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Agroforestry with contour planting of grass contributes to terrace formation and conservation of soil and nutrients on sloping land

Van Hung Do [a,b,*], Nguyen La [b,c], Göran Bergkvist [a], A. Sigrun Dahlin [d], Rachmat Mulia [b], Van Thach Nguyen [b], Ingrid Öborn [a,e]

[a] *Department of Crop Production Ecology, Swedish University of Agricultural Sciences (SLU), P.O. Box 7043, 75007 Uppsala, Sweden*
[b] *World Agroforestry (ICRAF) Vietnam, 13th Floor, HCMCC Tower, Thuy Khue Street, Thuy Khue Ward, Tay Ho District, Ha Noi, Viet Nam*
[c] *Soils and Fertilizer Research Institute (SFRI), 10 Duc Thang, Duc Thang ward, Bac Tu Liem district, Ha Noi, Viet Nam*
[d] *Department of Soil and Environment, Swedish University of Agricultural Sciences (SLU), P.O. Box 7014, 75007 Uppsala, Sweden*
[e] *World Agroforestry (ICRAF), UN Avenue, Gigiri, P.O Box, 30677–00100 Nairobi, Kenya*

A R T I C L E I N F O

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A B S T R A C T

In hilly areas, agroforestry can be a more sustainable way of producing food and other products and services than agriculture based on sole-cropping. However, research is needed to evaluate and quantify formation of natural terraces in agroforestry and their contribution to soil conservation. This study quantified natural terrace formation and examined its role in reducing soil and nutrient losses during early stages of agroforestry with fruit trees, contour grass strips and maize or coffee in agroforestry systems on sloping land in northwest Vietnam. Two agroforestry systems, comprising longan (*Dimocarpus longan* L.)-mango (*Mangifera indica* L.)-maize (*Zea mays* L.)-guinea grass (*Panicum maximum* Jacq.) (fruit-maize-AF) and son tra (*Docynia indica* (Wall.) Decne.)-coffee (*Coffea arabica* L.)-guinea grass (fruit-coffee-AF) were compared with sole-cropped maize (sole-maize) and sole-cropped coffee (sole-coffee), respectively. Terrace formation was evaluated over five years using erosion pins placed above grass strips and the volume of terrace formed was estimated. Soil and nutrient losses were quantified using soil traps. The results showed that terraces formed as the systems developed, through gradual deposition of soil sediment above the living grass strips and trees. Accumulated soil sedimentation above the grass strips during the five-year study period raised the soil surface by 4.0 cm in fruit-maize-AF and 4.2 cm in fruit-coffee-AF, and the volume of terraces generated by the grass strips was 0.26 and 0.43 m^3/m respectively. The fruit-maize-AF and fruit-coffee-AF systems significantly reduced losses of soil, soil organic carbon (SOC) and associated nutrients (N, P, K) compared with sole-maize and sole-coffee already in the first two years, while the reductions were greater from year 3 onwards. On average across experiments and years, the agroforestry systems reduced soil, SOC, N, P and K losses by 27–76%, 21–78%, 20–82%, 24–82% and 22–84%, respectively. These findings show that agroforestry with fruit trees, grass strips and crops could be a useful management practice and viable option for sustainable agricultural systems on sloping land, by reducing soil (and carbon and nutrient) losses through terrace formation.

1. Introduction

Soil degradation is a global issue caused by a variety of factors, including transformation of forests to agricultural land, increased use of farming practices that have negative impact on soils and pressure on land from other societal activities such as mining, construction and urban development to meet the needs of a growing population (Karlen and Rice, 2015). Soil erosion and associated nutrient losses contribute strongly to soil degradation on sloping land (Karlen and Rice, 2015).

Upland agriculture relies heavily on sloping land as a major land resource. Reduced soil infiltration capacity, topographical characteristics, erratic rainfall events and inappropriate agricultural management techniques all contribute to soil erosion and nutrient losses from sloping land (Mao et al., 2020). In Southeast Asia, much of the mountainous region is characterised by steep slopes, high rainfall intensities, seasonally dry periods and erodible soils (Sidle et al., 2006). Shifting cultivation has been practised for centuries throughout this region (Fox and Vogler, 2005), but in recent decades shifting cultivation has been

* Corresponding author at: Department of Crop Production Ecology, Swedish University of Agricultural Sciences (SLU), P.O. Box 7043, 75007 Uppsala, Sweden.
E-mail address: hung.do.van@slu.se (V.H. Do).

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replaced by intensive agriculture systems dominated by cultivation of sole crops, with frequent soil tillage and shorter or no fallow period (Dung et al., 2008; Hilger et al., 2013; Ziegler et al., 2009). This change has been driven by economic development, policy changes, new technologies and population growth (Schreinemachers et al., 2013). Sole-crop cultivation on steep slopes frequently results in significant soil degradation and unsustainable agricultural production, e.g. conventional cultivation in northwest Vietnam is dominated by sole cropping of e.g. maize, upland rice, cassava and coffee, which involves intensive tillage combined with burning of crop residues (Hoang et al., 2017; Tuan et al., 2014). Rapid expansion of these practices to meet the needs of a growing population has resulted in severe soil erosion and associated nutrient losses, lower yields and a decrease in smallholder income over time. This threatens environmental sustainability and food security in the region (Clemens et al., 2010; V.H. Do et al., 2020; H. Do et al., 2020; Schmitter et al., 2010; Tuan et al., 2014; Wezel et al., 2002).

Various soil conservation techniques have been proposed worldwide to reduce and reverse land degradation trends. Within agriculture, strategies for soil conservation include techniques such as contour farming, terracing, mulching, growing cover crops, conservation agriculture (including minimum tillage or zero tillage, cover crops and a diverse crop rotation) and agroforestry. The combination of trees and crops (and/or livestock) in agroforestry increases soil cover through canopy cover and contributions to the litter layer. It creates physical and biological structural barriers that reduce losses of water, soil and related nutrients compared with sole-crop cultivation (Atangana et al., 2014; Kang et al., 1989; Muchane et al., 2020; Young, 1989; Zhu et al., 2020). The combination of tree and crop components also enhances soil organic carbon (SOC) stocks and carbon sequestration, by adding higher quantities of aboveground and belowground biomass compared with sole-crop systems (Chatterjee et al., 2018; Hoosbeek et al., 2018). Turnover of this biomass contributes to soil improvement, e.g. by providing nutrients and modifying soil physical properties, which can help to improve tree and crop yields (Dollinger and Jose, 2018). In addition, deep-rooted trees and shrubs can absorb nutrients from subsoil layers and recycle them to the topsoil, contributing to nutrient supply and soil improvement.

Terraces are effective in reducing soil losses due to soil erosion while also preserving soil moisture, protecting landscape quality and increasing land value (Foster, 2004). Terraces divide slopes, allowing surface runoff to be intercepted, and reduce erosion by shortening the length of the slope (Koomson et al., 2020). Rather than constructing terraces, which is labour- and cost-intensive, an alternative is 'natural' terrace formation over time. Trees, crops and grass can be planted along contours as living barriers for this purpose, as a low-input technology in soil conservation (Tripp, 2017; Wojtkowski, 2008). For example, movement of sediment can help to create natural terraces in alley systems where annual crops are integrated with trees or grass strips planted along the contour (Garrity, 1996, 1999). This type of initiated 'natural' terrace formation can thus be an important component of green infrastructure as a nature-based solution for sustainable land use (Simelton et al., 2021). However, previous studies have not evaluated and quantified the reductions in soil and nutrient losses during sediment movement and terrace development behind trees and grass strips planted along contours on steep slopes.

The number of smallholder fruit tree plantations in different provinces in northwest Vietnam is increasing, driven by the significant economic benefits. According to General Statistics Office of Vietnam (2020), the combined area of fruit-tree plantations in the provinces of Dien Bien, Yen Bai and Son La reached 74,500 ha in 2020, a 60% increase from 2015. Smallholder farmers in the region have also switched large areas of annual crops to coffee, changing their dependence on subsistence agriculture to production of a commercial commodity (Nghiem et al., 2020). Farmers are interested in, and aware of, the benefits of combining trees and coffee (Nguyen et al., 2020). Livestock rearing is the second main source of income in northwest Vietnam, after tree plantations and crops, but population growth and increased demand for agricultural land have significantly reduced the area available for free-grazing, leading to increased demand for fodder grasses for livestock (Atieno et al., 2021). Agroforestry with fruit trees can significantly improve livelihoods, while the demand for livestock fodder grass can be met by integrating grass strips into agroforestry (H. Do et al., 2020; V.H. Do et al., 2020). Research is needed to evaluate and quantify formation of natural terraces in such agroforestry systems and their effectiveness in soil conservation and reducing nutrient losses.

The overall aim of this study was to evaluate and quantify natural terrace formation in agroforestry systems comprising fruit trees, crops and fodder grass grown along contours and to determine the contribution to soil conservation on sloping land following conversion from sole cropping to agroforestry. Specific objectives were to (i) evaluate sediment movement and terrace formation in agroforestry systems with fruit trees, crops and grass strips; and (ii) quantify the effectiveness of the terraces formed and the agroforestry system in reducing losses of soil, SOC and nutrients (N, P, K). Two agroforestry systems, comprising longan (*Dimocarpus longan* L.)-mango (*Mangifera indica* L.)-maize (*Zea mays* L.)-guinea grass (*Panicum maximum* Jacq.) and son tra (*Docynia indica* (Wall.) Decne., locally known as H'Mong apple)-coffee *(Coffea arabica* L.)-guinea grass, were compared with sole-crop maize and sole-crop coffee, respectively.

2. Materials and methods

2.1. Site description

Field experiments with the two agroforestry systems were established in 2017, at field sites in Mai Son district (21.10°N, 104.06°E; 566 m a.s.l) in Son La province and Tuan Giao district (21.33°N, 103.30°E; 1104 m a.s.l) in Dien Bien province, Vietnam (Fig. 1). Annual crops had been grown at the Mai Son site for more than 30 years, with upland rice until 2007 and then maize until the field experiment was established. The field at the Tuan Giao site lay fallow prior to 2007 and was planted with upland rice in 2007–2008, maize in 2009–2013 and sole coffee in 2014-early 2016 (all coffee plants died during a heavy frost event in January 2016), and then no crop was planted until the experiment was established.

