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Spatial and temporal variation in crop productivity and relation with soil fertility within upland agroforestry

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ABSTRACT

Agroforestry can be an option of sustainable farming practices for upland communities. However, information of spatial and temporal variation in soil fertility and crop productivity along slopes, which can guide e.g. effective management, such as application of fertilizers, is limited. This study evaluated spatial and temporal variability in crop productivity and soil fertility along slopes in two different fruit tree agroforestry systems in upland areas of north-west Vietnam: (1) longan-mango agroforestry integrating longan (*Dimocarpus longan* L.), mango (*Mangifera indica* L.), maize (*Zea mays* L.), and guinea grass (*Panicum maximum* Jacq.), and (2) plum agroforestry integrating plum (*Prunus salicina* L.), maize, and guinea grass. The two systems were established on relatively steep slopes, 37 % and 65 % slope, respectively. Crop performance and soil fertility were measured in different positions relative to the fruit tree-grass rows over 4–5 years and compared with sole-crop maize. The results showed that maize height, grain yield, and leaf nitrogen (N) concentrations were significantly higher at the upslope than downslope side of tree-grass rows. For example, the grain yields were 30–35 % higher at the upslope than downslope side. Regarding soil fertility, there was a tendency that SOC, total N, total phosphorus (P), available P, and available potassium (K) were higher at the upslope than downslope side of tree-grass rows. Thus, the forage grass strips played an important role in trapping N and other nutrients, and enhanced nutrient use efficiency within agroforestry at the steeply sloping study sites. The maize performance and soil fertility in the areas midway between two tree-grass rows were comparable to those in sole-crop maize. The results of this study can provide guidance for farmers managing fruit tree agroforestry in north-west Vietnam or other regions with similar cropping, climate, and biophysical characteristics to implement more effective plot management practices on sloping land.

1. Introduction

Agroforestry is defined as a land use system where perennials are grown on the same land unit as agricultural crops and/or where livestock are kept (Gordon et al., 2018). Agroforestry has long been recognized as a more sustainable way to produce food and other products and services than agriculture based on sole-crop cultivation of annual crops (Young, 1989). Agroforestry can thereby increase crop yield, enhance soil productivity, increase income for farmers, and contribute to food security and poverty reduction (Catacutan et al., 2017; Kuyah et al., 2019). In addition, agroforestry can reduce losses of soil, soil organic carbon (SOC), and nutrients compared with sole-crop cultivation (Atangana et al., 2014; Do et al., 2023; Muchane et al., 2020; Zhu et al., 2020). It can also contribute significantly to climate change adaptation and mitigation by providing resilience to extreme weather events (Montagnini and Nair, 2004; Nguyen et al., 2013; Ramachandran Nair et al., 2010).

Agroforestry systems differ in the density and arrangement of trees, ranging from a few scattered trees or line plantings to dense and intricate agroforests (Sinclair, 1999). Agroforestry exhibits natural heterogeneity in terms of the productivity of the trees and crops grown, soil fertility, and the nutrients available to plants, depending on the plant

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components used, system design, and tree and crop management techniques. This heterogeneity is likely due in part to competition between all tree and crop components and weeds (Malézieux et al., 2009). System design, tree/crop combination, and the spatial arrangement of the individual components have direct impacts on the performance and interactions of both trees and crops, and are key factors in determining the resource use efficiency of agroforestry systems (Nyaga et al., 2019). Determining the spatial variability in tree/crop performance and soil fertility within agroforestry is therefore essential for overall assessment of agroforestry performance and for revealing the complex interactions between trees and associated crops (Wengert et al., 2021). Knowledge of spatial variability is also key to managing agroforestry, with direct impacts on system productivity, provision of ecosystem services, and capacity to mitigate and adapt to climate change (Roupsard et al., 2020). In addition, understanding spatial variability in soil properties is essential to support land management decisions (Takoutsing et al., 2017).

Resource availability can vary more widely in agroforestry on steep slopes than in corresponding systems on flat terrain, due to the impact of slope on soil erosion, surface run-off, and plant-available water and sunlight (Garrity, 1996). Agroforestry systems on sloping land commonly involve growing annual crops between perennial shrub hedgerows planted along contour lines (Catacutan et al., 2017). In such systems, terraces progressively develop on steep slopes between two consecutive living hedgerows, due to soil translocation by tillage or erosion from upper to lower elevations, and hedgerows are thus often employed as soil conservation measures on steeply sloping land (Do et al., 2023; Quine et al., 1999; Tengberg et al., 1998; Turkelboom et al., 1997). In these so-called alley systems, the living hedgerows act as vegetative barriers that play a key function in preventing soil erosion, capturing nutrients lost from the slope above, and increasing fertility above the strips. Studies on alley systems, where annual crops are planted along contours with trees or grass strips, have shown that topsoil movement from upper to lower parts of the alley is the principal cause of spatial variation in soil nutrient concentrations, soil water availability, and crop yield along the slope direction (Caulfield et al., 2020; Dercon et al., 2006; Garrity, 1999, 1996; Guto et al., 2012; Niang et al., 1997). However, the degree of resource variability in agroforestry on steep slopes is also highly dependent on the type of trees/crops grown and their management, with more complex variations as systems incorporate more tree/crop components.

Previous research on spatial variation in crop performance and soil characteristics has found that the direction of tree rows and wind influence the symmetrical effects of fruit trees on crops and soil (Bellow et al., 2008; Cardinael et al., 2015; Gao et al., 2013; Guillot et al., 2021; Pardon et al., 2020; Qiao et al., 2019; Wei et al., 2024; Yang et al., 2016). However, these studies were carried out without grass strips and slope, which affect the spatial flow of resources. On sloping land, grass strips have been shown to play a significant role in reducing soil and nutrient losses on sloping land, through formation of natural terraces (Caulfield et al., 2020; Do et al., 2023) and to be an important contribution of fodder grass to smallholder farmers (Do et al., 2020). Furthermore, there has been little research on the spatial variation in crop performance and soil characteristics in agroforestry systems on steep slopes that include fruit trees, grass strips, and crops, as well as on resource competition between fodder grass and associated tree and crop components in agroforestry. Such knowledge is needed to identify how resources can be used more effectively in agroforestry on steep slopes.

The overall aim of this study was to increase knowledge of the importance of spatial and temporal variability in crop (maize) performance and its relation to soil fertility in complex agroforestry systems with fruit trees, fodder grass, and crops grown along contours on sloping land, to enable more efficient system management and improve productivity. The following research questions were addressed:

- What is the spatial and temporal impact of fruit trees and grass strips on maize growth, leaf N concentration and yield?
- Are there spatial and temporal differences in impact of fruit trees on grass height, leaf N concentration and yield depending on tree species?
- What is the spatial impact of fruit trees and grass strips on soil fertility along the slope after 4–5 years of agroforestry?
- Does agroforestry reduce yields of maize compared to sole cropping?

These questions were studied in two on-farm agroforestry experiments in sloping areas of north-west Vietnam, comprising (i) longan (*Dimocarpus longan* L.), mango (*Mangifera indica* L.), maize (*Zea mays* L.), and guinea grass (*Panicum maximum* Jacq.) and (ii) plum (*Prunus salicina* L.), maize, and guinea grass, which were compared with sole-crop maize.

2. Materials and methods

2.1. Study sites

Field experiments were established in Mai Son District (21.10°N, 104.06°E; 566 m a.s.l) in Son La Province and Tram Tau District (21.31°N, 104.21°E; 938 m a.s.l) in Yen Bai Province, Vietnam (Fig. 1). At both sites, the rainy season lasts from April to October, and the dry season is from November to March. The cumulative daily rainfall for the five cropping seasons (from planting to harvest) in Mai Son is presented in Fig. 2. The cultivation history of the field site in Mai Son is described in Do et al. (2023), but annual crops had been grown for more than 30 years. Mean annual temperature at that site is 21.5 °C and annual rainfall is 1200–1600 mm. The geography of Tram Tau is characterized by high mountains and deep ravines, with average altitude of around 800 m a.s.l. At the field site, shifting cultivation was practised before 1996, with crops planted for one year and the field left fallow for 2–3 years before a new crop was planted. Cassava, upland rice, and maize were rotated from 1996 to 2008, and maize was monocropped from 2009 until the field experiment was established. In Tram Tau, annual rainfall is 1800–2000 mm and mean annual temperature is 20 °C, but the temperature sometimes falls to 0 °C in winter (Hoang et al., 2023; Yen Bai Portal, 2019).

Based on soil profile description and characterization carried out before the field trials, the soils were classified as Acrisols (Table 1). The topsoil texture was found to be loam in Mai Son and silty loam in Tram Tau, with a higher clay content in the B-horizon at both sites (Table 1). The soil in Tram Tau had no stones, whereas the soil in Mai Son was slightly stony. Soil bulk density was relatively high at the Mai Son site, especially in the BC horizon, while it was in the optimum range in Tram Tau. Topsoil soil organic carbon (SOC) content was 1.8 % at both sites. Based on soil pH (1 M KCl) measurements, the topsoil in Mai Son was more acidic than that in Tram Tau. At the time of sampling, available P in the topsoil was just above 0.6 and 0.1 mg 100 g^{-1} in Mai Son and Tram Tau, respectively, while available K in the topsoil was 7.6 mg 100 g^{-1} and 2.6 mg 100 g^{-1}, respectively. At both sites, the concentrations of available P and K were relatively low according to the rating scale for soil nutrients in agricultural soils in Vietnam (Tran and Bui, n.d.).

2.2. Experimental design

It was not possible to find fields that were fully homogeneous, since they varied in slope, orientation, and soil conditions, but by applying a block design the heterogeneity was accounted for as far as possible. The experiments were laid out in a randomized complete block design (Fig. 3), with four replicates and two treatments (agroforestry and continuous sole-crop maize). Changes were evaluated over a five-year period (2017–2021) in Mai Son and a four-year period (2018–2021) in Tram Tau.

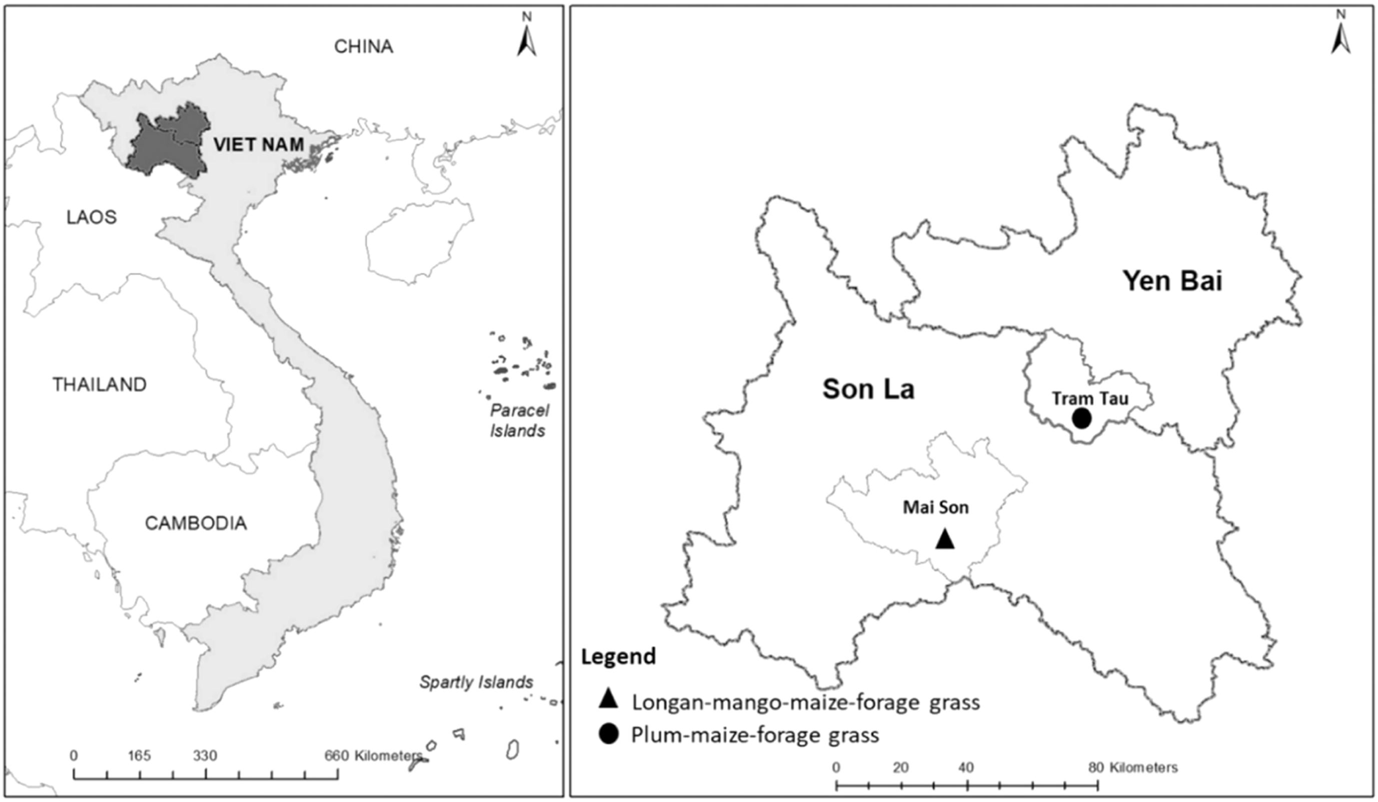

Fig. 1. Location of the agroforestry experiments with longan-mango-maize-forage grass in Mai Son District, Son La Province, and plum-maize-forage grass in Tram Tau District, Yen Bai Province, north-west Vietnam.

