Acta Universitatis Agriculturae Sueciae

Doctoral Thesis No. 2023:63
Faculty of Natural Resources and Agricultural Sciences

# Fruit tree-based agroforestry on sloping uplands in northwest Vietnam

## Effects on soil conservation, tree-crop performance and weed management

Hung Van Do

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SWEDISH UNIVERSITY
OF AGRICULTURAL
SCIENCES

**DOCTORAL THESIS**
Uppsala 2023

Acta Universitatis Agriculturae Sueciae
2023:63

Cover: Agroforestry comprised of fruit trees, grass strips and crops on steep slope in northwest Vietnam
(photo: Hung Van Do)

ISSN 1652-6880
ISBN (print version) 978-91-8046-178-8
ISBN (electronic version) 978-91-8046-179-5
https://doi.org/10.54612/a.5cjj68621c

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Print: SLU Grafisk service, Uppsala 2023

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## Abstract

On sloping land, agroforestry can be a more sustainable way to produce food and other products and services than sole-crop cultivation of crops. This thesis examined whether fruit tree-based agroforestry on smallholder farms on sloping uplands can have a positive impact on sustainability. Production, soil conservation, profitability, tree-crop performance, spatial variation in resource distribution and the impact of different weed management strategies were assessed in agroforestry systems (4-7 years old) comprised of fruit trees, crops (maize, coffee) and fodder grass on sloping uplands (slope ranging from 27 to 65%) in northwest Vietnam. Sole-crop trees and crops were used as controls. The results showed that agroforestry gave more diverse products and higher profitability than sole-crop systems, but also higher initial investment costs. Inclusion of tree-grass strips in agroforestry contributed to formation of terraces that prevented/reduced soil erosion and related losses of soil organic carbon (SOC) and plant nutrients. Crop growth and yields were higher above and between grass/tree rows than below. SOC and plant nutrients tended to accumulate/increase above tree-grass rows over time within agroforestry systems. Hand hoeing to complement or replace herbicide-based weed control proved to be better in supporting tree growth, increasing crop and fruit production and reducing weed abundance, which partly compensated for the high cost of manual weed control in agroforestry. Thus, agroforestry comprising fruit trees, grass strips and crops could be a viable option for sustainable agricultural production on sloping uplands, through improving profitability and soil conservation compared with sole trees or crops. To optimise tree/crop yield in such agroforestry systems, adaptive management is needed to reduce competition and improve spatial resource availability. Wider adoption will require initial incentives or loans, knowledge exchange and market links.



*Keywords:* ecosystem services, fruit tree-based agroforestry, grass strips, profitability, resource competition, spatial resource distribution, strategies, systems improvement, tree/crop yield, uptake and expansion, weed management



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# Nông lâm kết hợp dựa vào cây ăn quả trên đất dốc tại vùng Tây Bắc Việt Nam