The climate at both sites is sub-humid tropical, with a rainy season from April to October and a dry season from November to March. Mean annual temperature is 21.5 °C and 18.6 °C at Mai Son and Tuan Giao, respectively, and annual rainfall is 1200–1600 mm at both sites. Around 90% of annual rainfall is concentrated in the period April-September. The mean slope of the experimental plots was 37% at Mai Son and 56% at Tuan Giao.

Soil profile description and characterisation were carried out and the soils were classified as Acrisols (Table 1). The topsoil texture at both sites is loam and the topsoil at Tuan Giao is deeper than that at Mai Son. At both sites, the clay content is significantly higher in the B-horizon than in the Ap- and C-horizons. Soil bulk density is relatively high at the Mai Son site, especially in the BC horizon, while it is in the optimum range at Tuan Giao. Topsoil organic carbon content is 1.8% at Mai Son and 2.2% at Tuan Giao. Some SOC is also present in the B-horizon at both sites. Soil pH (H_2O) is fairly low at Mai Son, 5.5 in the topsoil and around 5 in the sub-surface horizons, and around 4 in all horizons at Tuan Giao, which is very low for agricultural soil. At the time of sampling, available P in the topsoil was just above 0.6 mg 100 g^{-1} at both sites, while available K in the topsoil was 7.6 mg 100 g^{-1} at Mai Son and 5.6 mg 100 g^{-1} at Tuan Giao. At both sites, the concentrations of available P and K were relatively low according the rating scale for soil nutrients in agricultural land in Vietnam (Tran and Bui, n.d.).

2.2. Experimental design

The experiments were laid out in a randomised complete block

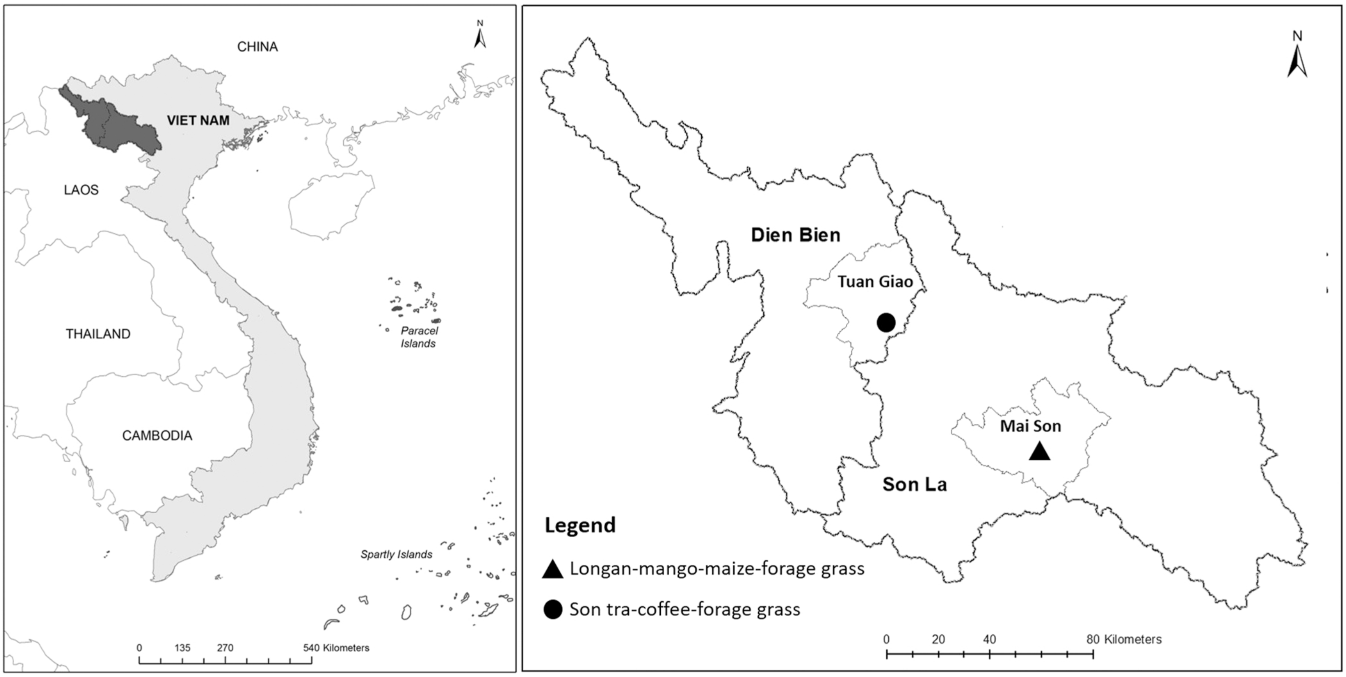

Fig. 1. Location of the agroforestry experiments with longan-mango-maize-forage grass in Mai Son District, Son La Province, and son tra-coffee-forage grass in Tuan Giao District, Dien Bien Province, north-west Vietnam.

design with four replicates and two treatments (agroforestry system versus continuous sole crop) and changes were evaluated over a five-year period (2017–2021). In the experiment at Mai Son, the agroforestry treatment consisted of longan-mango-maize-guinea grass (fruit-maize-AF) and was compared with annual cultivation of maize as sole crop (sole-maize). Longan and mango trees in the fruit-maize-AF treatment were planted in single-species rows, with 4.0 m spacing within rows, 20 m between rows of the same tree species and 10 m between tree rows (125 trees species^{-1} ha^{-1}) (Fig. 2a). Guinea grass was planted in double rows 1 m below the longan and mango trees, with a spacing of 0.5 m between the two grass rows. For sole-maize, seed rate, row spacing and distance between plants was 15 kg ha^{-1}, 0.65 m and 0.3 m, respectively. Maize plants were sown with the same row spacing and plant spacing in both treatments, but on a smaller area in fruit-maize-AF, where the distance to the upper grass row and outside the canopy of the fruit trees was kept to 0.8 m and 0.5 m, respectively. Therefore, the area of maize was reduced as the tree canopy expanded, so that maize was grown on 15% less land in fruit-maize-AF than in sole-maize in the first year and on 22% less land than in sole-maize in year 5 of the experiment. A grafted mango seedling variety (GL4), a grafted late-maturing longan variety (PHM-99–1–1) and forage guinea grass (Mombasa) were used in fruit-maize-AF. The hybrid PAC 999 maize variety was used in all treatments. All crops were planted along contour lines.

At Tuan Giao, the agroforestry treatment consisted of son tra-coffee-guinea grass (fruit-coffee-AF), with sole-crop coffee (sole-coffee) as the control. In fruit-coffee-AF, son tra trees were planted with 10 m spacing between rows and 4.0 m spacing between trees within rows (250 tree ha^{-1}) (Fig. 2b). A double row of guinea grass was planted 1 m downhill from the son tra row, with 0.5 m between the grass rows. Four rows of coffee (cv. Catimor) were planted between two rows of son tra, with 2.0 m spacing between rows and 1.4 m spacing between shrubs within rows (2857 shrubs ha^{-1}). The coffee shrubs in sole-coffee were planted across the whole plots, with the same distance between and within rows as in fruit-coffee-AF (3571 shrubs ha^{-1}), resulting in 20% higher density than in fruit-coffee-AF due to the smaller area of coffee in that treatment. Grafted son tra seedlings were used in the experiment. All son tra, coffee and forage grass were planted along contour lines.

The nutrients applied were adjusted to the crop (Table 2) and a number of fertiliser types were used (Table S1 in Supplementary Material (SM)). At Mai Son, the amount of N, P and K applied to maize in fruit-maize-AF was the same per unit area as in sole-maize, but the total amount was 15–22% lower due to the smaller area of maize. Each longan and mango tree received the same amount of composted animal manure (15 kg tree^{-1}) in year 1, and microbial fertiliser (0.5 kg tree^{-1} in year 2 and 2.5 kg tree^{-1} annually in years 3–5). Longan and mango trees also received the same amount of N, P and K, which was 3, 6 and 2 kg ha^{-1} in year 1; 8, 3 and 6 kg ha^{-1} in years 2–3; and 16, 12 and 13 kg ha^{-1} in years 4–5. In years 4–5, Ca, Mg and micronutrients were also applied to all trees.

In the Tuan Giao experiment, 5 kg of composted animal manure was applied to each coffee shrub in both sole-coffee and fruit-coffee-AF in year 1. In fruit-coffee-AF, each son tra tree received 15 kg of composted animal manure in year 1 and microbial fertiliser from year 2 onward (1 kg tree^{-1} in year 2 and 3 kg tree^{-1} in years 3–5). Each coffee shrub was fertilised with the same amounts of N, P and K in both treatments, but the total amount was around 20% lower in fruit-coffee-AF than in sole-coffee due to the smaller area of coffee shrubs in fruit-coffee-AF. Son tra trees in fruit-coffee-AF received 6, 13 and 4 kg ha^{-1} of N, P and K, respectively, in year 1, and 16, 6 and 11 kg ha^{-1}, respectively, in years 2–5. The purpose of planting grass strips was to utilise nutrients in runoff to produce fodder, while conserving the soil. Therefore, no nutrients were applied to the forage grasses.

Weed management in the agroforestry and sole-crop systems was adapted to the needs of the different systems and local practices. At Mai Son, weeds were hoed by hand before sowing of maize in both systems in all years. In year 1, this was complemented with one herbicide application (active ingredient: atrazine 800 g kg^{-1} + additives: 200 g kg^{-1}, dose 2 kg ha^{-1}) in both treatments when the maize had 3–4 fully expanded leaves. In years 2–5, weeds were controlled by hoeing in fruit-maize-AF when the maize had 3–4 and 10–11 fully expanded leaves, and with a herbicide (the same as in year 1) in sole-maize at 3–4 fully expanded leaves. Herbicide was not used in fruit-maize-AF, to avoid damage to the trees and to follow local practice, while it was used in sole-maize to avoid unrealistic soil losses compared with local practice.