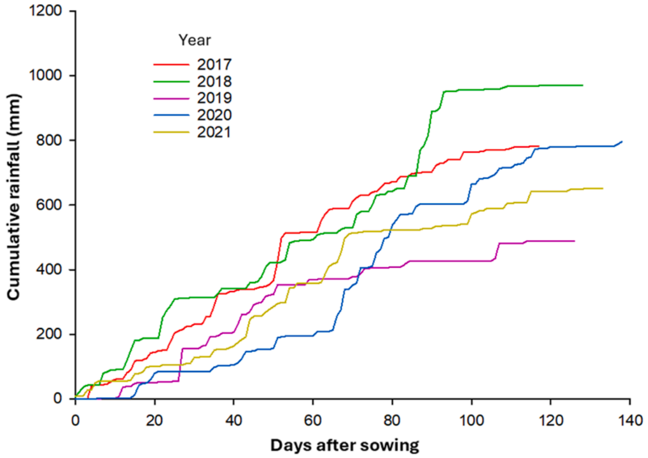

Fig. 2. Cumulative daily rainfall in Mai Son during five cropping seasons (from planting to harvest). In 2017, 2018, 2019, 2020, and 2021, the planting and harvesting dates were: 15 June and 9 October, 3 June and 8 October, 20 June and 23 October, 30 May and 15 October, and 9 June and 19 October, respectively.

Mean slope at the experimental site was 37 % in Mai Son and 65 % in Tram Tau. There were differences in slope gradient between the experimental blocks. In Mai Son, the slope gradients in blocks 2 and 3 were similar and significantly higher than in blocks 1 and 4, while the slope was steeper in block 4 than in block 1 (Table 2). In Tram Tau, blocks 2 and 4 had similar slope gradients, steeper than in blocks 3 and 1.

2.3. Experimental management

The experiments were established in June 2017 in Mai Son and in September 2018 in Tram Tau. The agroforestry treatments of longan-mango-maize-forage grass (guinea) (longan-mango-maize-AF) (Fig. 4a) in Mai Son and plum-maize-forage grass (guinea) (plum-maize-AF) (Fig. 4b) in Tram Tau were compared with cultivation of maize as a sole crop (SM) as control.

In the longan-mango-maize-AF system in Mai Son, the longan and mango trees were planted in alternating 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. 4a). Full details of the experimental design in Mai Son can be found in Do et al. (2023).

In the plum-maize-AF system in Tram Tau, the plum trees were planted with 4.0 m spacing between trees within rows and 10 m spacing between rows (250 tree ha^{-1}) (Fig. 4b). Guinea grass was planted in double rows 1 m below the trees, with a spacing of 0.5 m between the two grass rows. For SM, maize seed rate, row spacing, and distance between seeds was 15 kg ha^{-1}, 0.65 m, and 0.3 m, respectively. Maize seeds were sown with the same row spacing and within row spacing in both treatments and at both sites, with the distance to above the grass strips and outside the canopy of the fruit trees kept to 0.8 m and 0.5 m, respectively. The experiment in Tram Tau was established late in the growing season in 2018, and hence maize was sown from year 2 onwards, on 15, 20, and 24 % less land in plum-maize-AF than in SM in years 2, 3 and 4, respectively, because of expansion of the tree canopy.

A grafted mango variety (GL4) and a grafted late-maturing longan variety (PHM-99–1–1) were used in longan-mango-maize-AF, while a grafted plum variety (Tam Hoa) was used in plum-maize-AF. Forage guinea grass (Mombasa) and the hybrid PAC 999 maize variety were used in all treatments. All crops were established along contour lines.

The nutrients applied were adjusted to the crops (Table 3) and several fertilizer types were used (Table S2 in SI). At both sites, the

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

Sites	Hz	Depth [cm]	SC [%]	BD [g cm^{-3}]	pH [KCl]	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	Ap	0–17	10	1.37	4.2	1.78	0.15	0.03	0.31	0.64	7.6	15	18	40	36	6
	B1	17–36	2	1.35	4.0	0.97	0.13	0.02	0.29	0.14	3.8	11	36	28	32	4
	B2	36–56	6	1.32	3.9	0.81	0.14	0.02	0.34	0.08	3.4	16	42	22	31	5
	BC	56-	9	1.56	4.0	0.38	0.09	0.02	0.29	0.06	2.2	11	25	15	36	24
Tram Tau	Ap	0–18	0	1.18	4.2	1.76	0.15	0.07	0.10	0.14	2.6	13	16	33	45	6
	B1	18–40	0	1.01	4.3	0.81	0.10	0.04	0.07	0.07	1.4	14	49	19	29	3
	B2	40–80	0	1.07	5.3	0.69	0.07	0.05	0.08	0.06	1.0	14	50	17	29	3
	B3	80-	0	1.08	5.4	0.52	0.09	0.05	0.08	0.04	1.0	14	54	15	28	3

SC: stone content, BD: bulk density, pH (soil: 1 M KCl ratio 1:5-TCVN: 4401, 1987), 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).

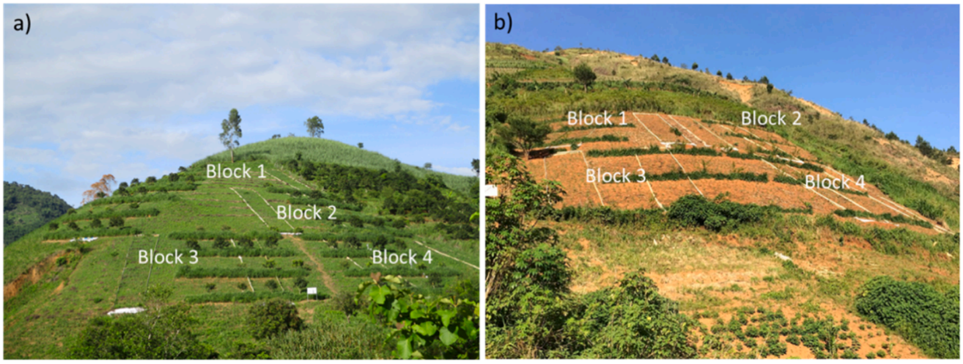

Fig. 3. Field experimental layout. (a) In Mai Son District (21.10°N, 104.06°E; 566 m a.s.l) in Son La Province, where agroforestry treatment plots included longan, mango, maize, and forage grass, with sole-crop maize plots as control. (b) In Tram Tau District (21.31°N, 104.21°E; 938 m a.s.l) in Yen Bai Province, where agroforestry treatment plots included plum, maize, and forage grass, with sole-crop maize plots as control.

Table 2
Slope gradient differences in blocks within the experiments in Mai Son and Tram Tau (values are mean ± standard error), different letters indicate significant differences ($p<0.05$).

Block	Mai Son (n=32)	Tram Tau (n=24)
Block 1	28.1 (±0.8)c	62.8 (±1.5)b
Block 2	39.9 (±0.4)a	68.7 (±2.3)a
Block 3	41.4 (±0.6)a	59.9 (±2.3)b
Block 4	37.6 (±0.3)b	69.2 (±2.0)a
Mean	37.0 (±3.0)	65.0 (±2.3)

At both sites, soil organic carbon (SOC) content was similar between blocks, while other parameters showed some variation (Table S1 in Supplementary Information (SI)).

differences in the amount of NPK between sole-crop maize and agroforestry were caused by the fact that sole-crop maize systems applied the same quantity of NPK each year. Meanwhile, in agroforestry, the areas for maize reduced as tree canopy expanded over time, so although the NPK per maize area remained the same the total amount of NPK for maize decreased. At the same time, more NPK was applied to the fruit trees as trees increased in size and nutrient demand during the experimental period. Therefore, the amount of N, P, and K applied to maize in longan-mango-maize-AF and plum-maize-AF was 15–22 % and 15–24 % lower than in SM, respectively.

The longan and mango trees received composted animal manure (15 kg tree^{-1}) in the first year and thereafter chemical fertilizers (NPK), microbial fertilizers, and micronutrients annually. Full details of fertilizers applied to the fruit trees in Mai Son can be found in Do et al. (2023). In Tram Tau, each plum tree received the same amount of composted animal manure (15 kg tree^{-1} in year 1) and microbial fertilizer (0.5 kg tree^{-1} in year 2 and 2.5 kg tree^{-1} annually in years 3–4). The mineral fertilizer supplied close to the plum trees provided the following amounts of N, P, and K as calculated per total plot area: 6, 12, and 4 kg ha^{-1} in year 1; 16, 6, and 12 kg ha^{-1} in years 2–3; and 32, 24, and 26 kg ha^{-1} in year 4. No calcium (Ca), magnesium (Mg), or micronutrients were applied.

In year 1, composted animal manure was used as the basal fertilizer to the fruit trees, but in later years, microbial fertilizer (Table 3) was employed to replace composted animal manure. Compost and microbial fertilizer were applied with the aim to increase the humus content of the soil by supplying more organic matter, making the soil more porous, and helping the root system of fruit trees to develop and absorb nutrients. In the microbial fertilizer, *Bacillus* sp. bacterium increases the availability of nutrients in the plant rhizospheres (Radhakrishnan et al., 2017) while the fungus *Trichoderma* sp. can counteract environment caused by agrochemical contamination, induce plant growth, increase plant resilience, and improve nutrient utilization efficiency (Yao et al., 2023).

At both sites, the purpose of planting grass strips was to utilize nutrients in runoff to produce fodder, while preventing soil erosion. Therefore, no nutrients were applied to the forage grass.

Weed management in the agroforestry and sole-crop systems was adjusted to the needs of the different systems and followed local practice at both sites. Weeds were hoed by hand before sowing maize in both systems in all years. In Mai Son, in year 1 the longan-mango-maize-AF and SM treatments both received one herbicide application (active ingredient: atrazine 800 g kg^{-1} + additives: 200 g kg^{-1}, dose 2 kg ha^{-1})

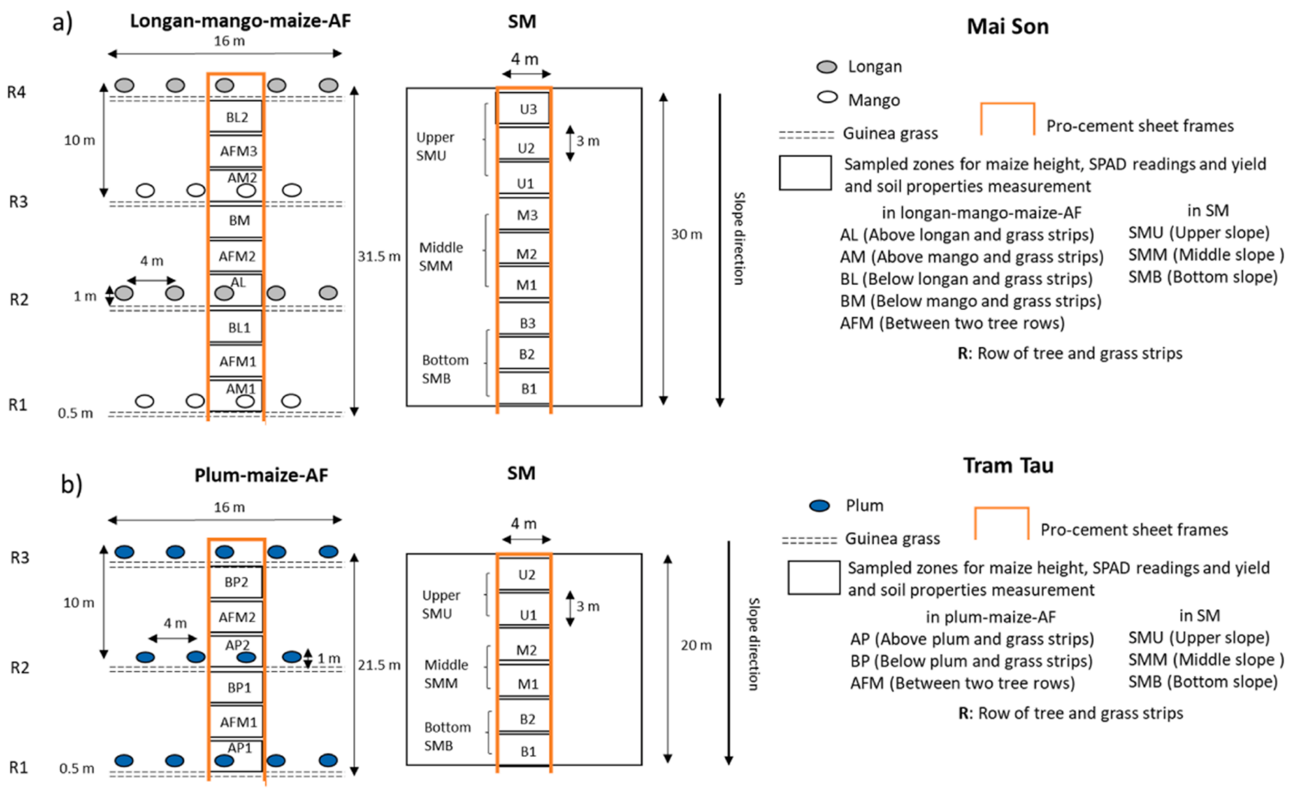

Fig. 4. Design of field experiments. (a) At Mai Son: longan-mango-maize-forage grass (longan-mango-maize-AF) and sole-crop maize (SM), with plot area 504 and 480 m^2, respectively. (b) At Tram Tau: plum-maize-forage grass (plum-maize-AF) and sole-crop maize (SM), with plot area 344 and 320 m^2, respectively.

Table 3

Nutrients supplied as chemical fertilizers and amounts of amendments applied in the sole-crop maize and agroforestry treatments at the Mai Son and Tram Tau sites during the study years. The fertilizers were applied to the respective crops, but amounts were calculated based on the whole plot area, explaining the differences in fertilizer doses between SM and agroforestry.

