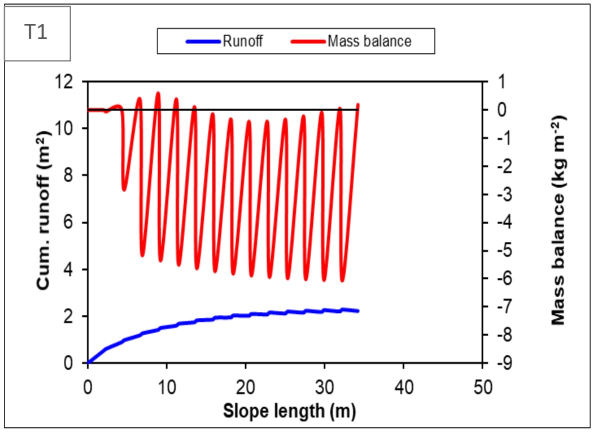
Appendix C: Modelled outcomes (Surface runoff, mass balance)

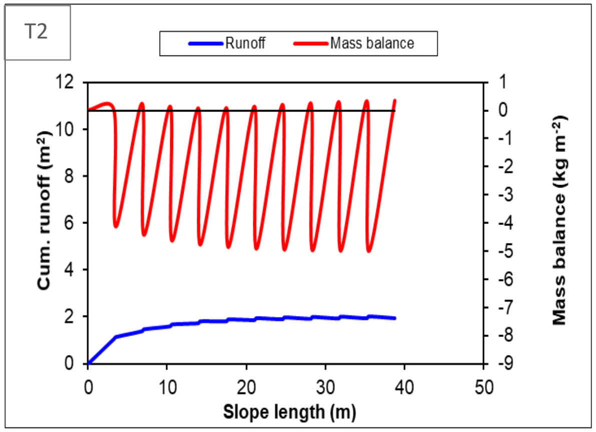
Surface runoff and mass balance modelled with the hMMF erosion model along the nine experimental fields at Shashui village, near to Soni town in the West Usambara Mountains, Tanzania. for October 2019. C1: Control 1; C2: Control 2; C3; Control 3; T1: Terraces 1; T2 Terraces 2; T3: terraces 3; AF1; Traditional agroforestry 1; AF2: Traditional agroforestry 2; AF3: Traditional agroforestry 3.

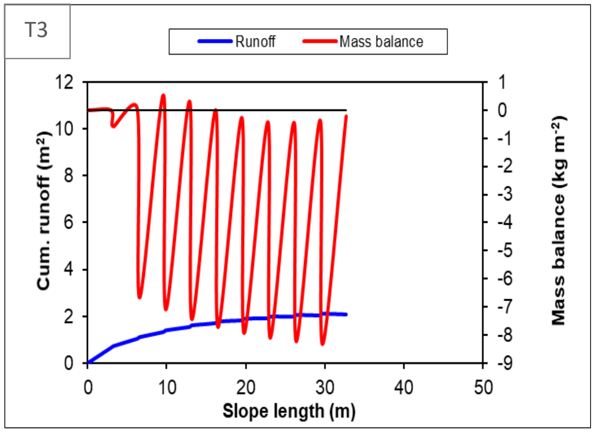

C1
Runoff
Mass balance
Cum. runoff (m²)
12
10
8
6
4
2
0
Mass balance (kg m⁻²)
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
0
10
20
30
40
50
Slope length (m)

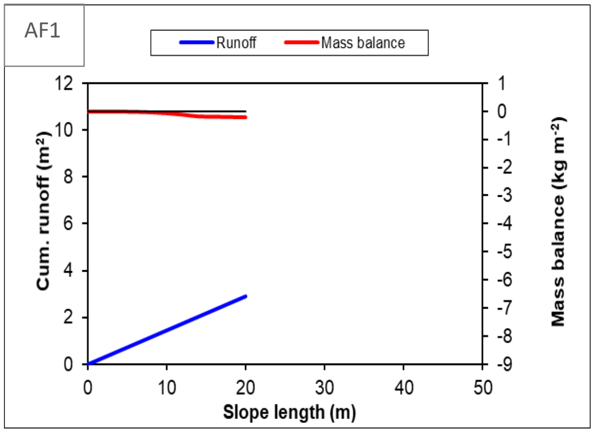

C2
Runoff
Mass balance
Cum. runoff (m²)
12
10
8
6
4
2
0
Mass balance (kg m⁻²)
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
0
10
20
30
40
50
Slope length (m)

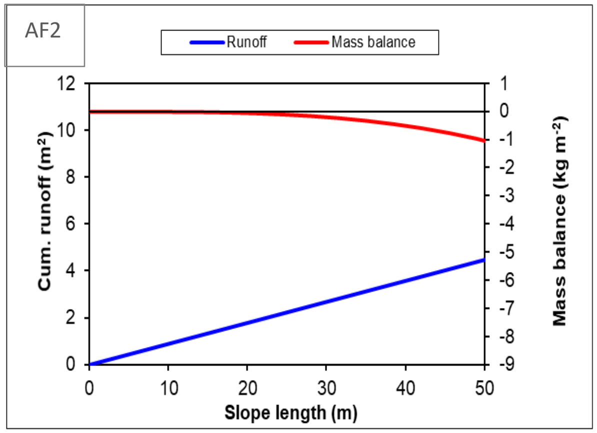

C3
Runoff
Mass balance
Cum. runoff (m²)
12
10
8
6
4
2
0
Mass balance (kg m⁻²)
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
0
10
20
30
40
50
Slope length (m)

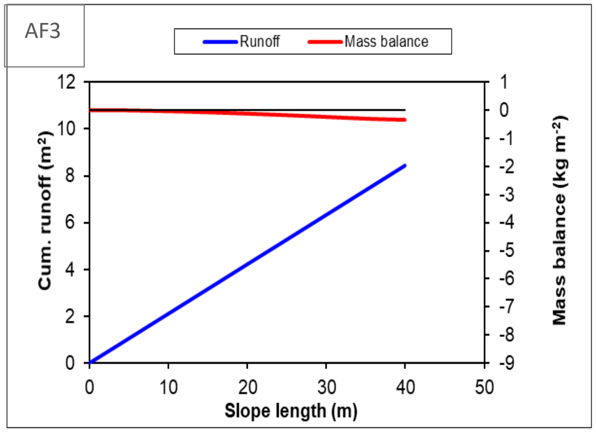

T1
Runoff
Mass balance
Cum. runoff (m²)
12
10
8
6
4
2
0
Mass balance (kg m⁻²)
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
0
10
20
30
40
50
Slope length (m)


T2
Runoff
Mass balance
Cum. runoff (m²)
12
10
8
6
4
2
0
Mass balance (kg m⁻²)
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
0
10
20
30
40
50
Slope length (m)


T3
Runoff
Mass balance
Cum. runoff (m²)
12
10
8
6
4
2
0
Mass balance (kg m⁻²)
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
0
10
20
30
40
50
Slope length (m)


AF1
Runoff
Mass balance
Cum. runoff (m²)
12
10
8
6
4
2
0
Mass balance (kg m⁻²)
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
0
10
20
30
40
50
Slope length (m)


AF2
Runoff
Mass balance
Cum. runoff (m²)
12
10
8
6
4
2
0
Mass balance (kg m⁻²)
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
0
10
20
30
40
50
Slope length (m)


AF3
Runoff
Mass balance
Cum. runoff (m²)
12
10
8
6
4
2
0
Mass balance (kg m⁻²)
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
0
10
20
30
40
50
Slope length (m)