## Tác động bảo tồn đất, hiệu suất cây trồng và quản lý cỏ dại


## Tóm tắt

Trên đất dốc, nông lâm kết hợp (NLKH) có thể là một phương thức canh tác bền vững hơn để sản xuất lương thực và dịch vụ khác so với canh tác độc canh cây hàng năm. Muc tiêu của luận án này nhằm xem xét liệu mô hình NLKH dựa trên cây ăn quả tại các nông hộ sản xuất nhỏ trên vùng đất dốc có thể tác động tích cực đến tính bền vững hay không. Năng suất cây trồng, tác dụng bảo tồn đất, lợi nhuận, sinh trưởng và phát triển của cây trồng, sự thay đổi không gian trong phân phối tài nguyên và tác động của các biện pháp quản lý cỏ dại khác nhau đã được đánh giá trong các hệ thống NLKH (4-7 tuổi) bao gồm cây ăn quả, cây trồng (ngô, cà phê) và cỏ làm thức ăn gia súc trên vùng đất dốc (độ dốc từ 27-65%) ở Tây Bắc Việt Nam. Các hệ thống trồng thuần cây ăn quả, ngô và cà phê được sử dụng làm đối chứng. Kết quả cho thấy NLKH cho sản phẩm đa dạng và lợi nhuận cao hơn so với hệ thống độc canh, nhưng chi phí đầu tư ban đầu cũng cao hơn. Việc đưa các dải cây-cỏ vào NLKH hợp đã góp phần hình thành các tiểu bậc thang giúp ngăn ngừa/giảm thiểu xói mòn đất và các tổn thất liên quan đến carbon hữu cơ trong đất (SOC) và chất dinh dưỡng thực vật. Tăng trưởng và năng suất cây trồng ở phía trên và giữa các hàng cỏ/cây cao hơn phía dưới. SOC và các chất dinh dưỡng thực vật có xu hướng tích lũy/tăng lên trên các hàng cây-cỏ theo thời gian trong các hệ thống NLKH. Việc áp dụng cuốc tay để bổ sung hoặc thay thế thuốc trừ cỏ giúp hỗ trợ cây phát triển tốt hơn và tăng sản lượng cây trồng, đồng thời giảm sự phong phú của cỏ dại, cũng như bù đắp một phần chi phí cao cho việc kiểm soát cỏ dại thủ công trong NLKH. Do đó, NLKH bao gồm cây ăn quả, dải cỏ và hoa màu có thể là một lựa chọn khả thi cho sản xuất nông nghiệp bền vững trên vùng đất dốc, thông qua cải thiện lợi nhuận và bảo tồn đất so với trồng độc canh cây hoặc hoa màu. Để tối ưu hóa năng suất cây trồng trong các hệ thống NLKH, quản lý thích ứng là cần thiết để giảm cạnh tranh và cải thiện tính sẵn có của tài nguyên không gian. Việc áp dụng rộng rãi NLKH sẽ đòi hỏi các ưu đãi hoặc khoản vay ban đầu, trao đổi kiến thức và liên kết thị trường.



*Từ khóa:* dịch vụ hệ sinh thái, NLKH dựa trên cây ăn quả, dải cỏ, lợi nhuận, cạnh tranh tài nguyên, phân bổ tài nguyên không gian, chiến lược, cải thiện hệ thống, năng suất cây/cây trồng, tiếp nhận và mở rộng, quản lý cỏ dại



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# Dedication

To my parents

# Contents

# List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Do, V.H., La, N., Mulia, R., Bergkvist, G., Dahlin, A.S., Nguyen, V.T., Pham, H.T. & Öborn, I. (2020). Fruit tree-based agroforestry systems for smallholder farmers in northwest Vietnam — A quantitative and qualitative assessment. *Land*, vol. 9 (11), p. 451.

II. Do, V.H., La, N., Bergkvist, G., Dahlin, A.S., Mulia, R., Nguyen, V.T. & Öborn, I. (2023). Agroforestry with contour planting of grass contributes to terrace formation and conservation of soil and nutrients on sloping land. *Agriculture, Ecosystems & Environment*, vol. 345, p. 108323.

III. Do, V.H., La, N., Bergkvist, G., Dahlin, A.S., Mulia, R. & Öborn, I. Spatial variation in crop growth, yield and soil fertility within fruit tree agroforestry on steeply sloping land (manuscript).

IV. Do, V.H., La, N., Öborn. I., Dahlin, A.S., Mulia, R. & Bergkvist, G. Impact of weed management practices in fruit tree agroforestry on sloping uplands (manuscript).

The contribution of Hung Van Do to the papers included in this thesis was as follows:

I. Main author. Planned the study together with the co-authors. Followed up the experimental work from 2014. Collected the data with the national partners and carried out data analyses with guidance from the supervisors. Wrote the manuscript together with the co-authors.

II. Main author. Designed the field experiments and planned the study together with the supervisors (co-authors). Conducted the experimental work with local farmers, extension workers and ICRAF staff. Collected the data and carried out data analyses with guidance from the supervisors. Wrote the manuscript together with the co-authors.

III. Main author. Designed the field experiments and planned the study together with the supervisors (co-authors). Conducted the experimental work with local farmers, extension workers and ICRAF staff. Collected the data and carried out data analyses with guidance from the supervisors. Wrote the manuscript together with the co-authors.

IV. Main author. Designed the field experiments and planned the study together with the supervisors (co-authors). Conducted the experimental work with local farmers, extension workers and ICRAF staff. Collected the data and carried out data analyses with guidance from the supervisors. Wrote the manuscript together with the co-authors.