Mineral fertilizer and amendment dose (kg^{-1} ha^{-1})							
			Amount of nutrient or amendment[b]				
Site	Cropping system[a]	Nutrient or amendment	2017	2018	2019	2020	2021
Mai Son	SM	N	160	160	160	160	160
		P	60	60	60	60	60
		K	76	76	76	76	76
	Longan-mango-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	0.11	0.11
		Composted animal manure	3750	0	0	0	0
		Microbial fertilizer[d]	0	125	625	625	625
Tram Tau[c]	SM	N	na		160	160	160
		P	na		60	60	60
		K	na		76	76	76
	Plum-maize-AF	N	na	6	151	143	153
		P	na	13	57	54	58
		K	na	4	76	72	80
		Composted animal manure[d]	na	3750	0	0	0
		Microbial fertilizer	na	0	125	625	625

[a] Sole-crop maize (SM) in Mai Son and Tram Tau; longan-mango-maize-forage grass (longan-mango-maize-AF) in Mai Son and plum-maize-forage grass (plum-maize-AF) in Tram Tau

[b] Details of fertilizer types used in the experiments in each year are provided in Table S2 in SI

[c] Maize was not sown in Tram Tau in 2018. na: not applicable, since the experiment was established in 2018.

[d] Microbial fertilizer (15 % organic matter, Bacillus sp. 1 ×10^6 CFU g^{-1}, Trichoderma sp. 1 ×10^6 CFU g^{-1}, pH_{H2O} = 5.0 and 30 % moisture).

when the maize had 3–4 fully expanded leaves. In years 2–5, weeds were controlled by two hand hoeings in longan-mango-maize-AF, when the maize had 3–4 and 10–11 fully expanded leaves, respectively, and by herbicide (the same as in year 1) in SM at 3–4 fully expanded leaves. In Tram Tau, the weed management regime was similar to that in years 2–5 in Mai Son. Herbicide was generally not used in the agroforestry plots, to avoid damage to the trees and to follow local practice, while it was used in SM to avoid unrealistic soil losses (caused by hand hoeing) compared with local practice. Thus, more tillage was applied in longan-mango-maize-AF and plum-maize-AF than in SM to reflect differences in management practice. Crop residues from the previous season and slashed weeds were left on the ground in all agroforestry and SM treatments.

2.4. *Data collection*

In Mai Son, an area of 4.0 m x 31.5 m and 4.0 m x 30 m was used for sampling and measurements in longan-mango-maize-AF and SM, respectively, while in Tram Tau an area of 4.0 m x 21.5 m and 4.0 m x 20 m was used for plum-maize-AF and SM, respectively (Fig. 4). To prevent soil and water from entering the sampling and measurement areas, as well as soil erosion and water runoff from higher grounds entering the plots, which could affect the sampling area, cement sheet frames (30 cm high) were installed at all but the lower side of each such area.

2.4.1. *Spatial and temporal variability in maize height and leaf N concentrations*

Spatial and temporal variations in maize growth and leaf N concentrations (using chlorophyll as a proxy) were measured in four maize growing seasons in Mai Son (2018–2021) and in three (2019–2021) in Tram Tau. Within the agroforestry plots, maize height and maize leaf N concentrations were measured in 12 m^2 zones at three positions relative to the tree and grass rows. These zones were areas with sown maize 0–3 m above the upper grass rows, 0–3 m below the lower grass rows and between two tree rows, i.e. 3–6 m above and below grass strips at both sites (Figs. 4a and 4b).

Within each longan-mango-maize-AF plot in Mai Son, there were three sampling zones for positions between two tree rows (AFM), two sampling zones for above mango and grass strips (above mango, AM) and one sampling zone downslope of grass strips under mango (below mango, BM). There was also one sampling zone above longan and grass strips (above longan, AL) and two sampling zones downslope of grass strips under longan (below longan, BL) (Fig. 4a). In Tram Tau, there were two sampling zones for each position between two tree rows (AFM), above plum and grass strips (above plum, AP) and downslope of grass strips under plum (below plum, BP), respectively (Fig. 4b). In SM, the sampling zones corresponded to three positions along the slope (bottom slope (SMB), middle slope (SMM), and upper slope (SMU), to identify potential differences due to the slope. Nine and six zones were sampled in each SM plot per measurement occasion in Mai Son and Tram Tau, respectively (Fig. 4).

Maize leaf N concentration was monitored using a soil plant analysis development (SPAD) 502 Plus chlorophyll meter (Minolta, 1989) to determine the amount of chlorophyll present in plant leaves. SPAD readings and maize plant height measurements were carried out in each zone of both agroforestry and SM at four vegetative stages of the maize crop (3–4, 6–7, and 10–11 fully expanded leaves, and silking, represented by the third, sixth, ninth, and index leaves, respectively). In each zone in both agroforestry and SM, measurements were made on five maize plants along a diagonal on each occasion. The SPAD readings were taken at two-thirds of the distance from the leaf tip towards the stem (Argenta et al., 2004).

2.4.2. *Spatial and temporal variability in maize yield*

Spatial and temporal variation in maize yield was measured during four and three maize growing seasons in Mai Son (2018–2021) and Tram Tau (2019–2021), respectively. Within the agroforestry plots, maize yield (grain and stover) was measured in the zones described in Section 2.4.1. Maize yield at the measurement positions in agroforestry plots was determined by whole area and by actual maize area. In both longan-mango-maize-AF and plum-maize-AF, yield was thus determined in an area of 12 m^2 for each zone (Figs. 4a and 4b). The actual maize area in zones above tree and grass strips at both sites was determined annually by subtracting the area occupied by trees from total zone area. Maize yield per unit actual maize area was then calculated. In SM, maize stover and grain were harvested in a 12 m^2 area in each zone in both Mai Son and Tram Tau (Figs. 4a and 4b).

Maize was harvested at physiological maturity and above-ground biomass was separated into stover (stems, leaves, cobs, and sheaths) and grain, and weighed to determine their fresh weight. Fresh subsamples of these materials were weighed and dried to constant weight. The ratio of fresh to dry weight was determined and used to calculate the total harvested dry weight of each material.

Harvest index (HI), i.e., the ratio of grain yield to total above-ground biomass at physiological maturity (Kawano, 1990), was calculated as:

$$HI = Y/B \tag{1}$$

where Y is maize grain yield and B is above-ground biomass including maize grain and stover (stems, leaves, sheaths, and maize cobs).

2.4.3. *Grass growth, grass leaf N concentration, biomass yield, and tree growth*

In Mai Son, forage grass growth and leaf N concentration were evaluated in four growing seasons (2018–2021) and grass biomass yield was quantified in five growing seasons (2017–2021). In Tram Tau, grass growth, leaf N concentration, and biomass yield were quantified in three growing seasons (2019–2021). Grass SPAD readings were carried out on 10 new fully expanded leaves (Viana et al., 2014) and height measurements were made on 10 grass plants every month in a 4-m section of each grass strip before cutting. Fresh biomass of forage grass under different fruit trees was measured during the maize growing season by harvesting a 4-m section of each grass strip per plot and weighing the biomass. During the growing season, forage grass was in most cases harvested every 30–40 days, but in a few cases the time span between harvests was shorter or longer. Forage grass in longan-mango-maize-AF was harvested on three occasions in year 1, on six occasions per year in years 2–4, and on seven occasions in year 5, while forage grass in plum-maize-AF was harvested on five, five, and six occasions in year 2, 3, and 4, respectively.

In both longan-mango-maize-AF and plum-maize-AF, the fruit trees were measured every three months during the whole experimental period, to determine base diameter 10 cm above the soil surface, canopy diameter, and plant height. These tree growth measurements were carried out within the areas also used for maize measurements and sampling in each plot (Figs. 4a and 4b).

2.4.4. *Spatial variability in soil organic carbon and nutrients*

Soil samples were collected on two occasions at the end of the maize growing season in both systems (Mai Son in 2018 and 2021, Tram Tau in 2019 and 2021). The soil samples were taken in the same zones as the maize measurements, except in the zones above tree row 1 and below grass row 4 in longan-mango-maize-AF (Fig. 4a) and the zones above tree row 1 and below grass row 3 in plum-maize-AF (Fig. 4b). Soil samples were taken in nine zones in each SM plot per sampling occasion in Mai Son (Fig. 4a) and in six zones in Tram Tau (Fig. 4b).

Topsoil samples were taken from two layers: 0–10 and 10–20 cm depth. In each sampling zone, one composite soil sample representing each soil depth was taken from 11 sampling points (Fig. 5).

To reduce the number of soil samples, samples from zones between two tree rows (AFM) were pooled into one sample per plot representing the AFM position. In each SM plot, soil samples from upper, middle, and bottom zones were pooled into three homogenized samples representing upper slope (SMU), middle slope (SMM), and bottom slope (SMB), respectively, of each plot, (Figs. 4a and 4b). The pooling process was performed separately for each soil layer.

The soil samples were analyzed for SOC, total-N, total-P, total-K, pH (KCl), available P, and available K using methods listed below Table 1.

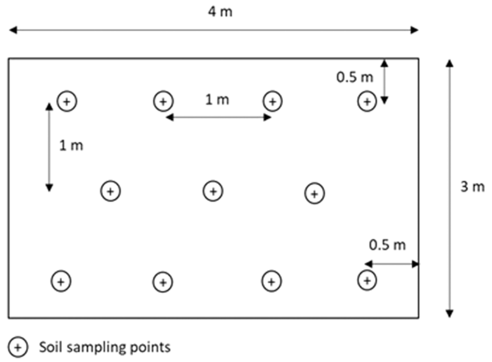

Fig. 5. Soil sampling points within one sampling zone in agroforestry and sole-crop maize in both the Mai Son and Tram Tau experiments.

2.5. Data analysis

The software R (version 3.6.1) was used for all statistical analyses. In all model analyses (see Table S3 in SI for all statistical model analyses), except for the guinea grass SPAD values, all data had a non-normal distribution and were normalized by log-transformation. In all ANOVA models, Tukey's HSD test was used to find means that were significantly ($p<0.05$) different from each other. In all repeated measures ANOVA with the mixed models was used. When a significant difference was indicated in the F-tests, estimated marginal means (emmeans) were used to identify significant ($p<0.05$) differences between means.

3. Results

3.1. Spatial and temporal variability in maize performance and yield

3.1.1. Spatial and temporal variability in maize growth and leaf N concentration

The fruit tree lines and grass strips were repeated along the slope (Fig. 4), but there were no significant difference in maize performance (3.1.1) (Figs. S1-S3, see Table S4 in SI for p-values) and yield (3.1.2), at the same position relative to the tree lines and grass strips, in the lower, middle or upper part of the slope. Therefore, we focused further analyses on the maize performance and yield (3.1.2) relative to the tree rows and grass strips and not the location along the slope.

In the longan-mango-maize-AF system, maize height and SPAD values were, on average, higher in positions above the longan (AL) and mango tree-grass rows (AM) and between two tree rows (AFM) than below longan (BL) and mango tree-grass rows (BM) (Figs. 6a1 and 6a2, see Table S5 in SI for p-values). These differences were particularly evident in the last two years. Maize height and SPAD values were similar below longan-grass rows (BL) as below mango-grass rows (BM). Maize height and SPAD values differed between years, but there were no general trends over time (Figs. 6a3 and 6a4, Table S5).

It was apparent that the maize plants was taller between (AFM) and above (AL, AM) the tree-grass rows than below the tree-grass rows (BM, BL) already when maize had 3–4 fully expanded leaves, but the effect was larger at later development stages causing a significant interaction (Fig. 6a6, Table S5). For SPAD the differences between locations became significant when maize had 6–7 leaves (Fig. 6a5).

In plum-maize-AF system, maize height was similar above and below plum tree-grass rows (AP, BP), but greater between two tree rows (AFM) (Fig. 6b2, Table S5). The SPAD values were overall highest in AFM, followed by AP, and lowest in BP (Fig. 6b1, Table S5).

Maize height in AP, AFM and BP was similar from 2019 to 2021 (Fig. 6b4, Table S5). There was, however, an interactive effect of position in relation to tree-grass rows and year on maize SPAD values (Fig. 6b3, Table S5). In 2019, SPAD values were highest in AFM, and similar in AP and BP, but in 2020, the values in AP were similar to in AFM and higher than that in BP. However, in 2021, all positions had comparable SPAD values.

There was an interactive effect of position relative to tree-grass rows and maize growth stage on maize height and SPAD values (Figs. 6b6 and 6b5, Table S5). Maize height and SPAD values were similar in all positions at stage 3–4 fully expanded leaves. Maize height was similar in AFM and AP, which were higher than in BP for all other stages. At 6–7 fully expanded leaves, maize SPAD values were highest in AFM, whereas at 10–11 fully expanded leaves, maize SPAD values were similar in AP and in AFM, and lower in BP. The SPAD values were similar in all positions at silking.

3.1.2. Spatial and temporal variability in maize yield

The maize yield in Mai Son did not differ significantly depending on where on the slope within plots that the zones above mango, below longan, or between two tree rows were positioned (Figs. S7-S9; Table S6 in SI for p-values). In Tram Tau, yields just below and above plum trees did not differ depending on position on the slope, but in 2021 yields were higher between tree rows in the bottom part of the plots than in the upper parts of the plots, causing a significant interaction between year and location (Figs. S7–9, Table S6).