Table 1
Soil characteristics in different horizons (Hz) at the Mai Son and Tuan Giao sites.

Sites	Hz	Depth [cm]	SC [%]	BD [g cm^{-3}]	pH (H_2O)	SOC [%]	Total N, P, K [%]			Available P, K [mg 100 g^{-1}]		CEC [cmol (+) kg^{-1}]	Texture [%]			
							N	P	K	P	K		< 0.002 mm	0.002–0.02 mm	0.02 – 0.2 mm	0.2 – 2 mm
Mai Son	A	0–17	10	1.37	5.5	1.78	0.15	0.03	0.31	0.64	7.6	15	18	40	36	6
	B1	17–36	2	1.35	5.0	0.97	0.13	0.02	0.29	0.14	3.8	11	36	28	32	4
	B2	36–56	6	1.32	4.9	0.81	0.14	0.02	0.34	0.08	3.4	16	42	22	31	5
	BC	56-	9	1.56	5.1	0.38	0.09	0.02	0.29	0.06	2.2	11	25	15	36	24
Tuan Giao	A	0–23	0	1.15	4.0	2.21	0.16	0.04	0.63	0.61	5.6	11.8	17	39	40	4
	B1	23–44	0	1.27	4.0	2.02	0.14	0.03	0.64	0.09	5.2	9.4	24	34	39	3
	B2	44–63	0	1.16	4.1	1.17	0.09	0.02	0.69	0.06	3.4	9.4	28	36	33	3
	B3	63–96	0	1.21	4.1	0.79	0.07	0.02	0.83	0.38	2.2	9.6	30	32	34	4
	BC	96-	0	1.26	4.0	0.50	0.05	0.02	0.81	0.05	1.2	10	22	38	35	5

SC: stone content, BD: bulk density, pH (soil: water ratio 1:5-TCVN: 5979, 2007), SOC: soil organic carbon (Walkley-Black method-TCVN: 8941, 2011). Total-N (Kjeldahl method-TCVN: 6498, 1999), total-P and total-K (digestion with mixed strong acids method-TCVN: 8940, 2011 and TCVN: 8660, 2011), available P (Bray II method-TCVN: 8942, 2011), available K (ammonium acetate method-TCVN: 8662, 2011), CEC: cation exchange capacity (ammonium acetate method to determine CEC-TCVN: 8568, 2010).

Thus, more tillage was applied in fruit-maize-AF than in sole-maize to reflect differences in management practice. Crop residues from the previous season and hoed weeds were left on the ground in both treatments.

Weed management in the coffee experiment at Tuan Giao was also adjusted to farmers' weeding practices. In year 1, weeding consisted of hand hoeing once at the end of the rainy season (October) in both treatments. Weeding was then carried out three times per year in both treatments, at the same time as fertilisers were applied to the coffee shrubs at the beginning (April), middle (July) and end (October) of the rainy season. Weeding was done by hand hoeing in years 2–3 and with a strimmer in years 4–5 to reduce soil disturbance and resulting erosion and to reflect changing practices among farmers.

2.3. Data collection

2.3.1. Sediment movement and terrace formation within agroforestry systems

Erosion pins were installed at the start of the 2018 season in the soil loss measurement area in all agroforestry plots (see Fig. 2). The pins were 30 cm long and inserted 15 cm into the soil at points close downslope of the grass strips (1 row of pins), midway between the grass strips (1 row), and close upslope (2 rows) of the grass strips in each plot of fruit-maize-AF (Fig. 3a) and fruit-coffee-AF (Fig. 3b). The downslope erosion pins were placed 0.7 m and 1.2 m below the lower rows of the grass strips in fruit-maize-AF and fruit-coffee-AF, respectively. At the upslope positions, the front and rear pins were 0.2 and 0.7 m above the upper row of the grass strips in both systems. One pin row comprised four erosion pins and there were in total 12 rows of pins per plot in fruit-maize-AF and eight per plot in fruit-coffee-AF, reflecting the different number of grass strips per plot in the two trials.

The distance from the top of the pin to the soil surface on the downslope side of the pin was determined at the end of each growing season (Hart et al., 2017). Soil loss/accumulation was estimated as the difference between measured pin height and initial pin height (15 cm above the ground).

2.3.2. Estimation of volume of terrace formed

The volume of terrace formed by the trees and grass strips within the agroforestry treatments was estimated in the fifth growing season after establishment of the experiments (i.e. to end of 2021). The terraces formed were estimated for three rows of trees and grass strips per plot in fruit-maize-AF and two rows of trees and grass strips in fruit-coffee-AF, excluding the uppermost tree and grass strips (cf. Fig. 2a and b).

Terrace volume (V) was estimated according to Sjödell and Thelberg (2020) as follow:

$$V1 = (h1 \times w)/2 \tag{1}$$

$$V2 = (h2 \times w)/2 \tag{2}$$

$$Vt = V1 - V2 \tag{3}$$

where *h1*, *h2* and *w* are distances indicated in Fig. 4. Distance *w* was calculated as the width of the strip between the trees and the lower grass row; height *h1* was determined by measuring the vertical distance from the terrace bottom to a horizontal measuring stick placed with one end at ground level by the trees above the grass strips; and height *h2* was measured as the distance from the lower grass row to the same horizontal measuring stick as for *h1*. In order to calculate the total soil volume (*Vt*) of a terrace (Eq. 3), two 90-degree triangles with different height (*h1* and *h2,* respectively) were constructed. The slope of the terrace was assumed to be perfectly straight from tree to the bottom of *h2*. Terrace volume (m^3 per linear metre terrace) was calculated by subtracting the volume (*V2*) of the triangle with height *h2* from the volume (*V1*) of the triangle with height *h1*.

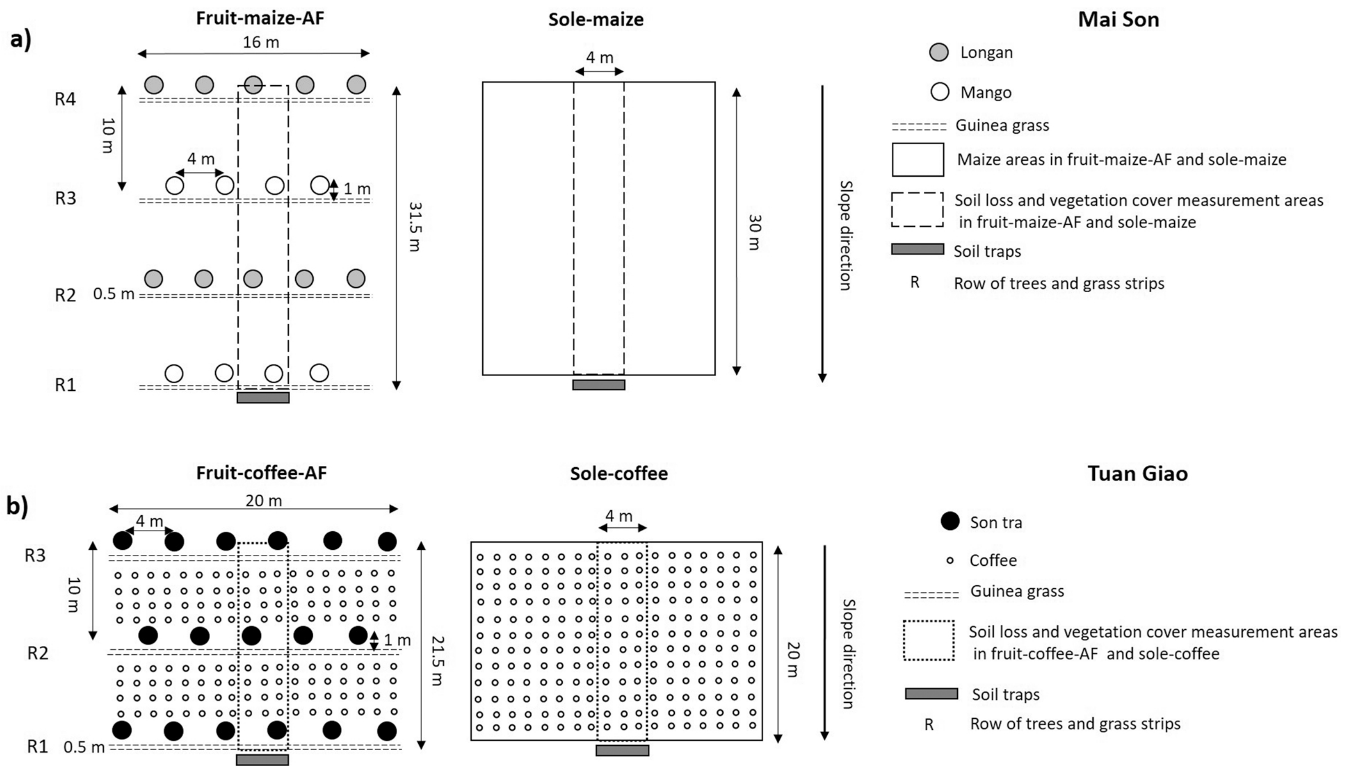

Fig. 2. Design of field experiments at (a) Mai Son: longan-mango-maize-forage grass (fruit-maize-AF) and sole-crop maize (sole-maize), with plot area 504 and 480 m^2, respectively, and (b) Tuan Giao: son tra-coffee-forage grass (fruit-coffee-AF) and sole-crop coffee (sole-coffee), with plot area 430 and 400 m^2, respectively. Soil traps were installed in all plots at both sites.

Table 2
Total nutrients supplied in chemical fertilisers and amount of amendments applied in the sole-crop and agroforestry systems at the Mai Son and Tuan Giao sites during the five-year study period.