# List of tables

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# Abbreviations

| | |
|---|---|
| 2xHAND | Two hand hoeings |
| AFM | Between two tree rows |
| AL | Above longan tree-grass row |
| AM | Above mango tree-grass row |
| AP | Above plum tree-grass row |
| BL | Below longan tree-grass row |
| BM | Below mango tree-grass row |
| BP | Below plum tree-grass row |
| HERB | One herbicide application |
| HERB+HAND | Herbicide application and hand hoeing |
| HI | Harvest index |
| K | Potassium |
| LER | Land equivalent ratio |
| Longan-maize-AF | Longan, maize and forage grass agroforestry system |
| Longan-mango-AF | Longan, mango, maize and forage grass agroforestry system |
| N | Nitrogen |
| P | Phosphorus |
| pLER | Partial land equivalent ratio |
| Plum-maize-AF | Plum, maize and forage grass agroforestry system |
| SOC | Soil organic carbon |
| Sole-coffee | Sole-crop coffee |
| Sole-longan | Sole-crop longan |
| Sole-maize | Sole-crop maize |

| | |
|---|---|
| Sole-son tra | Sole-crop son tra |
| Son tra-coffee-AF | Son tra, coffee and forage grass agroforestry system |
| Son tra-guinea-AF | Son tra and guinea grass agroforestry system |
| Son tra-mulato-AF | Son tra and mulato grass agroforestry system |

# 1. Introduction

Upland agricultural systems are critical to global food production (Wang *et al.*, 2022b). Agricultural landscapes in hilly and mountainous regions are widely associated with intensive food production, historical heritage and cultural ecosystem services (Wang *et al.*, 2022a). Sloping land is an important land resource for upland agriculture. However, on sloping terrain soil degradation and unsustainable farming systems are exacerbated by reduced soil infiltration capacity, topographical characteristics, irregular rainfall events and inappropriate agricultural management techniques (Mao *et al.*, 2020).

Southeast Asia has 8.5% of the world's population and accounts for 3.0% of global land area and 7.9% of the agricultural land base (van Noordwijk *et al.*, 2020). In the region, uplands represent 19% of total land area and contribute to 27% of agricultural production (Dixon *et al.*, 2001). Most of the upland areas in Southeast Asia are characterised by insufficient infrastructure, low productivity in smallholder crop and animal production, mounting environmental problems such as soil and forest degradation and biodiversity loss, increasing population pressure and widespread poverty, particularly in rural areas (Zeller *et al.*, 2010). Steep slopes, high rainfall intensity, seasonally dry periods and naturally erodible soils are common characteristics of natural systems in mountainous areas of Southeast Asia (Sidle *et al.*, 2006).

However, mountainous areas of Southeast Asia are now undergoing rapid change. Traditional shifting agriculture has been replaced by intensified systems with planting of annual crops, extensive tillage and shorter or no fallow period (Dung *et al.*, 2008; Ziegler *et al.*, 2009; Hilger *et al.*, 2013). The drivers of this transition include economic development, policy changes, new technologies and population growth (Schreinemachers *et al.*, 2013). In the region, agricultural intensification on sloping areas has altered land use patterns and water cycles, increased agrochemical use and accelerated erosion of mountain slopes. All of this has impaired livelihoods and access to resources for people living in these areas (Fox, 2000; Wezel *et al.*, 2002; Douglas, 2006; Clemens *et al.*, 2010; Schmitter *et al.*, 2010; Tuan *et al.*, 2014; Do *et al.*, 2020).

Vietnam has a total surface area of 33 million hectares, of which 75% of the land area is hilly and mountainous. Approximately 20% of Vietnam's upland areas are classified as 'barren lands' (Nikolic *et al.*, 2008), deriving from past forested areas and exhibiting severely low production. The mountainous region in the northwest of the country is particularly prone to erosion, due to its high proportion of cultivated sloping land and high rainfall intensity concentrated within a few months (Staal *et al.*, 2014). Around 60% of land in the region has slope ≥ 30% (Staal *et al.*, 2014) and 38% has a thin soil layer (<50 cm). Apart from steep slopes, frequent occurrences of extreme weather events such as droughts and flash floods characterise the region.