When considering the whole system area of the longan-mango-maize-AF system, average maize grain and stover yield between two tree rows was approximately 41 and 36 % higher than the average yield of positions just above or below tree-grass rows (Figs. 7a and 7c, see Table S7 in SI for p-values). When only considering the actual area of maize, the yield of maize above the tree-grass rows was similar to that between two tree rows and significantly higher than below tree-grass rows (grain: Fig. 7b, Table S7 in SI; stover: Fig. 7d, Table S7). There was no interaction between position relative to grass and tree rows and year on maize grain and stover yield by both whole and actual maize area in the longan-mango-maize-AF system.

In plum-maize-AF, in terms of whole area, maize grain and stover yield in positions between two tree rows (AFM) and below tree-grass rows (BP) was around 33 and 42 % higher in compared with those in positions above tree-grass rows (AP) (Figs. 7e and 7g, Table S7). In terms of actual maize area, only maize stover yield was affected by position relative to tree-grass rows, with significantly higher yield in AP than BP (Fig. 7h, Table S7). There was also an interaction between position relative to grass and tree rows and year on maize grain and stover yield by both whole and actual maize area. By whole area, maize grain yield and stover yield were greater in AFM than in other positions in 2020 and also tended to be greater in AFM and BP than in AP in 2019 and 2021 (Figs. 7e and 7g, Table S7). By actual maize area, the grain yield was greater in AFM and AP than in BP in 2020–2021, and the stover production was greater there in 2020 (Figs. 7f and 7h, Table S7).

In longan-mango-maize-AF, maize HI was similar in 2018 and 2019 (around 0.55) and decreased over time to around 0.48 in 2020–2021. There was a significant interactive effect ($p<0.05$) of position within longan-mango-maize-AF and year on maize HI (Fig. 8a, see Table S8 in SI for p-values). Maize HI was similar in all positions in 2018, 2019 and 2021, but maize HI in BL and BM was lower than in AL and AM in 2020. Maize HI in AFM was lower in 2021 than in 2018–2019 and that in AM was lower in 2021 than in 2018. Maize HI in AL remained constant between 2018 and 2021. In plum-maize-AF, the greatest maize HI was recorded in 2020 (0.55), followed by 2019 (0.47) and 2021 (0.45) (Fig. 8b, Table S8).

3.2. Height, leaf N concentration, and biomass yield of forage grass

Forage grass height and SPAD values varied between years of study at both sites and there was a significant interaction effect between year and grass performance (Figs. S4a and S4b, Table S9 in SI for p-values). Between 2018 and 2021, the forage grass height and SPAD values were similar below the two fruit tree species in the longan-mango-maize-AF.

In both experiments, forage grass height varied depending on when

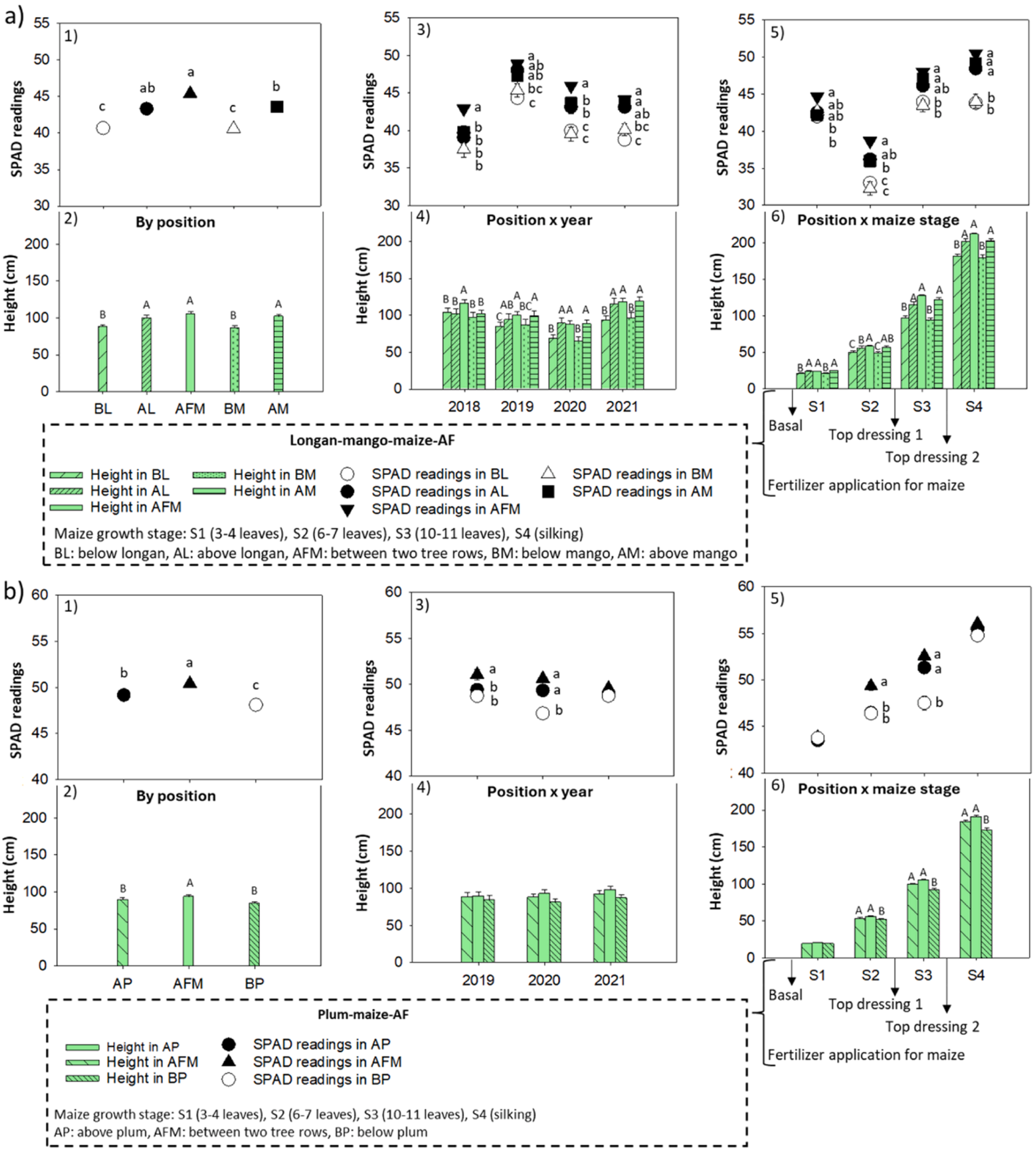

Fig. 6. Growth of maize (height) and leaf N concentration (SPAD; Minolta, 1989) within the agroforestry systems (values are mean ± standard error). Different upper-case and lower-case letters indicate significant differences ($p<0.05$). (a) In longan-mango-maize-forage grass (longan-mango-maize-AF) in Mai Son. 1) & 2) Main effect plot, 3) & 4) Interaction plot between position x year, 5) & 6) Interaction plot between position x maize stage on maize height and SPAD values. (b) In plum-maize-forage grass (plum-maize-AF) in Tram Tau. 1) & 2) Main effect plot, 3) & 4) Interaction plot between position x year, 5) & 6) Interaction plot between position x maize stage on maize height and SPAD values.

the grass was harvested during the growing seasons. An exception was the plum-maize-AF trial in 2020, where the forage grass height was greatest in the middle of the maize season. The SPAD readings for forage grass increased after maize was planted and fertilized, and also peaked in the middle of the maize season linked to top-dressing of the maize, before declining by maize harvest time in both the longan-mango-maize-AF (Fig. 9a, Table S9 in SI for p-values) and plum-maize-AF system (Fig. 9b, Table S9).

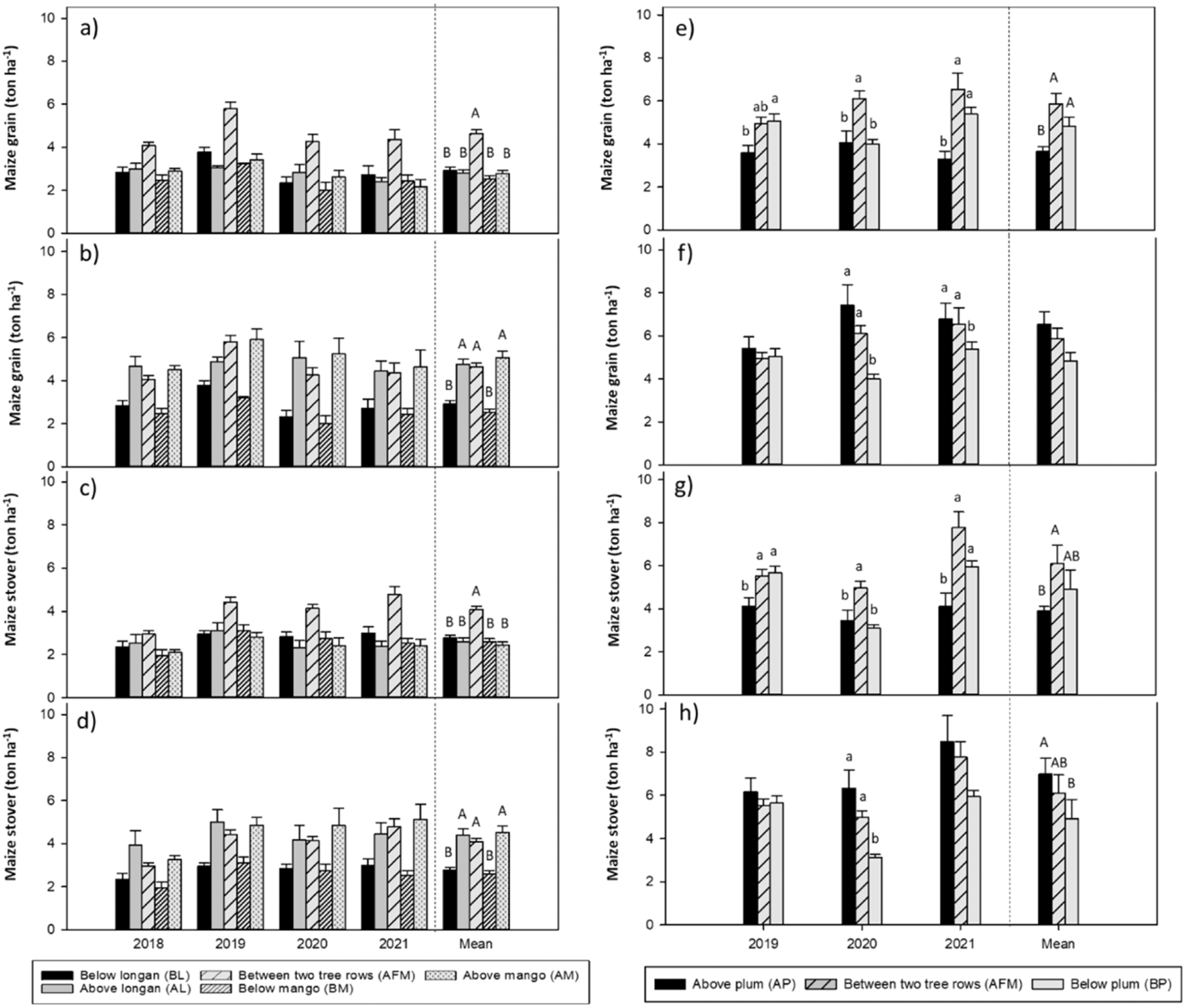

Fig. 7. Yield of maize (dry grain and stover) calculated by whole system area and by actual maize area within the agroforestry systems (values are mean ± standard error). Different upper-case and lower-case letters indicate significant differences ($p<0.05$) in the main effect of position within agroforestry and interactive effect of position and year on maize yield, respectively. (a) Maize grain yield by whole area in longan-mango-maize-forage grass (longan-mango-maize-AF). (b) Maize grain yield by actual maize area in longan-mango-maize-AF. (c) Maize stover yield by whole area in longan-mango-maize-AF. (d) Maize stover yield by actual maize area in longan-mango-maize-AF. (e) Maize grain yield by whole area in plum-maize-forage grass (plum-maize-AF). (f) Maize grain yield by actual maize area in plum-maize-AF. (g) Maize stover yield by whole area in plum-maize-AF. (h) Maize stover yield by actual maize area in plum-maize-AF.

There were no significant differences in forage grass height and SPAD readings below longan and mango trees within the individual study years. However, there was an interaction between forage grass height, SPAD value and time of measurement in most years (Fig. 9a and Table S9). The results showed that in the middle of the maize season, the height and SPAD values of forage grass below the trees were comparable across the years and higher than those measured other times during the seasons.

In longan-mango-maize-AF, the forage grass yield increased from 2017 to 2021 (Fig. S5a, Table S9), however in plum-maize-AF, the forage grass yield in 2020 was greater than that in 2019 and 2021 (Fig. S5b, Table S9).

In the establishment year of longan-mango-maize-AF (2017), the forage grass produced biomass two months after planting and there was no significant difference in harvested fresh biomass of forage grass below longan and mango trees (Fig. 10a, Table S9). Except for the first year, fresh biomass yield of fodder grass varied depending on the time of harvest (Fig. 10a, Table S9). In plum-maize-AF, harvesting of fresh biomass of forage grass started in the beginning of the maize season in 2019 (Fig. 10b, Table S9). At both systems, fresh biomass yield of forage grass increased from planting and fertilization of maize and reached its highest value in the middle of the maize season, then decreased by maize harvesting time.

3.3. Growth of fruit trees in fruit-tree agroforestry

Annual measurements of the growth of fruit trees showed that 5 years after planting (i.e., in 2021), mango trees had greater dimensions than longan trees ($p<0.05$), while plum trees after 4 years of planting had wider canopies than mango and longan but were intermediate in height (Fig. 11, see Table S10 in SI for p-values).