	Chemical fertiliser and amendment dose (kg^{-1} ha^{-1})						
Site	Cropping system[a]	Type of nutrient or amendment[b]	2017	2018	2019	2020	2021
Mai Son	Sole-maize	N	160	160	160	160	160
		P	60	60	60	60	60
		K	76	76	76	76	76
	Fruit-maize-AF	N	140	150	148	160	156
		P	64	57	56	71	70
		K	69	75	75	86	85
		Ca	0	0	0	24	24
		Mg	0	0	0	4.5	4.5
		Micronutrients (Fe, Cu, Zn, Mn, Si)	0	0	0	0.1	0.1
		Composted animal manure	3750	0	0	0	0
		Microbial fertiliser	0	125	625	625	625
Tuan Giao	Sole-coffee	N	112	41	83	138	138
		P	275	48	48	48	48
		K	71	27	83	146	146
		Composted animal manure	17855	0	0	0	0
	Fruit-coffee-AF	N	96	51	83	127	127
		P	232	45	45	45	45
		K	61	33	79	128	128
		Composted animal manure	18035	0	0	0	0
		Microbial fertiliser	0	250	750	750	750

[a] Sole-crop maize (sole-maize) and longan-mango-maize-forage grass (fruit-maize-AF) at Mai Son; sole-crop coffee (sole-coffee) and son tra-coffee-forage grass (fruit-coffee-AF) at Tuan Giao.
[b] Details of fertiliser types used in the experiments in each year are provided in Table S1 (Supplementary Materials).

2.3.3. Rainfall

Data on daily precipitation 2017–2021 were obtained from weather stations in Son La (21.20°N, 103.54°E; 24 km northwest of the Mai Son site) and in Dien Bien (21.34°N, 103.31°E; 1.2 km north of the Tuan Giao site). Precipitation data were used to investigate the link between daily rainfall, percentage of vegetation cover and soil loss data collected at both sites during the five-year period.

2.3.4. Soil loss determination

In fruit-maize-AF and sole-maize at Mai Son, the measurement area for soil loss was 4.0 m x 31.5 m and 4.0 m x 30 m, respectively, whereas in fruit-coffee-AF and sole-coffee at Tuan Giao it was 4.0 m x 21.5 m and

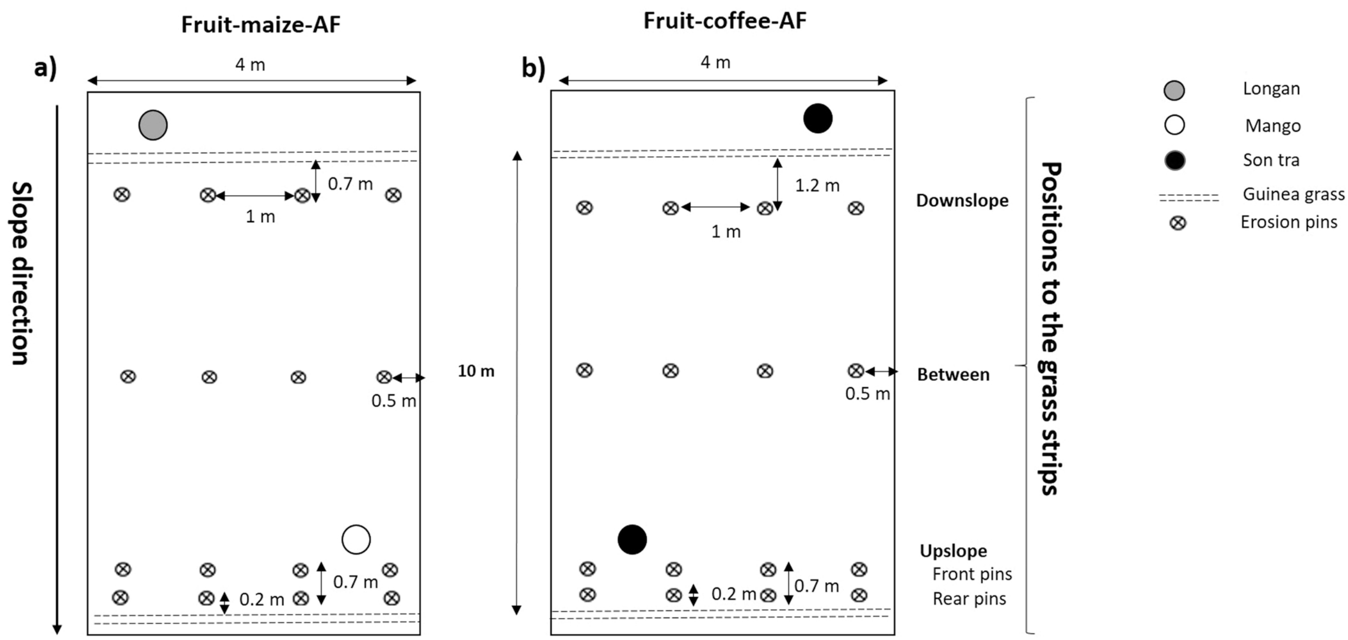

Fig. 3. Positions of erosion pins in one section of each agroforestry plot to evaluate sediment movement down the slope. (a) Longan-mango-maize-forage grass (fruit-maize-AF) at the Mai Son site and (b) son tra-coffee-forage grass (fruit-coffee-AF) at the Tuan Giao site.

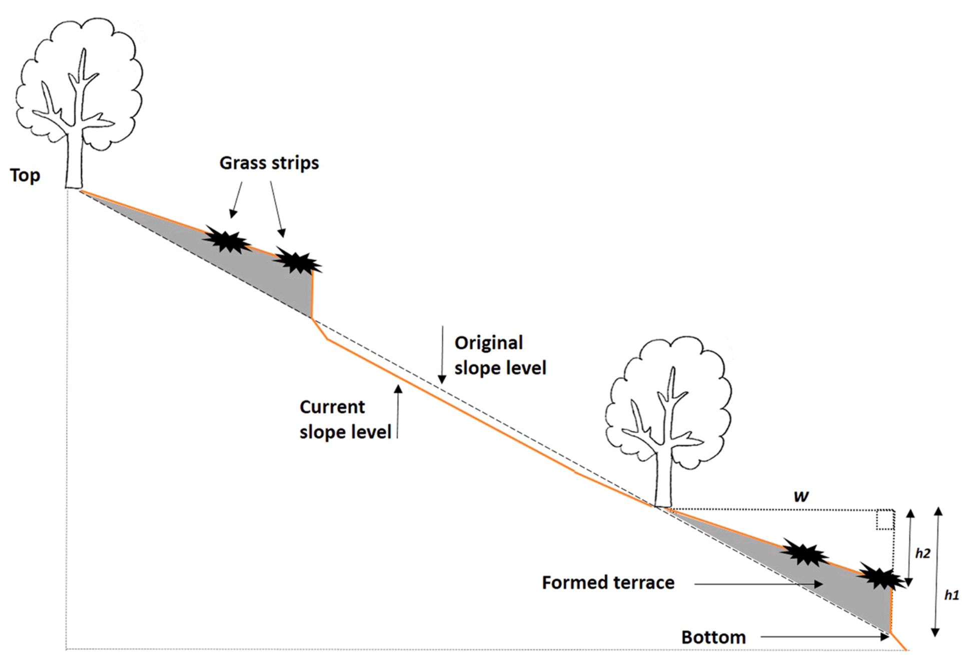

Fig. 4. Method used for estimation of volume of terrace formed in the five growing seasons after establishment of trees and grass strips in longan-mango-maize-forage grass (fruit-maize-AF) at the Mai Son site and son tra-coffee-forage grass (fruit-coffee-AF) at the Tuan Giao site.

4.0 m x 20 m, respectively. A soil trap was established at the bottom of each area (Fig. 2a and b). Each trap was 4.0 m long, 0.5 m wide and 0.8 m deep, and was covered with a permeable fabric to allow water infiltration. To prevent soil from entering the trap from outside the soil-loss determination area, 30 cm high pro-cement sheet frames were used to surround the area.

The eroded soil that fell into soil traps during the rainy season was collected and weighed. In years 1–4, soil was collected from the traps on 4, 5, 2 and 7 occasions at Mai Son and 4, 6, 6 and 3 occasions at Tuan Giao. In year 5, no soil loss occurred in any of the experimental plots, due to low rainfall early in the growing season. The soil collected on each occasion was homogenised and a 300 g sub-sample from each plot was used to evaluate the ratio between fresh and air-dry weight (25 °C). Annual soil loss in metric tons per hectare was calculated by adjusting the collected soil bulk for moisture content and dividing by the contributing area. The dried subsamples from each sampling occasion were saved for chemical analysis.

2.3.5. *Vegetation cover determination*

Vegetation cover was determined by taking photos at 3.5 m above the ground using a digital camera (Canon SX280 HS) placed on an L-shaped aluminium stick. Perpendicular positioning of the stick while photographing was achieved using a rope connected to a metal cone at one end and to the top of the L-shaped stick at the other end. The images were taken plot-wise on the left and right sides of the soil erosion measurement areas (cf. Fig. 2). In sole-maize and fruit-maize-AF, 30 images were taken in each plot, covering approximately 25% of the plot area. In sole-coffee and fruit-coffee-AF, 20 images were taken in each plot, covering approximately 20% of the plot area.

At Mai Son, the images were taken four times per season from 2018 to 2021, when the maize had 3–4, 6–7 and 10–11 fully expanded leaves and at silking. At Tuan Giao, the images were taken in September and December in 2017, and in March, June, September and December from 2018 to 2021. Vegetation cover was calculated using ImageJ version 1.52 (Xiong et al., 2019).

2.3.6. Nutrient loss determination

The 300-g eroded soil sub-samples were analysed to determine the concentrations of total SOC, N, P, and K, using the same analytical protocols as for the initial soil samples (Table 1). Annual losses of SOC, N, P, and K due to soil erosion in kilograms per hectare were calculated by multiplying the concentration of each nutrient in eroded soil by the total amount of eroded soil collected in soil traps over the monitoring year.