Northwest Vietnam is home to ethnic minorities with a poverty rate of roughly 14% in 2016, which is 8% higher than the national average, according to official 2017 statistics (GSO, 2018). The local people rely heavily on smallholder agriculture as their primary source of income (Hoang *et al.*, 2017). In the region, sole-crop cultivation on steep slopes, *e.g.* of maize, upland rice, cassava and coffee, involves intensive tillage combined with burning of crop residues (Tuan *et al.*, 2014; Hoang *et al.*, 2017), and is accompanied by poor handling of herbicides for weed control. This frequently results in unsustainable agricultural production and threatens environmental sustainability, human health and food security in the region.

Annual soil erosion from slash and burn practices ranges from 174 tons $ha^{-1}$ in maize production (Tuan *et al.*, 2014) to 200-300 tons $ha^{-1}$ in upland rice production (Bui, 1990). Soil loss in upland areas with seasonal crops is estimated to be 40-100 tons $ha^{-1}$ $year^{-1}$, or 124 tons $ha^{-1}$ $year^{-1}$ after shifting cultivation (Siem & Phien, 1999). This represents a major nutrient loss route, along with residue burning (Tuan *et al.*, 2014). Nutrient losses have a negative impact on crop yield, *e.g.* one study found that yield of maize and cassava was significantly reduced, by 27% and 31%, respectively, due to 10-22% reductions in soil organic matter, nitrogen (N) and phosphorus (P) concentrations (Wezel *et al.*, 2002). Weeds are also a major issue reducing agricultural productivity in the region (Casimero *et al.*, 2022). This results in yield losses and high investment costs for labour or chemicals for weed management. Due to labour shortages and increasing costs of farm labour, farmers have become reliant on herbicides to control weeds.

Owing to uncertain prices and markets, farmers in the region have recently changed from maize or low-value crops to fruit trees or other crops with higher economic value (Dang & Nguyen, 2020). The number of smallholder fruit tree farms in several areas of northwest Vietnam is growing, owing to the substantial economic benefits. For example, according to the General Statistics Office of Vietnam (2020), the combined area of fruit-tree plantations in Dien Bien, Yen Bai and Son La provinces reached 74,500 ha in 2020, a 60% increase from 2015. Longan (*Dimocarpus longan* L.), mango (*Mangifera indica* L.) and plum (*Prunus salicina* L.) are the primary fruit commodities. Son tra (*Docynia indica* (Wall.) Decne), commonly known as H'Mong apple, is a native of the region and can grow at high elevation (Tiep *et al.*, 2018). Smallholder farmers in northwest Vietnam have also replaced 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 thus interested in, and aware of, the benefits of combining coffee with trees (Nguyen *et al.*, 2020). In addition, livestock rearing is a main source of income in the region, after tree plantations and crop production. At the same time, 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 (Otieno *et al.*, 2021).

Agroforestry has been proposed as an option to secure the livelihoods of smallholders and as a suitable farming system for areas where people are particularly poor and natural forests have degraded (Luedeling *et al.*, 2014; Mbow *et al.*, 2014; Hoang *et al.*, 2017; van Noordwijk *et al.*, 2020). Agroforestry has long been recognised 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). One of the most common agroforestry practices on sloping land is growing annual crops in between perennial shrub hedgerows, where shrub species are planted in single or double rows along contour lines (Catacutan *et al.*, 2017). Agroforestry based on fruit or timber trees has been suggested for use in sustainable future agricultural production on steeply sloping land in northern Vietnam (Zimmer *et al.*, 2018). Growing fruit trees with an annual crop could offer farmers a stable income (Hilger *et al.*, 2013).

However, information on agroforestry practices that are suitable, beneficial and economically, socially and environmentally sustainable for upland areas of northwest Vietnam is still limited. Furthermore, farmers in the region generally lack technical knowledge of agroforestry, particularly fruit tree-based agroforestry, in terms of appropriate species composition, optimal plant arrangement and spacing, and management practices to optimise product and ecosystem service delivery over time. Reliable scientific-based knowledge on permanent combinations of fruit trees and crops is required to develop agroforestry systems into sustainable agricultural systems on sloping terrain and to provide farmers in the region with long-term and diverse income sources through product diversification.

# Objectives

## 1.1 Overall aim

The overall aim of this thesis was to examine whether fruit tree-based agroforestry on smallholder farms on sloping uplands can be designed to have a positive impact on sustainability.