3.4. Spatial variability in SOC and in soil N, P, and K in fruit-tree agroforestry

In the longan-mango-maize-AF system, available P and K were significantly lower below the longan (BL) and mango (BM) tree-grass rows than above the longan (AL) and mango (BM) trees (Fig. 12a5

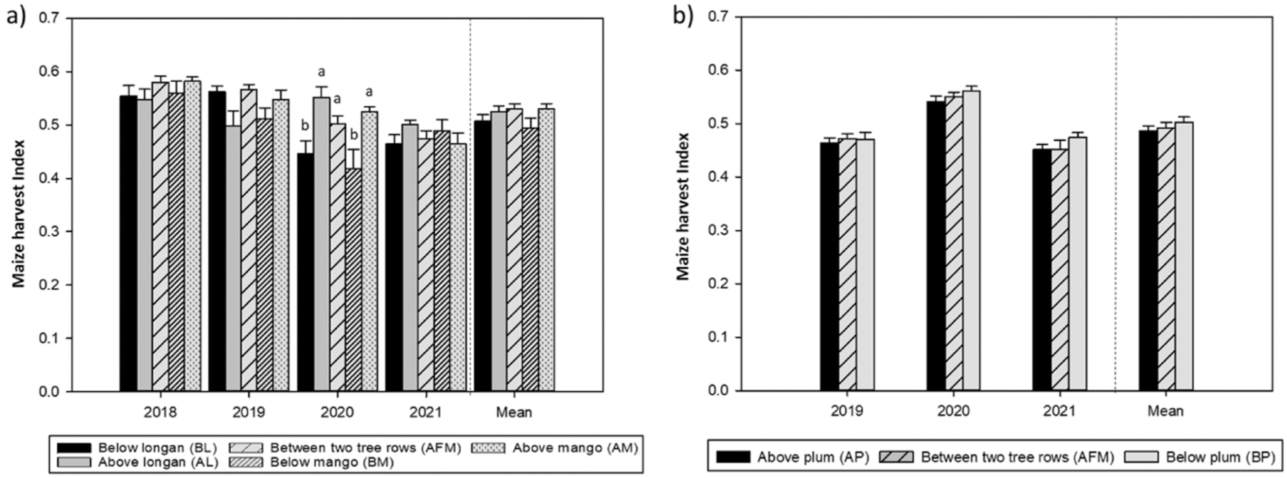

Fig. 8. Maize harvest index (HI) within the agroforestry systems (values are mean ± standard error). (a) Below longan (BL), above longan (AL), between two tree rows (AFM), below mango (BM), and above mango (AM) in the longan-mango-maize-forage grass (longan-mango-maize-AF) in Mai Son. (b) Above plum (AP), between two tree rows (AFM), and below plum (BP) in the plum-maize-forage grass (plum-maize-AF) in Tram Tau.

and 12a6, see Table S15 in SI for p-values). There was an interaction between position relative to the tree-grass rows and year on SOC, total-P, and available-P, with SOC decreasing over time BL (Fig. 12a1, Table S15), but no change at other positions. In 2018, total-P concentration was similar across all positions, but in 2021, it was higher AL than BM (Fig. 12a3). In 2021, available-P concentration in BL and BM decreased compared to 2018, and the concentration was higher above than below the tree-grass rows (Fig. 12a5, Table S15).

In plum-maize-AF system, SOC concentration was highest above plum tree-grass rows (AP), followed by between two tree rows (AFM), and lowest below plum tree-grass rows (BP) (Fig. 12b1, Table S15). Total-N concentration was comparable in AP and AFM, but significantly lower in BP (Fig. 12b2, Table S15). There was an interaction between position relative to the tree-grass rows and year on SOC concentration, which decreased over time in AFM and BP. SOC concentration was also influenced by position in relation to the tree-grass rows and the soil layer. At 0–10 cm depth, SOC concentration was highest in AP, followed by AFM, and lowest in BP. At a depth of 10–20 cm, SOC concentration was higher in AP than in BP.

Overall, the concentrations of SOC and plant nutrients (total-N, total-P, available P, available K) were higher in the 0–10 cm soil layer than in the 10–20 cm layer.

3.5. *Crop performance and soil fertility in sole-crop maize compared with maize areas between tree rows in fruit-tree agroforestry*

3.5.1. *Maize height and leaf N concentration*

In Mai Son, comparisons of agroforestry and SM plots revealed that maize height and SPAD values in SM and positions between two tree rows (AFM) in agroforestry, were similar (Fig. 13a2 and 13a1, Table S11 for p-values). There was an interaction between SM, AFM and year on maize height and SPAD values (Figs. 13a4 and 13a3, Table S11), with maize height being higher in SM than AFM in 2018 and 2020. In 2018, SPAD values were higher in SM than in AFM, but in 2021, they were higher in AFM. In addition, there was an interaction between SM, AFM and maize growth stage on maize height and SPAD values (Figs. 13a6 and 13a5, Table S11). At the 3–4 and 10–11 fully expanded leaf stages, maize height was higher in SM than in AFM. Meanwhile, AFM had higher SPAD values than SM at the 6–7 fully expanded leaf stage, while SM had higher SPAD values at the silking stage.

In Tram Tau, maize height and SPAD values in SM and AFM were comparable (Figs. 13b2 and 13b1, Table S11). There was an interaction between SM, AFM and year on SPAD values (Figs. 13b3, Table S11), which were greater in AFM than SM in 2019.

3.5.2. *Yield of maize*

The average maize grain yield in SM and AFM was around 4.6 tons ha^{-1} in Mai Son, whereas it was 6.0 tons ha^{-1} in Tram Tau. In both Mai Son and Tram Tau, maize grain and stover yield, i.e., the actual maize area, were similar in SM and between two tree rows (AFM) in agroforestry (Fig. 14, see Table S12 in SI for p-values). However, in Mai Son, there was an interaction between AFM, SM and year on yield of maize grain and stover, where grain and stover yield were higher in SM than in AFM in 2018, while stover yield was higher in AFM than in SM in 2021, (Figs. 14a and 14b, Table S12).

In Mai Son, maize harvest index (HI) was similar in 2018 and 2019 (around 0.57) and decreased over time to around 0.49 in 2020–2021 (Fig. 15a, Table S8). In Tram Tau, maize HI was highest in 2020 (0.54) and around 0.46 in 2019 and 2021 (Fig. 15b, Table S8).

3.5.3. *Soil organic carbon and nutrients*

In both Mai Son and Tram Tau, concentrations of SOC and nutrients (total-N, total-P, available P, available K) in SM and in the actual maize area between two tree rows (AFM) did not differ and were higher in the 0–10 cm than the 10–20 cm soil layer (Fig. 16, Table S16). In Tram Tau, total-K was significantly higher in SM than in AFM.

3.6. *Maize performance and soil fertility in three different positions along the slope in sole-crop maize*

In Mai Son, maize height in sole-crop maize (SM) was higher at upper position along the slope (sole maize upper - SMU) as compared with maize in middle (SMM) and bottom slope (SMB) positions (Figs. S6a2, see Table S13 in SI for p-values). Maize SPAD values were highest at SMU, followed by SMM, and lowest at SMB (Fig. S6a1, Table S13). There was an interactive effect of slope position and year on maize height and SPAD values (Figs. S6a4 and S6a3, Table S13), indicating that maize height was higher in SMU than SMB in 2018, and the maize was taller in SMU than the other positions in 2021. The SPAD values were highest in SMU, followed by SMM, and lowest in SMB in 2018. In 2020 and 2021, SPAD values were lower at SMB compared to other slope positions. In addition, there was an interactive effect of slope position and maize growth stage on maize height and SPAD values (Figs. S6a6 and S6a5, Table S13), with maize height being higher in SMU than in SMB from 6 to 7 fully expanded leaves to silking. The maize height in SMU and SMM was similar at 10–11 fully expanded leaves. In Tram Tau, maize height and SPAD values were similar at all positions (SMU, SMM, and SMB) in SM (Fig. S6b, Table S13).

Maize yield (grain and stover) at SMU and SMM was comparable in

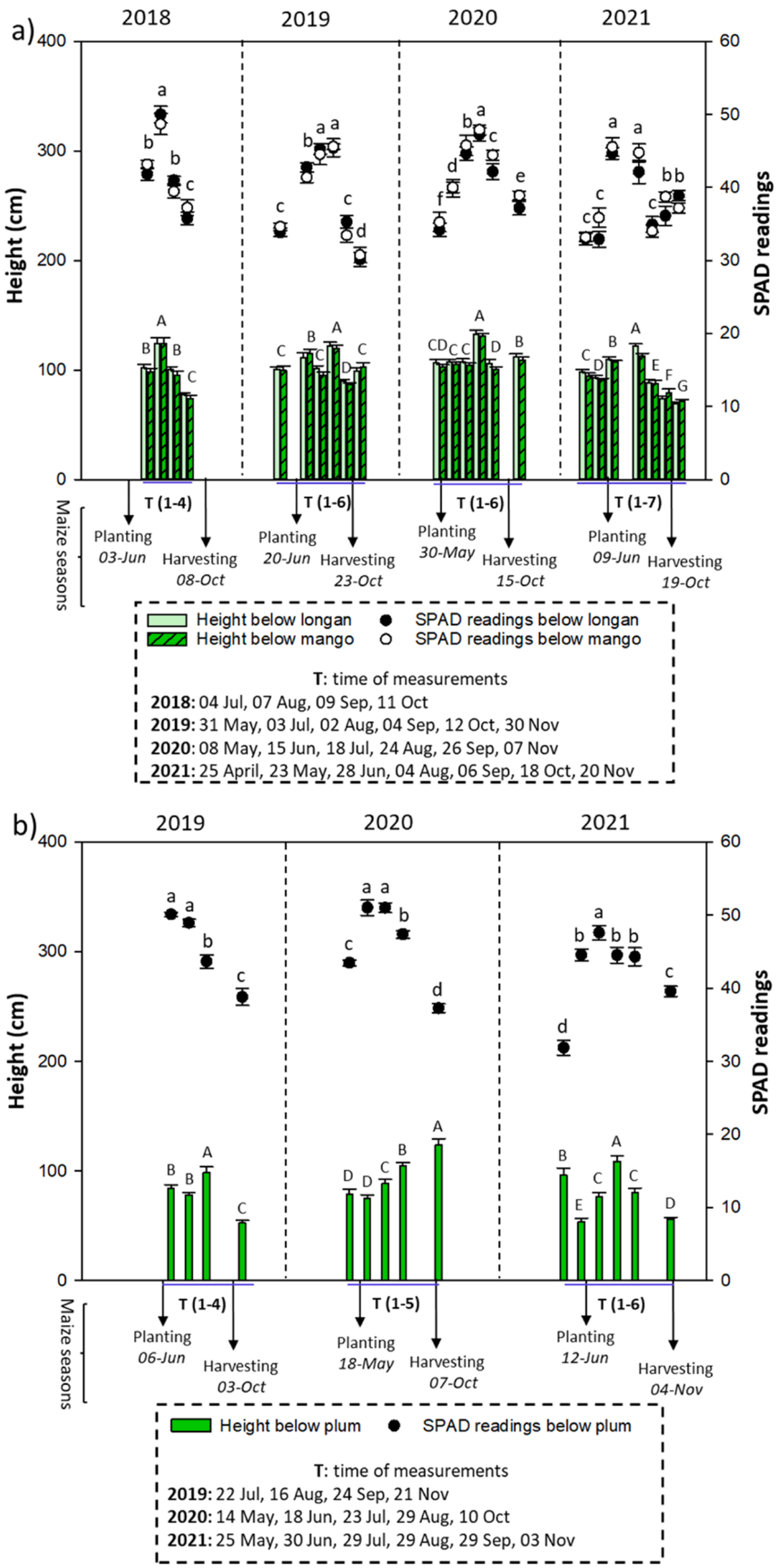

Fig. 9. Height and leaf N concentration (SPAD; Minolta, 1989) of forage grass in the two agroforestry systems (values are mean and standard error). Different upper-case (height) and lower-case (SPAD readings) letters on bars indicate significant differences ($p<0.05$) between measurement occasions. (a) Longan-mango-maize-forage grass (longan-mango-maize-AF) in Mai Son. (b) Plum-maize-forage grass (plum-maize-AF) in Tram Tau.