2.4. Statistical analysis

The software R (version 3.6.1) was used for all statistical analyses. Repeated measures ANOVA with the mixed model was used to assess the effects of various factors on soil and nutrient losses by soil erosion and vegetation cover over the years. Site, cropping system, year and their interactions were treated as fixed effects in the soil and nutrient loss analysis model. Cropping system, year, measurement period and their interactions were used as fixed effects in the vegetation cover analysis model. Blocks and plots were treated as random effects in both models. Log-transformation was used to normalise the data when necessary. When a significant difference was indicated in F-tests, estimated marginal means (emmeans) were used to identify significant ($p < 0.05$) differences between means. ANOVA was used to compare the volume of terrace formed over five years in the agroforestry systems. Tukey's HSD test was used to test for significant differences in the volume of terrace created by the different tree and grass strips in the agroforestry systems.

3. Results

3.1. Sediment movement and terrace formation within agroforestry systems

Measurements of changes in erosion pin height over four growing seasons (2018–2021) in fruit-maize-AF showed that 4.6 cm of soil were added at the rear pins, upslope from the grass strips, which was 1.4 times more than the height of soil added at the front pins upslope from the grass strips (Fig. 5a). In contrast, approximately 2.2 and 1.6 cm soil were lost from positions downslope of and midway between the grass strips, respectively.

In the fruit-coffee-AF system, measurements of changes in pin height throughout the growing seasons (2018–2021) indicated that around 5 cm of soil had accumulated at the rear pins, which was 1.5 times more than that at the front pins upslope from the grass strips (Fig. 5b). The pins midway between and downslope from the grass strips lost an average of 0.8 and 1.6 cm of soil, respectively.

There were no significant differences in terrace formation after five growing seasons between uphill and downhill tree and grass strips within plots (Fig. 6). The average volume of terrace formed was 0.26 m^3 per m of terrace in the fruit-maize-AF system and 0.43 m^3 per m terrace in the fruit-coffee-AF system.

Since the control systems (sole-maize and sole-coffee) do not form terraces, no comparison was made between agroforestry systems and sole-crop systems.

3.2. Rainfall

Total annual rainfall over the five-year period (2017–2021) ranged from 1015 to 1540 mm at Mai Son and from 1229 to 2086 mm at Tuan Giao (Table 3). The highest annual rainfall was recorded at Tuan Giao in 2017 and Mai Son in 2018, while the lowest was recorded at Tuan Giao in 2019 and Mai Son in 2019 and 2021. Small rainfall events (less than 10 mm) dominated at both sites, but 1–5 high-intensity rainfall events (50–100 mm) occurred each year.

3.3. Soil loss to erosion traps

The agroforestry systems reduced soil loss significantly compared with the sole crops already in year 2, while the impacts were even greater in years 3 and 4, resulting in a significant interaction between cropping system and year (Table 4 and Fig. 7).

During years 2–4, the agroforestry systems (fruit-maize-AF and fruit-coffee-AF) reduced soil loss by 27–76% compared with the sole crop

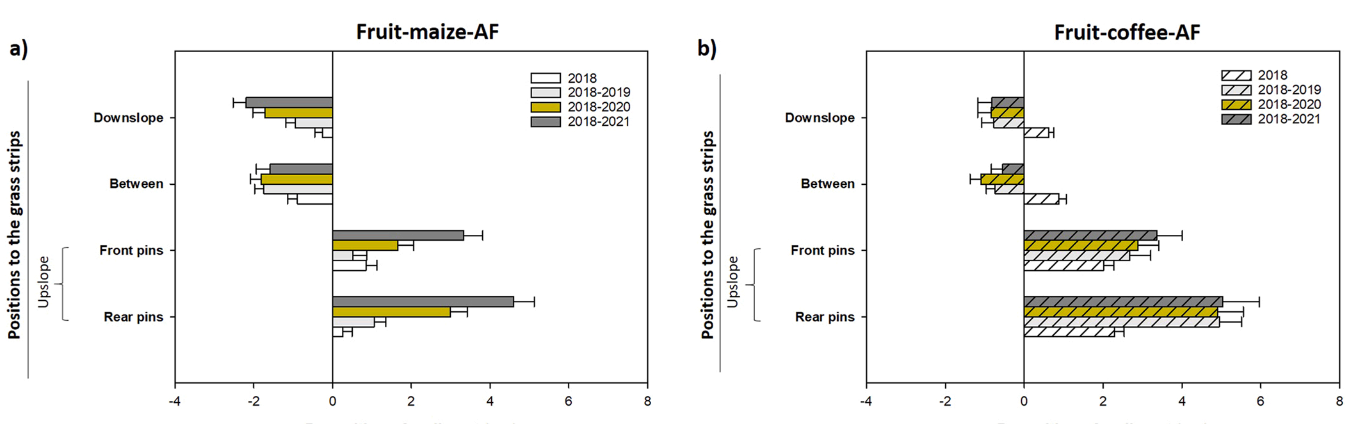

Fig. 5. Sediment movement downslope within the two agroforestry systems based on changes measured at erosion pins. The X-axis shows soil loss (negative values) or accumulation (positive values) over time, and the error bars indicate standard error. (a) Longan-mango-maize-forage grass (fruit-maize-AF) system at the Mai Son site and (b) Son tra-coffee-forage grass (fruit-coffee-AF) system at the Tuan Giao site.

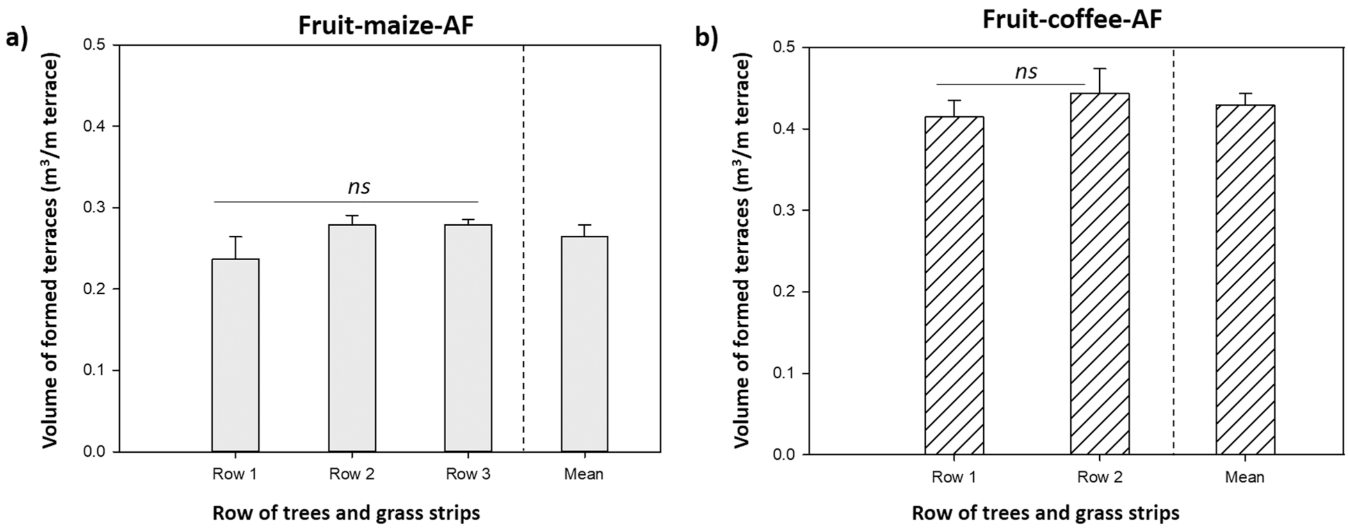

Fig. 6. Mean volume of terrace formed by tree and grass strips in the two agroforestry systems after five growing seasons. Error bars indicate standard error. (a) Longan-mango-maize-forage grass (fruit-maize-AF) system at the Mai Son site and (b) Son tra-coffee-forage grass (fruit-coffee-AF) system at the Tuan Giao site.

Table 3
Cumulative annual rainfall and number of days with rainfall events of different categories of intensity at the study sites.

Rainfall	Mai Son					Tuan Giao				
	2017	2018	2019	2020	2021	2017	2018	2019	2020	2021
Total amount (mm)	1382	1540	1015	1194	1016	2086	1885	1229	1547	1425
< 10 mm	109	96	73	87	90	138	126	104	121	131
10–20 mm	27	18	14	19	17	43	34	24	27	24
20–30 mm	11	16	7	8	7	15	17	9	9	11
30–50 mm	7	9	6	8	7	11	11	6	11	10
50–100 mm	3	5	3	3	1	3	4	4	3	3
Total days	157	144	103	125	122	210	192	147	171	179

Table 4
Annual soil loss (mean ± standard error) in the agroforestry systems fruit-maize-AF (longan-mango-forage grass) and fruit-coffee-AF (son tra-coffee-forage grass) compared with sole-crop maize (sole-maize) and sole-crop coffee (sole-coffee), respectively, at the Mai Son and Tuan Giao sites.

Year	Soil loss (ton ha^{-1})			
	Mai Son		Tuan Giao	
	Fruit-maize-AF	Sole-maize	Fruit-coffee-AF	Sole-coffee
2017	16.0 (± 8.2)	19.2 (± 7.5)	59 (± 17.7)	46 (± 15.8)
2018	12.0 (± 4.7)	19.8 (± 3.0)	113 (± 18.4)	151 (± 28)
2019	1.2 (± 0.9)	2.3 (± 0.4)	31 (± 7.2)	89 (± 12.3)
2020	1.4 (± 0.5)	3.8 (± 1.2)	7.1 (± 2.0)	32 (± 15.6)
2021[a]	–	–	–	–
Significance	*By site: p = 0.005, By system: p = 0.06, System x year: p = 0.01, System x site: p = 0.45*			

[a] No soil loss by erosion occurred in 2021.