## 1.2 Specific objectives

Specific objectives of the work were to:

- Evaluate tree/crop performance and the profitability of agroforestry systems compared with sole-crop trees and crops, identify possibilities for improvement and wider-scale development, and assess whether farmers' perceptions on agroforestry system performance can be used to identify possibilities for improvements and wider-scale development of agroforestry (Paper I).

- Assess the impact of agroforestry practices on soil movement, terrace formation, soil and nutrient conservation (soil organic carbon, N, P, K losses) compared with sole crops on sloping land (Paper II).

- Determine the spatial variation in maize crop performance (plant height, leaf N concentration, yield) and soil fertility within fruit tree agroforestry on sloping land, assess the effect of different fruit trees species on maize and fodder grass performance and yield, and compare soil fertility at various positions along the slope in relation to tree and grass rows (Paper III).

- Evaluate the impact of weed management practices on weed abundance, tree/crop growth and yield of fruits, maize and fodder grass in agroforestry on sloping land and the effects of complementing or replacing one herbicide treatment with hand hoeing (Paper IV).

# 2. Background

## 2.1 Agroforestry

Agroforestry is a collective term for “land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land management unit as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence. In agroforestry systems there are both ecological and economic interactions between the different components” (Lundgren & Raintree, 1982).

In order to evaluate and formulate an action plan for improvement, the different agroforestry practices need to be categorised and divided into distinct groups (Nair, 1991; Sinclair, 1999). This can be done based on factors such as structure (composition and arrangement of components), functions, socioeconomic management scale and ecological dispersion. However, because all agroforestry systems comprise only three fundamental sets of components, namely woody perennials (often referred to as ‘trees’), herbaceous plants/crops and animals, a logical and straightforward first step is to classify agroforestry practices based on their component composition. Thus, there are three primary types of agroforestry: agrosilvicultural (crops and trees), silvopastoral (grazing animals + trees) and agrosilvopastoral (crops + grazing animals + trees) (Table 1).

The literature on this topic has grown to create a major scientific field throughout the past 40 years of agroforestry research (Liu *et al.*, 2019; van Noordwijk, 2019). Agroforestry is seen as a viable solution for sustainable farming as it can 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).

Table 1. *Types of agroforestry practices (sources: Nair, 1991; Sinclair, 1999)*

| | |
|---|---|
| *Agrosilvicultural* | - Improved fallow: woody species planted and left to grow during the fallow period.<br>- *Taungya*: combined stand of woody and agricultural species during early stages of establishment of forest plantations.<br>- Alley cropping (hedgerow intercropping): woody species in hedges; agricultural species in alleys between hedges; micro zonal or strip arrangement.<br>- Multilayer tree gardens: multispecies, multilayer dense plant associations with no organised planting arrangement.<br>- Multipurpose trees on cropland: trees scattered haphazardly or according to some systematic patterns on bunds, terraces or plot/field boundaries.<br>- Plantation crop combinations: integrated multi-storey mixtures of plantation crops; plantation crops in alternating bands; shade trees for plantation crops; shade trees scattered; intercropping.<br>- Home gardens: an intimate, multi-story mixture of diverse trees and crops surrounding homesteads.<br>- Trees used for soil conservation and reclamation in crop fields: trees on bunds, terraces, raisers *etc*. with or without grass strips for fodder.<br>- Shelterbelts and windbreaks, live hedges: trees around farmland/plots.<br>- Fuelwood production: inter-planting fuelwood species on or near agricultural lands. |
| *Silvopastoral* | - Trees on rangeland or pastures: trees scattered irregularly or arranged according to some systematic pattern.<br>- Protein banks: production of protein-rich tree fodder on farmland/rangeland for cut-and carry fodder production.<br>-Plantation crops with pastures. |
| *Agrosilvopastoral* | - Home gardens involving animals: intimate, multi-storey combination of various trees and crops, and animals, around homesteads.<br>- Multipurpose woody hedgerows: woody hedges for browsing, mulch, green manure, soil conservation *etc*., together with crops<br>- Apiculture with trees and crops for honey production.<br>- Aqua forestry: trees lining fishponds in crop fields, tree leaves being used as 'forage' for fish.<br>- Multipurpose woodlots: for various purposes (wood, fodder, soil protection, soil reclamation *etc*.) |