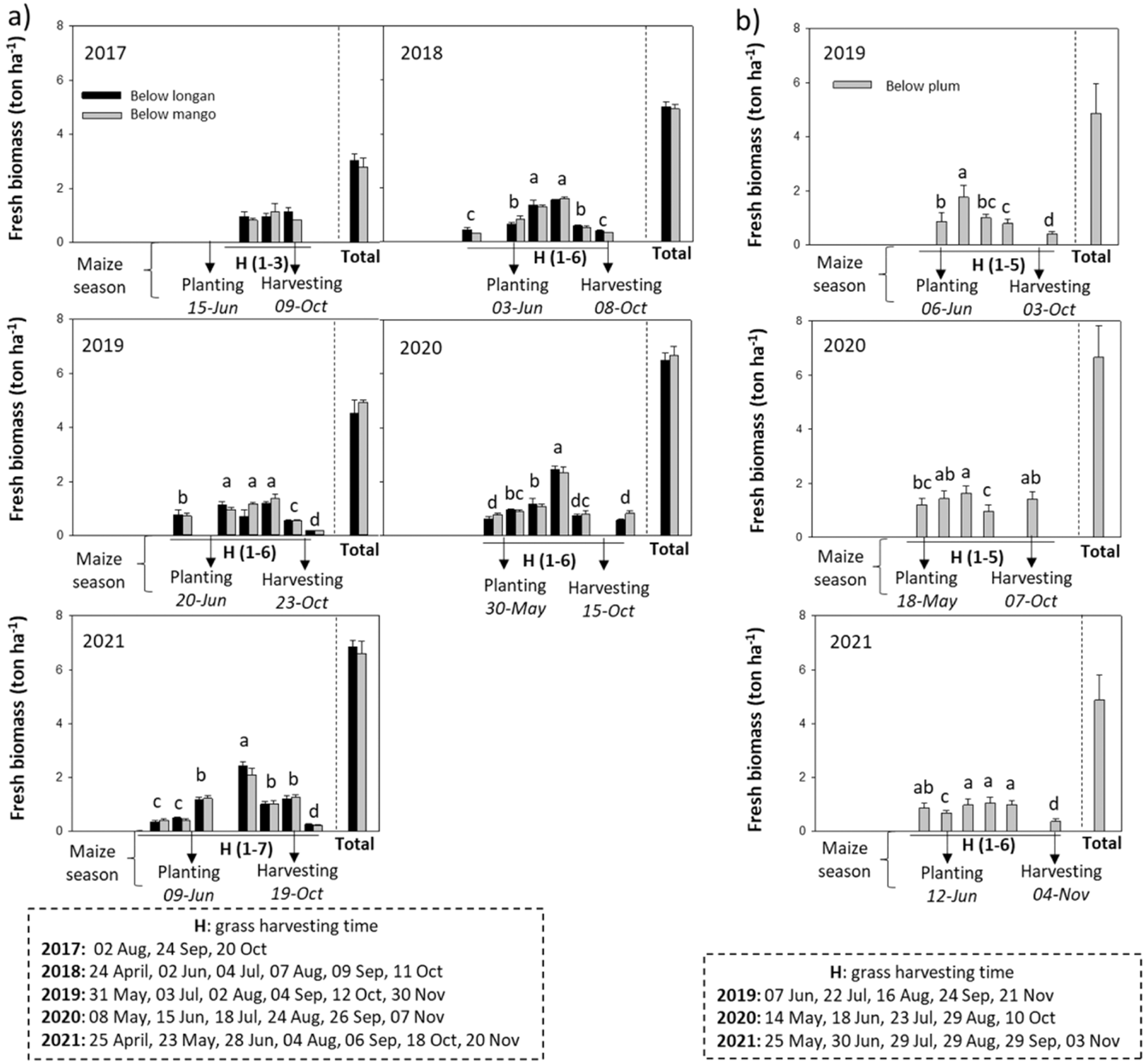

Fig. 10. Yield of forage grass (fresh biomass) harvested in the agroforestry systems (values are means and standard errors). Different lower-case letters on bars indicate significant differences ($p<0.05$) between harvesting times. a) Longan-mango-maize-forage grass (longan-mango-maize-AF) in Mai Son. (b) Plum-maize-forage grass (plum-maize-AF) in Tram Tau.

Mai Son and Tram Tau, but lower at SMB (Fig. S10, see Table S14 in SI for p-values).

SMU had a higher available K concentration than SMB (Fig. S11a6 and Table S17) in Mai Son. In all zones at both sites, SOC and nutrient concentrations were higher in the 0–10 cm soil layer compared to the 10–20 cm soil layer.

4. Discussion

4.1. Spatial and temporal impact of fruit trees and grass strips on maize performance and yield

4.1.1. The spatial impact

Cultivation on sloping land significantly contributes to soil erosion due to various factors, including steep gradients, rainfall intensity, and unsustainable agricultural management practices (Mao et al., 2020). The slopes in this study were substantial gradients of 37 % and 65 % for longan-mango-maize-AF and plum-maize-AF, respectively. In these steep slopes, agroforestry which involves planting trees and grass strips on contour lines, have proven to greatly contribute to terrace formation as well as soil and nutrient conservation (Do et al., 2023). In addition, in this study we have shown that maize growth (height), leaf N concentration (SPAD), and yield (based on the actual maize area) were significantly higher between and above tree-grass rows than below the tree-grass rows, reflecting spatial variation in crop performance within the two studied agroforestry systems. Hand hoeing was utilized to suppress weeds in maize, which can further have added to the soil erosion experienced when cultivating steep sloping land. Hoeing causes disturbed soil to gradually move down the slope and accumulate at the upslope side of the tree-grass rows (Do et al., 2023). During the sediment

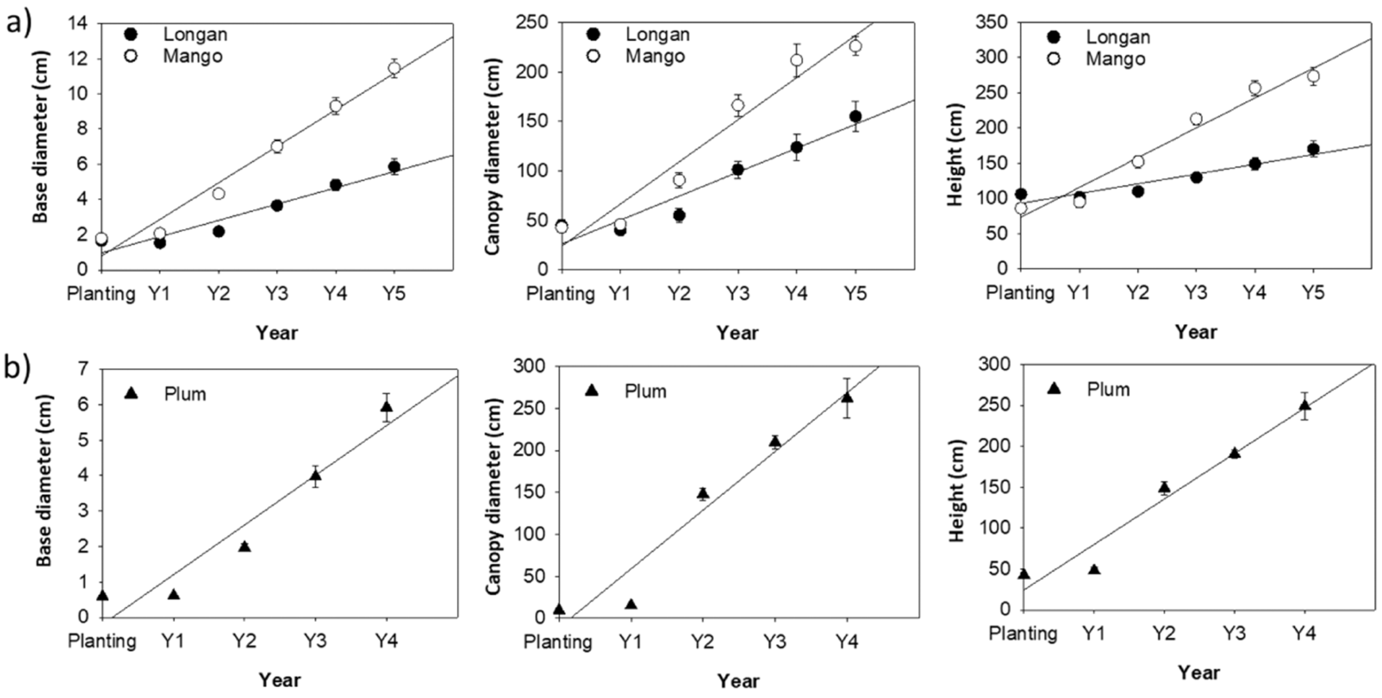

Fig. 11. Regression lines for tree growth over time (mean and standard error). (a) Growth of longan and mango trees in longan-mango-maize-forage grass (longan-mango-maize-AF) in Mai Son. (b) Growth of plum trees in plum-maize-forage grass (plum-maize-AF) in Tram Tau.

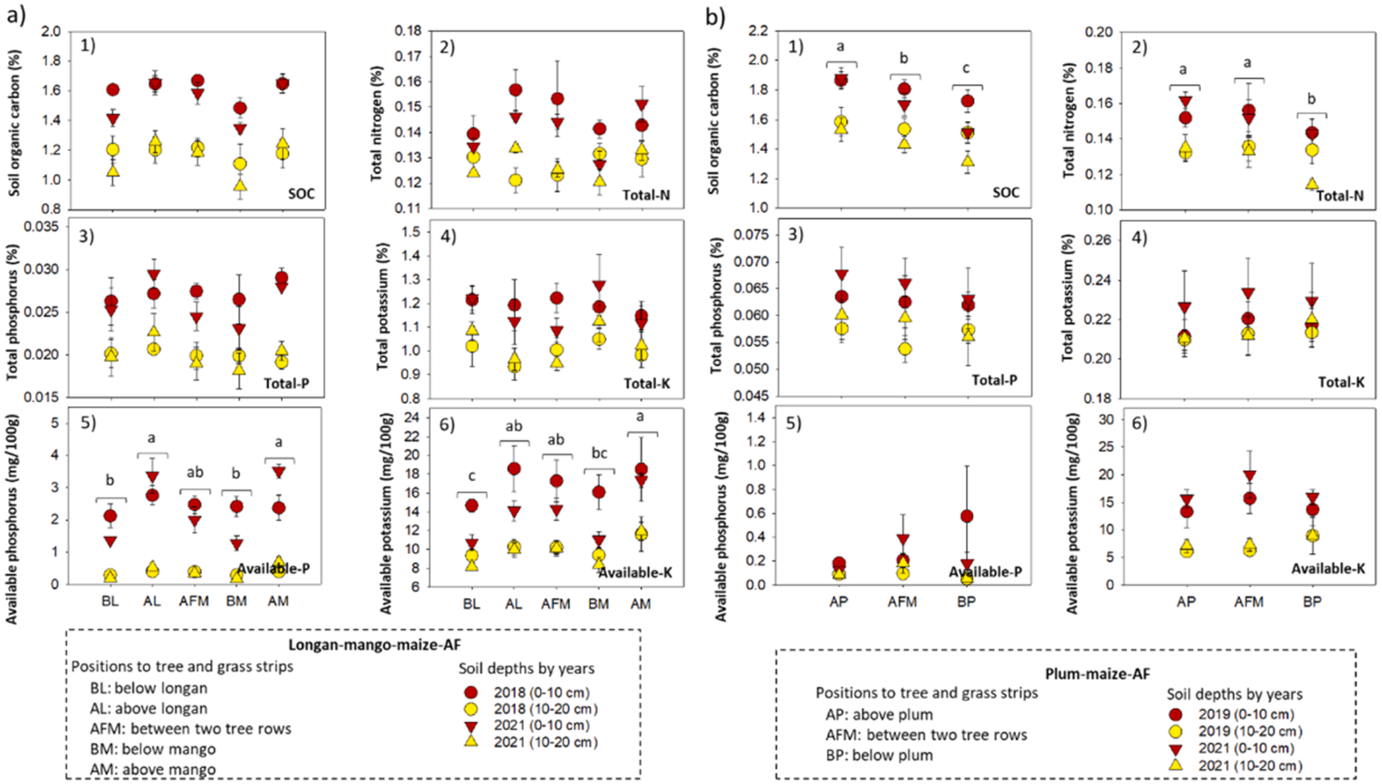

Fig. 12. Soil nutrient concentration within agroforestry (values are mean ± standard error). Different lower-case letters indicate significant differences ($p<0.05$) in main effect of position relative to tree and grass rows (across years and soil depths) on soil organic carbon (SOC) and nutrients. (a) Longan-mango-maize-forage grass (longan-mango-maize-AF) in Mai Son: 1) SOC, 2) total nitrogen, 3) total phosphorus, 4) total potassium, 5) available phosphorus, and 6) available potassium. (b) Plum-maize-forage grass (plum-maize-AF) in Tram Tau: 1) SOC, 2) total nitrogen, 3) total phosphorus, 4) total potassium, 5) available phosphorus, and 6) available potassium.