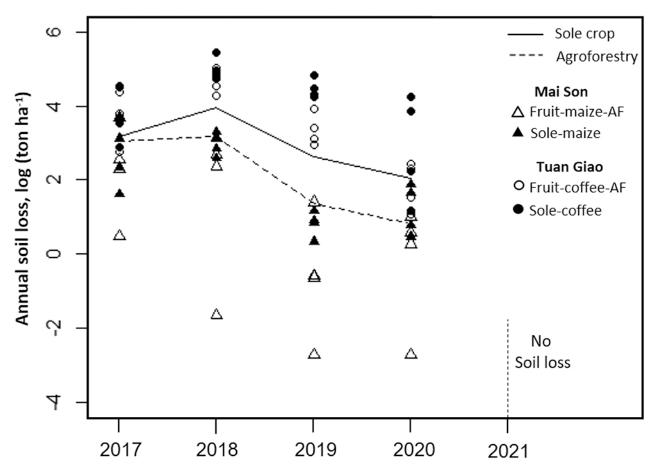

Fig. 7. Interaction plot for annual soil loss in the agroforestry systems fruit-maize-AF (longan-mango-maize-forage grass) and fruit-coffee-AF (son tra-coffee-forage grass) compared with sole-crop maize (sole-maize) and sole-crop coffee (sole-coffee), respectively, at the Mai Son and Tuan Giao sites. Soil loss data were log-transformed.

systems (sole-maize and sole-coffee) (Table 4 and Fig. 7).

Soil loss was substantially greater at Tuan Giao than at Mai Son over the five growing seasons (Table 4 and Fig. 7).

3.4. Impact of rainfall and vegetation cover on soil loss

There was no significant difference in vegetation cover between fruit-maize-AF and sole-maize, and there was no significant interaction between cropping system and year, or between cropping system and measurement period during the cropping season (Fig. 8a). The majority of the soil erosion in fruit-maize-AF and sole-maize plots occurred between planting of the maize crop, when the soil surface was bare owing to tillage operations, and the silking stage of maize, i.e. the period when vegetation cover was less than 50% (Fig. 8a). From the silking stage onwards, the average vegetation cover in both fruit-maize-AF and sole-maize was greater than 50% and there was no observed soil loss, despite high rainfall from silking to the end of the rainy season in all study years.

At Tuan Giao, there was a significant effect of cropping system on vegetation cover, with significantly greater ($p = 0.008$) vegetation cover

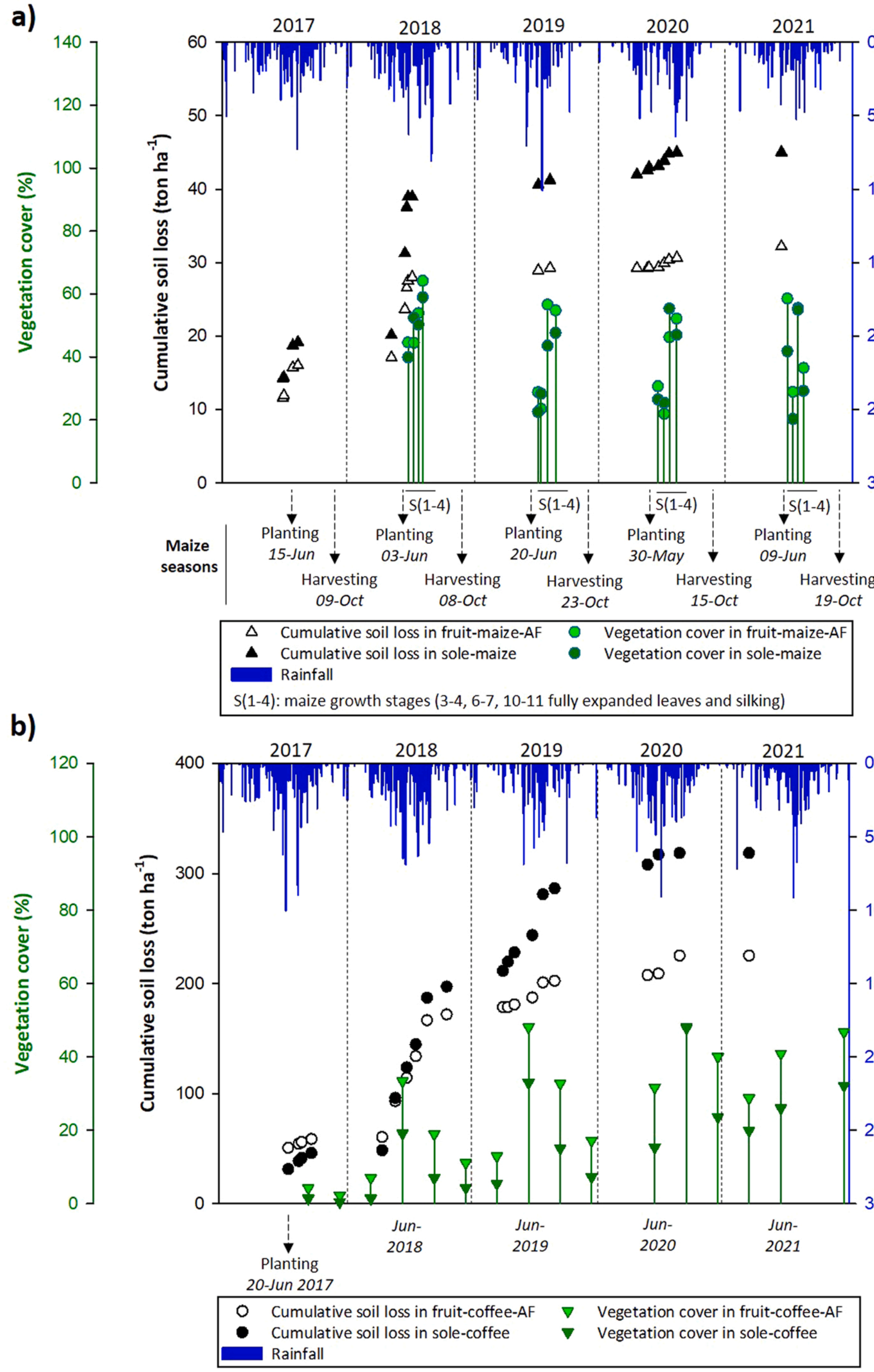

Fig. 8. Cumulative soil loss over the five-year study period, daily rainfall and percentage vegetation cover over time in the agroforestry systems and sole-crop systems. (a) Longan-mango-maize-forage grass (fruit-maize-AF) and sole-crop maize (sole-maize) and (b) Son tra-coffee-forage grass (fruit-coffee-AF) and sole-crop coffee (sole-coffee).

in the fruit-coffee-AF system than in sole-coffee (Fig. 8b). In addition, there was a significant interaction between cropping system and year ($p = 0.007$), and between cropping system and measurement period ($p = 0.009$). In year 1, the average vegetation cover in both systems was less than 10% (Fig. 8b). The vegetation cover increased in both systems from year 2 onwards, with fruit-coffee-AF having greater vegetation cover than sole-coffee (Fig. 8b). However, soil loss continued even during the periods of greatest vegetation cover in both systems during 2017–2020.

3.5. *Nutrient losses through soil erosion*

In both the agroforestry and sole-crop systems at Tuan Giao, the concentrations of SOC and total-K in eroded soil was 1.4 and 2 times higher, respectively, than at Mai Son (Table S2 in SM). The concentrations of total-N and total-P in eroded soil were similar at both sites.

There was a significant interaction between cropping system and year for losses of SOC and nutrients (N, P, K) (Table 5 and Fig. 9). During years 2–4, the agroforestry systems showed SOC, N, P and K losses that were 21–78%, 20–82%, 24–82% and 22–84% lower, respectively, than those in the sole crop systems (Table 5 and Fig. 9).

Table 5
Annual soil organic carbon (SOC) and nutrient losses (total-N, total-P, total-K) in the agroforestry systems fruit-maize-AF (longan-mango-maize-forage grass) and fruit-coffee-AF (son tra-coffee-forage grass) compared with the sole-maize (sole-crop maize) and sole-coffee (sole-crop coffee) systems, respectively, at the Mai Son and Tuan Giao sites. Values are means ± standard error.

Site	SOC loss (kg ha^{-1})		Total-N loss (kg ha^{-1})		Total-P loss (kg ha^{-1})		Total-K loss (kg ha^{-1})	
Mai Son	Fruit-maize-AF	Sole-maize	Fruit-maize-AF	Sole-maize	Fruit-maize-AF	Sole-maize	Fruit-maize-AF	Sole-maize
2017	202 (± 129)	239 (± 97)	19.1 (± 12.2)	22 (± 8.4)	4.5 (± 2.8)	4.9 (± 1.9)	43 (± 28)	45 (± 17.2)
2018	187 (± 86)	314 (± 48)	15.2 (± 6.7)	25 (± 3.7)	3.2 (± 1.3)	5.5 (± 0.8)	31 (± 13.5)	47 (± 9.3)
2019	28 (± 19.4)	55 (± 6.5)	2.7 (± 1.9)	4.3 (± 0.6)	0.5 (± 0.3)	0.8 (± 0.1)	3.7 (± 2.7)	8.8 (± 2.4)
2020	17.2 (± 6.3)	54 (± 11.4)	1.4 (± 0.5)	4.2 (± 0.9)	0.3 (± 0.1)	0.8 (± 0.2)	7.3 (± 2.9)	22 (± 4.9)
2021[a]	–	–	–	–	–	–	–	–
Tuan Giao	Fruit-coffee-AF	Sole-coffee	Fruit-coffee-AF	Sole-coffee	Fruit-coffee-AF	Sole-coffee	Fruit-coffee-AF	Sole-coffee
2017	1254 (± 365)	940 (± 322)	97 (± 30)	71 (± 27)	19.0 (± 5.6)	16.2 (± 6.6)	211 (± 53)	163 (± 49)
2018	2590 (± 360)	3214 (± 523)	188 (± 30)	230 (± 39)	38 (± 5.8)	50 (± 11.4)	522 (± 82)	665 (± 88)
2019	570 (± 149)	2030(± 316)	45 (± 12.8)	164 (± 29)	8.5 (± 2.3)	30 (± 4.9)	107 (± 32)	382 (± 40)
2020	158 (± 87)	727 (± 348)	9.4 (± 5.1)	54 (± 26)	1.6 (± 0.7)	9.1 (± 4.6)	100 (± 46)	641 (± 299)
2021[a]	–	–	–	–	–	–	–	–
By site	*p = 0.007*		*p = 0.01*		*p = 0.01*		*p = 0.005*	
By system	*p = 0.06*		*p = 0.06*		*p = 0.06*		*p = 0.06*	
System x year	*p = 0.005*		*p = 0.003*		*p = 0.01*		*p = 0.006*	
System x site	*p = 0.34*		*p = 0.40*		*p = 0.41*		*p = 0.42*	

[a] No SOC or nutrient losses due to no soil loss by erosion in the agroforestry and sole crops at Mai Son and Tuan Giao in 2021.