Agroforestry can also supply environmental services, including controlling surface runoff and erosion, increasing soil fertility, contributing significantly to climate change adaptation and mitigation, and providing resilience to extreme weather events compared with sole-crop cultivation (Montagnini & Nair, 2004; Ramachandran Nair *et al.*, 2010; Atangana *et al.*, 2014; Muchane *et al.*, 2020; Zhu *et al.*, 2020). Moreover, the system can increase biodiversity by incorporating various plant/crop species that serve as homes for various wildlife (Kalaba *et al.*, 2010; Assogbadjo *et al.*, 2012; Santos *et al.*, 2019).

## 2.2 Tree/crop interactions in agroforestry

When plants grow close together, they interact either positively (complementarity) or negatively (competition). The essence of agroforestry from a biophysical perspective is to manipulate the relationship between the tree component and the crop and/or livestock components in terms of light, water and nutrients to the advantage of the farmer (Sanchez, 1995). The interactions between trees and crops have always been a major factor influencing the management practices used by farmers in mixed agricultural systems (Bayala *et al.*, 2015). These interactions generate differences between agroforestry and sole crop cultivation or pure forestry stands, and are at the core of agroforestry studies. In many environments, interactions between trees and crops can result in higher yields in agroforestry compared with sole tree and crop cultivation (Graves *et al.*, 2007; Osman *et al.*, 2011; Dubey *et al.*, 2016). Agroforestry system design can capitalise on these advantages to generate economic benefits (Dyack *et al.*, 1998; Artru *et al.*, 2017; Lovell *et al.*, 2018), but this requires specialist knowledge of the intricate tree-crop interactions in operation (Dupraz *et al.*, 2019).

### 2.2.1 Aboveground utilisation of light

Capture and use of solar radiation has received the most attention among the primary environmental parameters that contribute to reported advantages of agroforestry (Keating & Carberry, 1993). The higher total yield in agroforestry are frequently attributed to more efficient utilisation of light by tree canopies. Light capture in agroforestry is dependent on the fraction of incident photosynthetically active radiation (PAR) partitioned by heterogeneous canopies and intercepted by each species, as well as the efficiency with which intercepted radiation is converted by photosynthesis (Malézieux *et al.*, 2009). However, agroforestry practices may cause crops and trees to compete for resources, and crops may not receive enough light because of dense tree canopy (Gao *et al.*, 2013). Compared with sole-crop systems, intense shading by large, evergreen trees reduces the yield of intercropped crops in agroforestry systems (Bayala *et al.*, 2002; Teklehaimanot, 2004; Pouliot *et al.*, 2012; Coulibaly *et al.*, 2014; Zhang *et al.*, 2019; Blanchet *et al.*, 2022). Pruning as a tree management technique can be used to change tree crown architecture in order to increase light availability (Bayala *et al.*, 2015; Dilla *et al.*, 2019; Nyaga *et al.*, 2019). Growing C3 crops instead of C4 crops may be another option, as previous studies have indicated that C3 crop yields are less affected by shade from trees (Rao *et al.*, 1997; Thevathasan & Gordon, 2004). Another option is to grow shade-tolerant crops underneath the tree canopy (Bazié *et al.*, 2012). Greater plant spacing between trees, crops and grass strips would lessen competition, in particular in maturing agroforestry systems (Bazié *et al.*, 2012; Gao *et al.*, 2013).

### 2.2.2 Belowground utilisation of water and nutrients

Belowground competition occurs when plants reduce the growth, survival, or fertility of neighbouring plants by limiting access to soil water and nutrients. However, analysis of belowground processes and resource use by plants presents enormous challenges and, despite advances in techniques and equipment design, there are still general methodological difficulties (Malézieux *et al.*, 2009). In belowground competition, plants compete for a wide range of soil resources, including water and nutrients that differ in molecular size, valence, oxidation state and mobility within the soil, whereas aboveground competition primarily involves a single resource such as light (Casper & Jackson, 1997). In agroforestry, tree roots can compete with intercrop root systems for soil water and nutrients (Casper & Jackson, 1997; Zamora *et al.*, 2008; Bouttier *et al.*, 2014). Due to belowground competition for nutrients and water, trees planted as hedgerows can have a negative impact on the growth of crops planted next to them (Pansak *et al.*, 2007; Guo *et al.*, 2008; Hussain *et al.*, 2015). The presence of tree roots, particularly in the cropping zone, influences crop competitiveness determined by factors such as inherent rooting patterns, management and soil conditions. Crops in turn inhibit root development of trees in the cropping zone (Schroth &