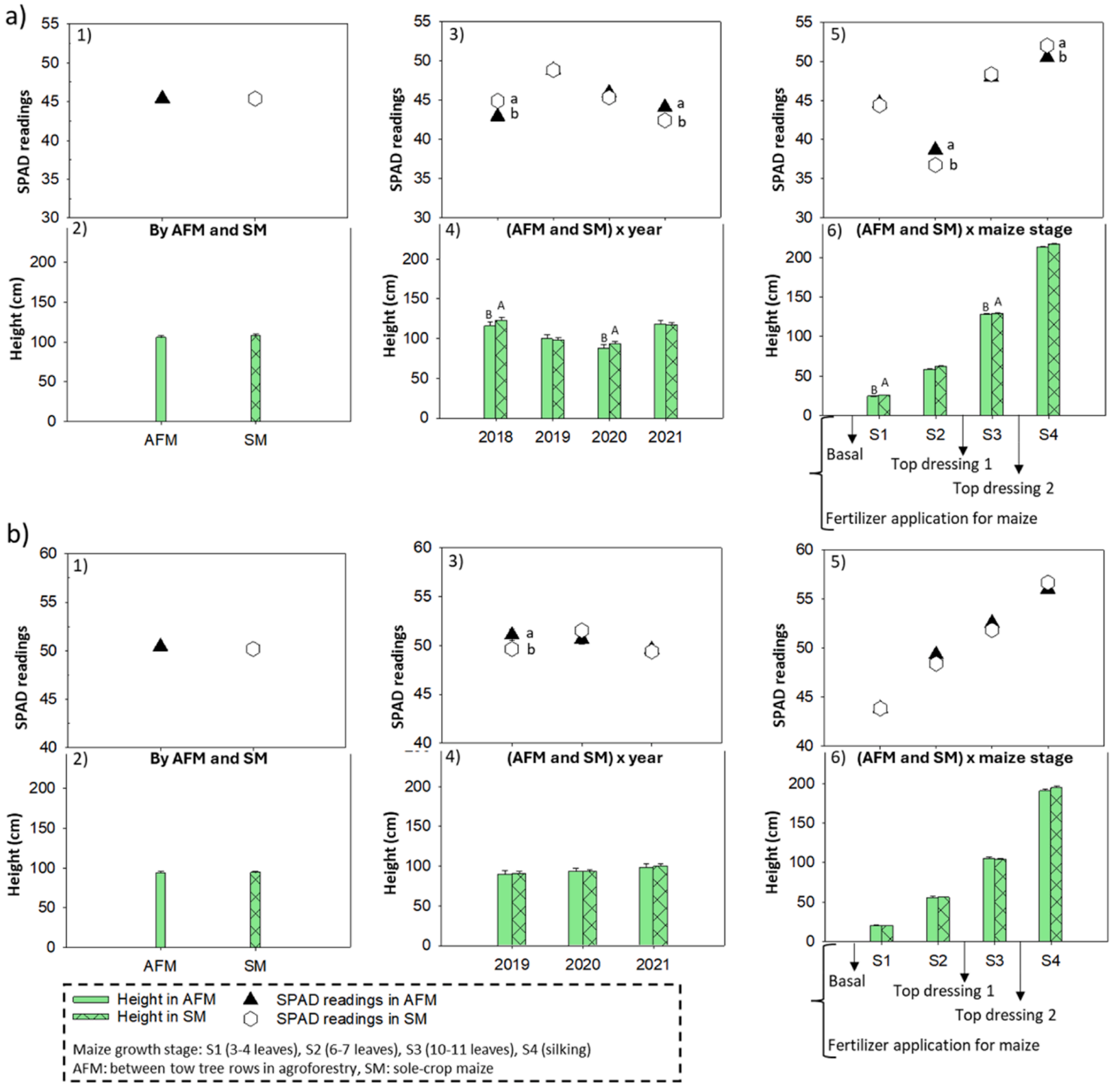

Fig. 13. Growth of maize and leaf N concentration (SPAD; Minolta, 1989) in sole-crop maize (SM) and in positions between two tree rows (AFM) in agroforestry (values are mean ± standard error). Different upper-case and lower-case letters indicate significant differences ($p<0.05$) in maize height and SPAD readings, respectively. (a) In Mai Son. 1) & 2) Main effect plot, 3) & 4) Interaction plot between AFM and SM x year, 5) & 6) Interaction plot between AFM and SM x maize stage on maize height and SPAD readings. (b) In Tram Tau. 1) & 2) Main effect plot, 3) & 4) Interaction plot between AFM and SM x year, 5) & 6) Interaction plot between AFM and SM x maize stage on maize height and SPAD readings.

movement, topsoil rich in organic matter, water and nutrients supplied to maize and trees moved down the slope and retained on the upslope side of tree-grass rows. According to Lenka et al. (2012), soil moisture content is higher in positions above tree-grass rows, due to infiltration of water that has been transferred along the slope. The impact of position on soil water availability was not investigated in this study, but other studies have shown that when cultivating slopes, grass strips play an important role in slowing runoff velocity, spreading runoff water, and allowing more water infiltration into the soil (Babalola et al., 2007; Kinama et al., 2007). Water infiltration above the tree-grass strips is likely to benefit the grass, as well as trees and maize growing above the grass strip. The higher availability of water might also result in greater nutrient use efficiency above the grass strips.

Another factor that could influence maize growth in agroforestry systems is competition. Tuan et al. (2016) found that in a system where maize was sown with contour planting of grass strips, competition with maize occurred, resulting in reduced maize growth, leaf N concentration, and yield, especially in rows close to both the up and downslope side of grass barriers. However, in the current experiments maize was planted further away from the grass above than below the grass strips since the tree row was between the maize and the grass strips. In addition, no fertilizer was added to the grass, and thus more nitrogen is likely

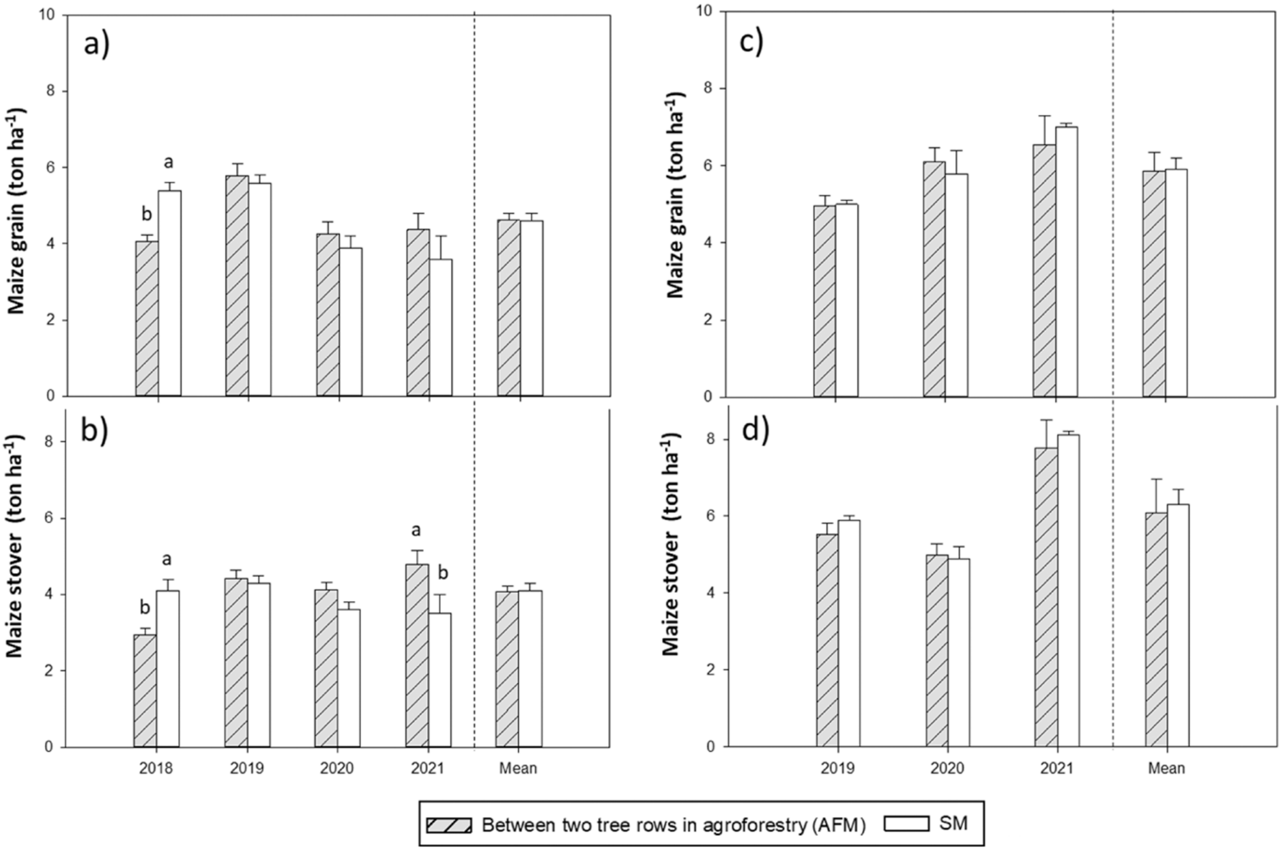

Fig. 14. Yield of maize (dry grain and stover) in positions between two tree rows (AFM) in agroforestry and in sole-crop maize (SM) (values are mean ± standard error). Different lower-case letters indicate significant differences ($p<0.05$) interaction between AFM and SM x year on maize yield. (a) Maize grain in Mai Son. (b) Maize stover in Mai Son. (c) Maize grain in Tram Tau. (d) Maize stover in Tram Tau.

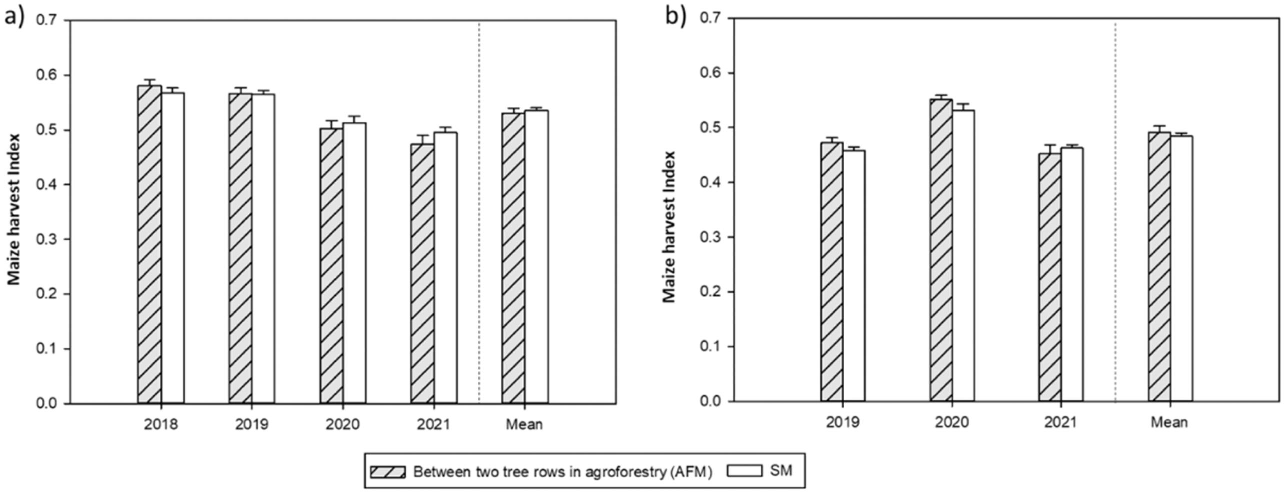

Fig. 15. Maize harvest index (HI) in between tree rows (AFM) in fruit-tree agroforestry and sole-crop maize (SM) (values are mean ± standard error). (a) Mai Son. (b) Tram Tau.

to become available from zones above where the maize and the trees have been fertilized annually, than below the grass that is an efficient nutrient sink.

Our results support findings in previous studies of greater yield of associated crops (e.g., potato, maize, cabbage) at the upslope side of grass strips than the downslope side (Kagabo et al., 2013; Poudel et al., 1999). Wolka et al. (2021) found that even without competition from vegetative barriers, areas above the terraces produced more maize, broad beans, and sorghum than areas below. However, our results differed from the findings for hedgerows composed of Napier grass (*Pennisetum purpureum*), which has been shown to have negative influence on yield of e.g., wheat and soybean at the upslope side of tree-grass rows, caused by competition for nutrients and moisture (Dercon et al., 2006; Guto et al., 2012; Niang et al., 1997).

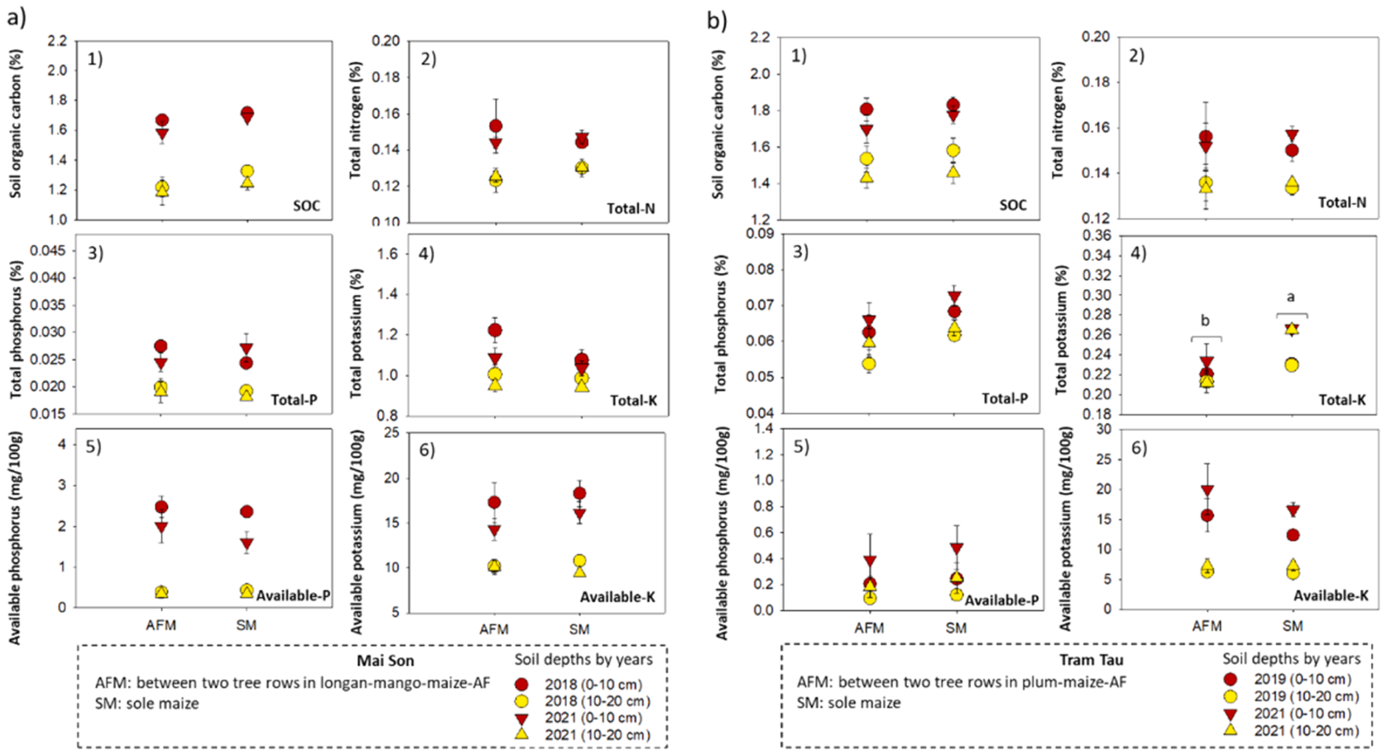

Fig. 16. Soil nutrient concentration in the actual maize area between two tree rows in agroforestry (AFM) compared with sole-crop maize (SM) (values are mean ± standard error). Different lower-case letters indicate significant differences ($p<0.05$) in main effect (SM and AFM) (across the years and soil depths) on soil organic carbon (SOC) and nutrients. (a) Mai Son: 1) SOC, 2) total nitrogen, 3) total phosphorus, 4) total potassium, 5) available phosphorus, and 6) available potassium. (b) Tram Tau: 1) SOC, 2) total nitrogen, 3) total phosphorus, 4) total potassium, 5) available phosphorus, and 6) available potassium.