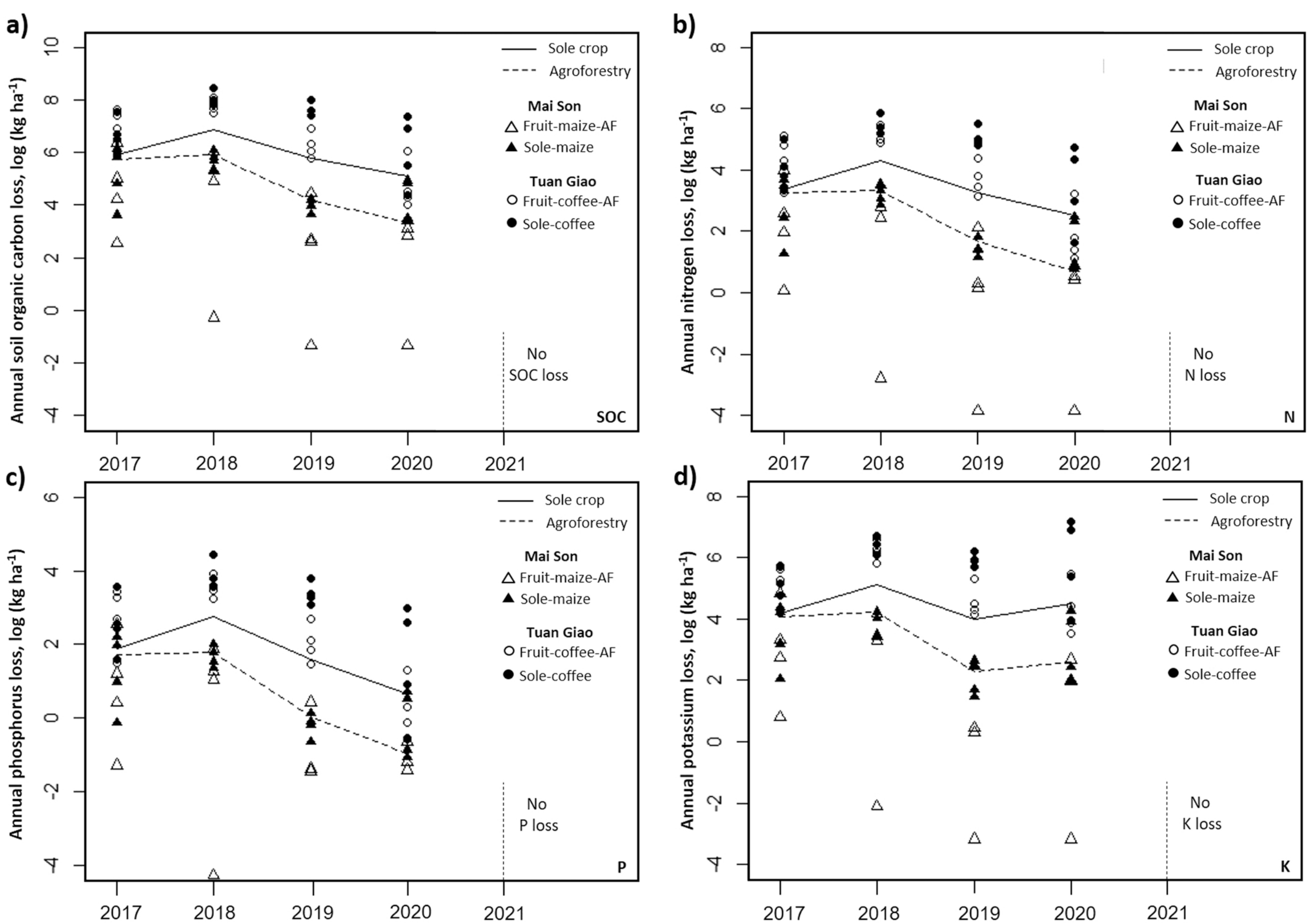

Fig. 9. Interaction plot for annual losses of (a) soil organic carbon (SOC), (b) nitrogen (N), (c) phosphorus (P) and (d) potassium (K) through soil erosion in fruit-maize-AF (longan-mango-maize-forage grass) and fruit-coffee-AF (son tra-coffee-forage grass) compared with sole-maize (sole-crop maize) and sole-coffee (sole-crop coffee), respectively, at the Mai Son and Tuan Giao sites. SOC and nutrient loss data were log-transformed.

Tuan Giao had much higher losses of SOC and nutrients than Mai Son in both the sole-crop and agroforestry systems (Table 5 and Fig. 9), reflecting the greater losses of bulk soil and the higher soil concentrations of SOC and K at that site. Accumulated SOC, N, P and K losses at Tuan Giao were 10, 9, 8 and 13 times higher, respectively, than those at Mai Son over the period 2017–2020.

4. Discussion

4.1. Sediment movement and terrace formation within agroforestry systems

The build-up of soil observed upslope of the grass strips and the loss of soil between and downslope of the grass strips clearly shows that sediment was moved within the two agroforestry systems evaluated in this study. These movements of sediment on steep slopes are probably associated with soil tillage operations (ploughing), weeding and rainwater flow entering the field from above (Rymshaw et al., 1997). However, guinea grass develops a deep, strong, dense and fibrous root system (Humphreys and Patridge, 1995), which has the ability to penetrate and bind soil particles and may also reinforce soil shear strength and increase soil surface roughness (Welle et al., 2006). As a result, the guinea grass strips in the two agroforestry systems in this study delayed downhill movement of sediment by retaining sediment (Kagabo et al., 2013) and facilitating terrace formation on steep slopes.

Measurements using erosion pins showed that progressive sedimentation of soil behind living guinea grass strips occurred within two years of establishment. This confirms previous findings that contour planting of grass strips plays a significant function in trapping sediment, contributing to terrace formation in sloping cultivation in e.g. Kenya (Owino and Ralph, 2002) and Ethiopia (Welle et al., 2006). However, those studies only examined sediment deposition upslope of grass strips planted along contours with annual crops in gently sloping fields (gradient 8–9%). The present study quantified the contribution of tree and grass strips to terrace formation in agroforestry on steeper slopes than in previous studies. Tuan Giao (the steeper site, gradient 56%) showed considerably greater soil losses (according to the soil traps, but not according to the erosion pins) than Son La (gradient 37%). Despite these losses, the terraces formed still captured considerable amounts of sediment that had been lost from between-row areas. Hence, the results show that grass strips can be a functional system component and induce terrace formation even on steep slopes.

The terraces formed in agroforestry by grass strips and trees planted along contour lines were characterised by progressive sedimentation behind living grass strips, but nearby trees may also help reinforce and stabilise terrace structures (Rutebuka et al., 2021). On steep slopes, such as those at the two experimental sites, terraces occasionally succumb (i.e. landslides occur), although that did not happen in the present study. The trees in agroforestry systems can be expected to stabilise terrace structure through their deep root systems, through increasing soil cover contributing to the canopy and litter layer, and through supplying organic matter from dead leaves, twigs and branches and living material from prunings falling to the ground (Atangana et al., 2014).

The importance of position on the slope was not investigated in the present study, but there are indications in the literature that hedgerows cause a skewed yield distribution along the slope, with lower yields in upper parts of the slope than farther down, due to breaks in the stability of the first rows of hedges (Garrity, 1996). Other limitations of this study are that weather data from existing climate stations was used, rather than the actual experimental sites, and that we assessed the effect of agroforestry systems on soil erosion, but water run-off was not monitored.

4.2. Soil and nutrient losses

The two agroforestry systems evaluated showed significant reductions in erosion-derived losses compared with the annual sole crops at the sites over the five-year study period. The vegetation cover ranged from 40% to 50% during the rainy season in both the fruit-maize-AF and fruit-coffee-AF systems, which could slightly reduce soil erosion, as reported by Zhou et al. (2008). From year 2, soil loss in both the agroforestry systems (fruit-maize-AF and fruit-coffee-AF) and sole-crop systems (sole-maize and sole-coffee) tended to decrease, but more rapidly for agroforestry than for sole crops. The vegetation cover was similar in the fruit-maize-AF and sole-maize systems during the maize growing season, but greater in fruit-coffee-AF than sole-coffee. It is likely that the grass strips (and trees) in fruit-maize-AF were responsible for much of the reduction in erosion at Mai Son, even in the early season of annual crops when the soil surface was bare due to tillage operations and after hand hoeing to control weeds. At Tuan Giao, the increased vegetation cover (Fig. 8b) might have mitigated soil loss in both systems, but the grass strips likely played a significant role in further reducing soil loss in fruit-coffee-AF. Thus well-established barriers such as natural terraces formed by grass strips and fruit trees can play a significant role in reducing soil and nutrient losses at an early stage after transition from sole annual crops to agroforestry.

A greater reduction in soil and nutrient losses due to soil erosion can probably be expected in mature agroforestry, when the trees have a larger canopy cover and the grass strips are more dense and stable. In this study, soil and nutrient losses from sole-crop systems showed a tendency to decrease over the study period. In sole-maize, this was probably because only one herbicide application was made and no hand hoeing was used for weed management during the maize growing season. Differences in total rainfall and in number of intense rainfall events between years might also have influenced the results. The year-round soil cover of coffee trees in the sole-coffee system protected the soil from rainfall-induced erosion better than annual crop cultivation, where the soil is left bare for parts of the year (Nzeyimana et al., 2017).