Lehmann, 1995; Lehmann *et al.*, 1998; van Noordwijk *et al.*, 2015; Zhang *et al.*, 2015; Nyaga *et al.*, 2019). The level of competition varies depending on the tree and crop species present. For example, in maize agroforestry, leguminous tree species compete less with maize for N than non-leguminous species (Okorio *et al.*, 1994; Bertomeu, 2012; Nyaga *et al.*, 2019). Tree root pruning effectively reduces root development and may lessen potential belowground competition with intercropped plants (Peter & Lehmann, 2000). According to Zhao *et al.* (2012), depending on species combination, the necessity for modifying the spacing arrangement between trees and crops in agroforestry systems to reduce competition for natural resources may change over time.

However, many of the beneficial effects on soil expected from agroforestry derive from the root system of trees. Agroforestry components may be spatially complementary by utilising different layers of soil for their root systems. Compared with sole cropping systems, the deep roots of trees in agroforestry systems increase nutrient cycling because they can reach far down into the soil profile and access nutrients that may not be available to the root system of annual crops (Kang *et al.*, 1986; Bambo *et al.*, 2009). They can also act as a nutrient and hydraulic pump, drawing to the surface water and nutrients that are typically unavailable to crops (Allen *et al.*, 2004).

## 2.3 Agroforestry production and profitability

Agroforestry can improve plot productivity and yield over sole-crop cultivation when diverse plant components, spacing and plot management practices are used appropriately (Catacutan *et al.*, 2017). Diversification of plant components and integration of species that can provide both short-term income from annual crops and medium- to long-term products from trees or shrubs can lead to more stable plot production, food supply and economic returns over time (Xu *et al.*, 2019; Dev *et al.*, 2020). Agroforestry practices have been adopted in different regions throughout the world due to their improvement of the environment, productivity and sustainable profitability (Garrity, 2012; Thevathasan *et al.*, 2012; Wilson & Lovell, 2016).

Land equivalent ratio (LER) (Mead & Willey, 1980) can be used to calculate the productivity of intercropping in agroforestry and estimate the benefits. LER compares yields from two or more species grown together with yields from the same crops grown as pure stands. It is calculated as follows:

$$\text{LER} = \text{Intercrop1/Sole crop1} + \text{Intercrop2/Sole crop2} + \ldots \quad \text{(Eq. 1)}$$

LER >1.0 implies that mixed systems are advantageous, whereas LER <1.0 suggests that mixed systems have a yield disadvantage.

Partial land equivalent ratio (pLER) is the land equivalent ratio of specific crops grown in intercropping compared with their yield when grown alone (Himmelstein *et al.*, 2017). It is calculated as:

$$\text{pLER} = \text{Crop yield in intercropping/Crop yield in sole crop} \quad \text{(Eq. 2)}$$

According to Lehmann *et al.* (2020), LER can be employed to estimate agronomic productivity, whereas gross margin is used as an indicator for determining economic viability. The latter is essential since increasing yield and stable prices for farm products are the primary drivers of agroforestry adoption (Network, 2018). However, agroforestry has a significant initial investment cost that results in net losses in the first few years (Do *et al.*, 2020). Farmers may be able to increase economic profitability and land use efficiency by using appropriate plant spacing and management practices in agroforestry (Das *et al.*, 2022). In addition, in order for farmers to overcome the effects of competition and maximise the efficiency of land use, management of the tree and crop components of agroforestry needs to change from the year of establishment to when the trees are mature and high-producing (Thevathasan & Gordon, 2004).

## 2.4 Agroforestry for soil conservation

Soil degradation is a global issue and is exacerbated by a variety of factors, such as rapid land use intensification, rapid expansion of unsustainable agricultural practices, deforestation, mining, construction and urban development to meet the needs of a growing population (Karlen & Rice, 2015). This endangers sustainable development by degradation of natural resources, leading to reduced crop yields, lower income for farmers and threats to food security. Soil degradation processes include soil loss by erosion, loss of soil organic matter, nutrient depletion and imbalances, salinisation, surface sealing, depletion of soil biodiversity, contamination, acidification, compaction and waterlogging (Karlen & Rice, 2015).