4.1.2. The temporal impact

Maize performance in terms of plant height, leaf N concentration (SPAD) and yield (actual maize area) was higher between and above than below the tree-grass rows in longan-mango-maize-AF, as were SPAD values and yield (actual maize area) in plum-maize-AF, over the 4–5 years of the study. The reason for this is most likely resource competition below the tree-grass strip, as well as changes in resource distribution over time, particularly in terms of soil water and nutrient availability along the slope, as detailed in Section 4.1.1.

In our 4–5 years study, maize performance in positions upslope of tree-grass rows and between two tree rows was similar. Since the trees were still young and the maize plants were planted 0.5 m away from the tree canopy in the upslope side of the tree-grass rows, and thus seemed to be unaffected by light competition. According to Nyaga et al. (2019), maize sown outside tree canopies performs better (height and yield) than maize sown under tree canopies, but we did not sow maize beneath the tree canopies. However, the trees reduced the area available for maize as the trees grew and the canopies expanded. Thus, the area of maize was reduced by 7.6 and 10.4 % from year 1 to the 5th and 4th year in the longan-mango-maize and the plum-maize-AF system studies, respectively. This resulted in reduction of the total maize yield in agroforestry when comparing the whole system area and SM (Do, 2023).

Water, on the other hand, is likely one of the limiting elements throughout the growing season on sloping lands in northwest Vietnam, where maize cultivation is fully dependent on rainfall (Ha et al., 2004). Total annual rainfall was lower in Son La, where the longan-mango-maize-AF trial was located, than in Yen Bai, where the plum-maize-AF trials was situated. Thus, in both study sites, competition for water resources among maize, trees, fodder grass, and weeds was likely a significant factor influencing maize yield over time. Higher rainfall during the growing season probably mitigated water competition between maize and trees, fodder grass, and weeds in agroforestry at the Yen Bai site. The plum-maize-AF results showed that even at positions below tree-grass rows, maize yields (whole maize area) were comparable to those between tree rows across the experimental period. The maize in the longan-mango-maize-AF experienced very dry conditions between stages 6–7 and 10–11 leaves in 2020 (Do et al., 2023), which most certainly influenced plant development and affected maize grain yield and HI.

Maize HI in the longan-mango-maize-AF system remained unaffected in positions above longan tree-grass rows from 2018 to 2021, while it decreased above mango tree-grass rows and other positions. During the study period, the mango trees developed larger canopies and grew taller than the longan trees. Pham et al. (2024) found that maize planted near mango trees received less light than that planted near longan trees. As a result, the mango trees were more light-competitive with maize than the longan trees, which had an impact on maize yield close to mango trees in the longan-mango-maize-AF system.

4.2. Effects of fruit tree species on spatial and temporal variation on grass performance and yield

The performance of forage grass was similar under all three tree species in the agroforestry experiments. The canopy of mango and plum trees in Mai Son and Tram Tau exceeded 2.0 m from year 4 and 3, respectively, whereas the canopy of longan trees did not exceed 2.0 m 5-years after planting. The guinea grass planted 1.0 m away from the trees showed similar biomass-yield, height, and leaf N concentrations under longan and mango trees in the longan-mango-maize-AF. Thus, during the early stages of that agroforestry system, i.e., the first 4–5 years, the performance of the grass seemed to be unaffected by the trees in terms of competition for light resources. There were no sole-crop guinea grass plots in full sun for comparison in this study. However, guinea grass is a C4 photosynthetic forage crop (Carvalho et al., 2020), and its biomass production is known to be affected by shading by tree canopies in agroforestry (Dibala et al., 2021; Kumar et al., 2001; Pandey et al., 2011). In mature agroforestry, when the trees have a larger canopy cover and fully shade the grass strips, a greater reduction in forage grass biomass yield caused by shading can be expected.

When trees and forage grass are planted next to each other, nutrient and water competition can occur (Sarto et al., 2022). As a result, when trees are planted near grass strips, they face significant competition, reducing growth and yield (Schaller et al., 2003). Sole fruit tree plots were not available for comparison in this study, but in a previous study we observed that forage grass had a negative impact on longan trees planted close by (0.5 m away), which led to lower tree growth and fruit yield compared with sole trees (Do et al., 2020). Although the trees were planted 1.0 m away from the guinea grass strips in the present study, there was probably still competition between the forage grass and the fruit trees. In other studies, guinea grass has been found to have a negative impact on *Eucalyptus deglupta* trees planted 0.9 and 1.0 m away from grass strips (Schaller et al., 2003) and on *Docynia indica* (Wall.) Decne trees planted 1.0 m away from grass strips (Do et al., 2020).

This study did not investigate the effect of various tree species on the nutritional value of the guinea grass. However, the guinea grass was unfertilized and must have used nutrients supplied to maize and fruit trees that was retained upslope of tree-grass rows, and partially also on the downslope side. Furthermore, forage grass that grew during the rainy season played a vital role in controlling runoff and improved water infiltration above tree-grass strips, which is likely to benefit the grass as discussed in Section 4.1. High water availability may also result in a higher nutrient utilization efficiency of the grass strips. This is confirmed by the fact that grass height, leaf N concentration, and biomass production increased after the maize was sown, and peaked in the middle of the maize season, which co-occurred with fertilizer application (top-dressing) to maize. The results demonstrated that the grass strips played a vital role in trapping N during the growing season, a key function contributing to higher nutrient use efficiency within the two studied agroforestry systems on steep slopes.

4.3. *The spatial impact of fruit trees and grass strips on soil fertility along the slope*

Over the study period, significant spatial variability in total P and available P and K developed within the longan-mango-maize-AF system, while spatial variability in SOC and total-N distribution developed in the plum-maize-AF system. Lower concentrations of SOC and plant nutrients were observed in positions downslope of grass strips compared with positions upslope. Downslope of tree-grass rows, SOC tended to decrease in both plum-maize-AF and longan-mango-maize-AF during the experimental period, and in the latter system total-P and available P concentrations also decreased. SOC, total-P, and available P concentrations remained at the same levels on the upslope side of tree-grass rows and in positions between two tree-grass rows during the study period. In these systems, the tree-grass strips played a significant role in preventing loss of soil and associated nutrients and in facilitating formation of terraces (Do et al., 2023). The study plots were on steep slopes, and tillage was carried out three times per year (soil preparation for maize planting and two hand hoeings during the maize growing season to control weeds). Tillage caused gradual movement of soil from the downslope side of grass strips and accumulation at the upslope side of the tree-grass rows farther down (Dercon et al., 2006; Do et al., 2023; Ziegler et al., 2007). Runoff and water erosion also transported soil particles, dissolved SOC and nutrients downhill, where they were retained on the upslope side of tree-grass rows. In addition, there was probably competition for nutrients between tree/crop/grass components, causing a decline in soil fertility at the downslope side of grass strips in both agroforestry systems as discussed in Section 4.1.1.

4.4. *Maize performance in agroforestry as compared to sole cropping*

Maize performance in terms of height, leaf N concentration, yield, and HI was comparable between two tree rows in agroforestry and in SM at both study sites. However, the trees were only 4–5 years old and still relatively small. Thus, in terms of resource competition, maize between two tree rows was unaffected by the trees and forage grass. This supports previous research, which found that the yield of maize planted 3.0 m from the tree canopy in 7-year-old (Do et al., 2020) and 17-year-old agroforestry systems (Nyaga et al., 2019) or from guinea grass strips in a 2-year-old system involving maize and grass strips (Tuan et al., 2015) was comparable to sole-crop maize. Meanwhile, the maize yield (whole area) in positions above and below trees in longan-mango-maize-AF and above trees in plum-maize-AF was lower than in that one in SM, caused by competition and maize area reduction in agroforestry as discussion in Section 4.1.

4.5. *System improvement in space and time*

Our results demonstrated spatial and temporal variability in maize growth and yield and spatial variations in soil fertility in both agroforestry systems studied. In both experiments, lower yield and decreased soil fertility occurred on the downslope side of tree-grass strips. This implies that adaptive management to improve spatial resource availability needs to be developed. Increasing the spacing or applying higher rates of soil amendments and fertilizers to low-fertility areas such as downslope of grass strips could increase productivity. However, the current investigation cannot distinguish competition for nutrients from competition for water. Thus, to optimize management, more knowledge is needed about the distribution and impact of all resources independently. When the roots of the fruit trees have descended deep into the downslope side of tree-grass strips in mature agroforestry, targeting fertilizer application to the maize in that area and/or to the fodder grass would also help the fruit trees grow better by indirectly supplying them with nutrients.

Soil tillage for weed control may have accelerated erosion, which had a significant negative impact on productivity and soil fertility on the downslope side of the grass strips. Farmers in the area use herbicides or mowing to control weeds on sloping land, but these methods also have environmental consequences in the form of poor health and pollution. More environmentally friendly alternatives for weed management are minimum tillage in combination with an understory service crop, or minimum tillage and the under-sowing of a relay crop in maize (Tuan et al., 2014).

Well-established grass barriers can play a significant role in fruit tree agroforestry by decreasing soil and nutrient losses through the creation of natural terraces (Do et al., 2023). They also provide early products and potential income for farmers as fodder for livestock (Do et al., 2020). However, forage grass competes for resources with tree/crop components within agroforestry systems. To increase the amount of forage for livestock while lowering competition with other tree and crop components in the system, fertilizers may need to be applied to the forage grass. Furthermore, in the locations where the demand of forage grass for livestock is less, forage grass can be utilized as mulch to cover the soil surface around fruit trees, suppressing weed growth and thus lowering costs for weed management, reducing competition for soil nutrients, and enhancing soil moisture (FAO, 2008). In addition, when the mulch decomposes, it adds organic matter and nutrients to the soil for fruit trees and improves nutrient cycling in agroforestry system.

It is possible to reduce competition between tree/crop and grass components by using C3 crops instead of C4 crops, since previous studies have found that yields of C3 crops are less reduced in agroforestry systems (Rao et al., 1997; Thevathasan and Gordon, 2004). Sowing or planting legume species such as soybean and groundnut instead of maize has been suggested (Do et al., 2020). However, the replacement crop depends on farmers' needs and market demands. Greater planting distance between trees, crops, and grass strips would also reduce competition, and may be suitable at more gentle slopes.

Management of tree and crop components in a fruit tree-based agroforestry system must change from the year of establishment to when the trees are mature and high-producing, allowing farmers to minimize competition, enhance land use efficiency (Xu et al., 2019) and improve the productivity of the various agroforestry system components. In the first three years of the studied systems, when the trees had not yet produced fruit, the main priority of the farmers was the annual crop and fodder grass, whereas they paid more attention to the trees when they started bearing fruit. Farmers will thus require short-term income from annual crops to supplement long-term benefits from fruit trees.

Lime was not applied to fruit trees despite the soil pH in the study area being low. This is a limitation of our study, since evidence in the literature shows that lime effectively neutralizes soil acidity, which is required for proper root functions and nutrient uptake (Márcio Cleber Medeiros De et al., 2018). In addition, lime application has been shown to increase the plant available concentration of vital nutrients in the soil, promoting plant growth and canopy size and thus improving plant nutritional status, increasing fruit productivity and fruit quality (Almeida et al., 2012; Ennab et al., 2023; Zhang et al., 2021). Thus, given widespread soil acidity in the upland areas of the Mekong, supplying lime to fruit tree components in agroforestry over time is essential to enhance fruit yield and quality, while also giving long-term economic benefits to farmers.

5. Conclusions

- In 4–5 year old agroforestry systems, integrating fruit trees (mango, longan, or plum), maize, and guinea grass grown along contours, a spatial and temporal variation in crop productivity and soil fertility was observed along slopes.
- Maize height, leaf N concentration, yield, and harvest index were higher at the upslope side of grass strips than on the downslope side of fruit tree-grass rows.
- At initial stages (4–5 years) of agroforestry systems, forage grass height, leaf N concentration, and biomass were comparable when grass strips were planted under different fruit tree species. The grass strips played a vital role in trapping N during the growing season and in enhancing nutrient use efficiency within agroforestry on steep slopes.
- A gradient of SOC, total-N, total-P, available P, and available K was observed along the slopes as a result of terrace formation, and the fruit tree-grass rows played a key role in creating such soil fertility gradients.
- The maize performance (height, leaf N concentration, yield) and soil fertility in the actual maize areas between two tree-grass rows were comparable to those in sole-crop maize.
- The spatial and temporal variation in crop performance, soil properties, and inter-plant competition along the slope should be considered when designing and managing agroforestry systems on sloping land and formulating adaptive management to improve spatial resource availability over time.

CRediT authorship contribution statement

Van Hung Do: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nguyen La:** Writing – review & editing, Supervision, Methodology. **Göran Bergkvist:** Writing – review & editing, Supervision, Methodology. **A. Sigrun Dahlin:** Writing – review & editing, Supervision, Methodology. **Rachmat Mulia:** Writing – review & editing, Supervision, Methodology. **Ingrid Öborn:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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.

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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.fcr.2024.109675.

Data availability

Data will be made available on request.

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