In 2021, no soil loss to the soil traps occurred in the agroforestry or sole crop systems at Mai Son or Tuan Giao. At Mai Son, this was probably due to the low total rainfall and very few high-intensity rainfall events during the period with good vegetation cover. The highest rainfall intensity (42 mm day^{-1}) in June occurred before maize planting time (Fig. 8a), when the experimental plots were covered with dense plant residues and weeds. In addition, the highest rainfall intensity in July and August (52 and 47 mm day^{-1}, respectively) occurred when the maize had 6–7 fully expanded leaves or was silking (Fig. 8a), and the vegetation cover at these stages was around 55% in both fruit-maize-AF and sole-maize. At Tuan Giao, the absence of soil loss to the soil traps could be further explained by the fact that the soil surface was less disturbed by using a strimmer instead of hoeing to manage weeds.

A meta-analysis by Muchane et al. (2020) of the impact of agroforestry systems on soil loss due to erosion in the humid and sub-humid tropics concluded that agroforestry can reduce soil erosion rates by about 50% compared with sole-crop cultivation. The findings in the present study are in line with previous findings for soil conservation measures in northwest Vietnam, e.g. Hoang Fagerström et al. (2002) found that *Tephrosia candida* (Roxb.) D.C. intercropped with upland rice (*Oryza sativa* L.) reduced soil loss by 49% compared with sole-crop upland rice. In a study combining maize with guinea grass strips, maize with minimum tillage and cover crop, and maize with minimum tillage and relay crop as conservation measures, soil loss was reduced by 27–84, 39–100 and 25–94%, respectively, compared with sole-crop maize (Tuan et al., 2014). In the present study, the grass (and tree) strips in the agroforestry systems obviously compensated for the high intensity of soil tillage in steep slope cultivation, as demonstrated by the gradual formation of terraces along the grass (and tree) strips over time.

Losses of SOC and nutrients (N, P, K) followed a similar pattern as loss of soil material, as also observed in other studies (e.g. Hombegowda et al., 2020). Erosion has the greatest impact on the surface soil horizon and since SOC fractions have lower density than soil mineral particles and the SOC concentration is higher in topsoil, there is preferential removal of SOC from surface layers during the erosion process (Lal, 2005). This appears to have been especially pronounced at the steeper site in this study (Tuan Giao), where the collected eroded soil had a high SOC concentration, indicating that crop residues were also preferentially lost. Furthermore, erosion prevents the formation of a stable soil-humus complex from soil organic matter accumulated during non-erosion periods. Therefore, much of the light fraction and particulate organic matter, which represent most of the unstable SOC fraction, can be expected to be lost through erosion. Nitrogen is an integral component of soil organic matter and is therefore lost simultaneously with SOC. Mineralised N is probably also lost, as it is highly soluble in water. However, loss of mineralised N was not determined in this study and, although likely to be considerably smaller than the loss of particulate total-N, it is important because of its immediate plant availability. Several studies world-wide have shown that various agroforestry practices play an important role in reducing SOC and nutrient losses compared with sole-crop cultivation (Hombegowda et al., 2020; Lenka et al., 2012; Zhu et al., 2020). The present study confirmed that agroforestry combining trees, crops and grass strips planted on contours leads to natural terrace formation on steeply sloping land, significantly reducing SOC and nutrient losses in comparison with sole crops.

4.3. *Weed management effects*

Tillage and manual hoeing for weed control increase soil detachment and loss (Ziegler et al., 2007). They also contribute to terrace formation along grass strips on steep slopes, as demonstrated in the present study, where soil surface tillage activities such as weed management by hand hoeing and slope gradient had a significant impact on the rate of soil deposition above the grass strips. The soil surface in fruit-maize-AF was affected by tillage three times per year, first by land preparation for maize planting and later by hand hoeing twice during the maize growing season. As a result, the rate of soil deposition above the grass strips in fruit-maize-AF was rather similar across the years (Fig. 5a). In fruit-coffee-AF, which had a higher slope gradient than fruit-maize-AF and used manual weeding by hand hoeing three times annually during years 1–3, the rate of soil deposition above grass strips was considerably higher during this period. When a strimmer was used to control weeds in fruit-coffee-AF (years 4–5), the rate of soil deposition above grass strips tended to decrease (Fig. 5b). In fruit-coffee-AF, the repeated weeding by hand hoeing led to large sediment movements, resulting in higher terraces and a greater volume of terrace formed than in fruit-maize-AF. The decrease in the initially high soil deposition above grass strips and the reduction in soil loss in the Tuan Giao experiment when weeds were controlled with the strimmer confirmed the importance of tillage/hand hoeing/mechanical weeding for soil erosion and the need for alternative management technologies. Many local farmers have in fact switched to using strimmers, providing evidence of the applicability of using machinery to control weeds in practice.

4.4. *Natural terrace formation for erosion management*

Although the agroforestry systems reduced soil losses on the steep slopes at the study sites, there was still sediment movement and some soil loss. This shows that on very steep slopes, agroforestry systems need to be complemented with other changes to farming practices, e.g. regarding tillage and weed management, and an understorey crop to provide year-around soil cover may be needed. Appropriate weed management seems to be key for a functioning system on steep slopes, to reduce soil and nutrient losses and promote terrace formation. Terrace formation in this study appeared to be accelerated by tillage, because it generated sediment movement. However, as the agroforestry systems developed, soil was gradually scoured from the downslope side of the grass strips (upper parts of the terraces) and accumulated on the upslope side of the grass strips (lower parts of the terraces). This probably caused spatial variation in soil quality and crop growth, likely resulting in higher crop yield and soil fertility in the lower parts of terraces than in the upper parts (Wolka et al., 2021). Although not considered in this study, adaptive management such as application of soil nutrients and organic matter to upper terrace parts may be needed.

In addition, the stability of natural terrace formation for erosion management in agroforestry is dependent on a variety factors, including e.g. density and height of the grasses or other vegetation that border the terraces, management of tree/crop components and tillage along contour lines (Ng et al., 2008; Van Dijk et al., 2003; Rutebuka et al., 2021). Therefore, an integrated approach to the development and long-term management of erosion control measures, including natural terrace formation in agroforestry, is recommended. Otherwise, inappropriately designed and managed terraces become ineffective in erosion control.

4.5. *Potential for upscaling fruit tree agroforestry and contour planting in upland areas of Southeast Asia*

In contrast to sole-crop systems, fruit tree agroforestry with grass strips significantly reduced soil and nutrient losses caused by soil erosion on the steep slopes at the two experimental sites. In addition to reducing soil and nutrient losses by forming natural terraces, agroforestry can also generate greater and more steady annual income than the sole-crop maize conventionally grown in the region (H. Do et al., 2020; V.H. Do et al., 2020). Well-established fruit tree agroforestry with grass strips can also offer fodder for livestock and reduce the labour requirement for finding/collecting feedstuffs (H. Do et al., 2020; V.H. Do et al., 2020; Tuan et al., 2014). Farmers can easily create grass strips along contour lines on steep slopes without using any special techniques, to aid in formation of natural terraces on their sloping fields. Guinea grass is drought-tolerant (Tuan et al., 2014) and performed well on the steep slopes and in the dry conditions at the experimental sites.

However, a number of factors influence the adoption of fruit tree agroforestry with grass strips as a soil conservation option in sloping areas, e.g. higher investment costs, an unstable market for agroforestry products and concern about intense resource competition among tree/crop components (trees, annual crops, grass) (H. Do et al., 2020; V.H. Do et al., 2020). Farmers often lack knowledge and expertise in soil conservation practices and agroforestry policy for the region is still ambiguous (Simelton et al., 2017).

Augmenting fruit tree agroforestry with grass strips to reduce erosion and soil fertility loss on sloping land will require financial support for investment and an improved product value chain, particularly in terms of market stability (V.H. Do et al., 2020; H. Do et al., 2020). In addition, the capacity of farmers and advisors to implement soil conservation techniques involving agroforestry must be developed and improved. At policy level, use of fruit tree agroforestry with grass strips as a soil conservation option needs to be flexibly integrated into land use plans for agriculture and forestry and into agricultural support programmes in the region.

Other smallholder farmers in Southeast Asia will likely face similar challenges in adopting agroforestry and decision makers in other countries in the region will likely encounter obstacles to supporting wider introduction of agroforestry across rural landscapes (Catacutan et al., 2018). There are already detailed guidelines on the principles and design of agroforestry with contour planting on sloping uplands (e.g. La et al., 2016; Xu et al., 2013) and also guidelines on supporting agroforestry development for stakeholders in Southeast Asia, including authorities and decision makers (Catacutan et al., 2018).

5. Conclusions

- In agroforestry with fruit trees, crops and fodder grass grown along contours, natural terraces are formed as a result of progressive deposition of soil sediment above grass strips and tree rows. In the fruit-maize-AF and fruit-coffee-AF agroforestry systems in this study, a terrace volume of 0.26 and 0.43 m^3 per metre of terrace, respectively, was recorded over the five-year study period.
- Soil erosion and nutrient losses occurred both in sole-crop and agroforestry plots during the five-year experiment. However, contour planting with fruit trees and fodder grass reduced soil and nutrient losses by 20–84% in comparison with sole crops.
- Terrace formation and soil and nutrient losses were influenced by rainfall intensity within and across years, and also by degree of

vegetation cover and tillage practices (especially the methods used for weed control).

- Field measurements demonstrated good ability of agroforestry and contour planting to form natural terraces as green infrastructure for soil conservation on steeply sloping uplands. In parallel, these systems produce agricultural products, generating income and ecosystem services such as agro-biodiversity.
- The approach of using agroforestry and contour planting to support natural terrace formation in order to reduce soil and nutrient losses and sustain soil fertility and productivity, as demonstrated in this study, needs to be encouraged in steeply sloping areas as a nature-based solution for soil conservation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2022.108323.

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