Soil conservation refers to maintenance of soil fertility based on control of soil erosion, preservation of soil organic matter, soil physical properties, soil nutrients and avoidance of toxic substances (Young, 1989). The contributions of agroforestry to soil conservation include maintenance of soil fertility and erosion control (Atangana *et al.*, 2014). More specifically, agroforestry contributes to soil conservation by providing soil cover through tree/crop canopy and litter deposition, forming a physical barrier to mitigate soil loss from sloping areas through rows or hedgerows of trees and shrubs, enhancing and preserving soil organic matter and forming stable soil structure with root systems (Kang *et al.,* 1986). Furthermore, trees in agroforestry can improve soil quality by retaining water, cycling nutrients, improving nutrient uptake by tree/hedgerow deep root systems and preserving soil fertility with residues and litter (Young, 1989). Since tree roots extend into portions of the soil profile and extract nutrients that may not be available to root systems of annual crops, agroforestry promotes more efficient nutrient cycling (Kang *et al.,* 1986).

However, a variety factors, such as system design, tree selection, rate of addition of fertiliser and manure, tree pruning, tree/crop residues, rainfall and soil vegetation cover all influence soil erosion control and soil fertility enrichment in agroforestry practices (Oelbermann *et al.*, 2006).

### 2.4.1 Agroforestry for erosion control

Agroforestry with tree and crop combinations such as contour planting and alley cropping is commonly used in the tropical region to control soil erosion. These tree and crop combinations increase soil cover through canopy cover and litter (dead leaves, twigs, branches and living material from pruning), create vegetative barriers and preserve or provide soil organic matter to minimise erosion rates and stabilise physical soil structures (Atangana *et al.*, 2014). The litter decomposes and is partly transformed into soil organic matter, which helps to reduce runoff flow rates and increases water infiltration, as well imparting resistance to erosion (Smith *et al.*, 2013). In addition, a mulch or litter cover on the soil surface reduces the effect of raindrops and creates a micro-barrier to runoff and erosion (Young, 1989).

The most common agroforestry systems in sloping areas involve growing annual crops in between perennial shrub hedgerows, where shrub species are planted in single or double rows on sloping land and along contour lines (Catacutan *et al.*, 2017). Through this, biological barriers are established and play a direct role in erosion reduction. These vegetative barriers minimise slope length and inclination, and alter the hydrology of overland flow (Kagabo *et al.*, 2013; Atangana *et al.*, 2014; Are *et al.*, 2018).

Growing a combination of trees and grass in strips along contours is another successful measure to reduce surface run-off and erosion by agroforestry (Udawatta *et al.*, 2002; Lenka *et al.*, 2012; Rutebuka *et al.*, 2021). This may include using trees and grasses to create physical soil conservation structures such as bench terraces that mitigate erosion in cultivation on sloping land (Garrity, 1996, 1999). Physical soil conservation structures often develop over time through progressive sedimentation of soil behind living grass strips, and trees or shrubs planted on or near the structures may help reinforce and stabilise these structures (Rutebuka *et al.*, 2021).

In non-mountainous regions, windbreaks (shelterbelts) and riparian (riverside) buffer systems are important for controlling soil erosion caused by wind and water (Gordon *et al.*, 2018). Windbreaks are classified as trees or shrubs planted in a straight line for environmental reasons. The effectiveness of a windbreak in minimising wind speed and thus contributing to soil loss control can be calculated in part from its external structure, which is defined by height, duration, orientation, continuity, width and cross-sectional shape (Brandle *et al.*, 2004). Riparian buffers are planted strips of trees, shrubs and grass between cropland or pasture and surface watercourses. Riparian buffer plants aid in managing soil erosion by stabilising soil with their roots and serving as a physical barrier to limit overland water flow (Schultz *et al.*, 1997). In addition, herbaceous vegetation in tree rows helps to reduce surface run-off and erosion and can have a terracing effect when planted along contour lines (Dupraz *et al.*, 2018).

### 2.4.2 Agroforestry for soil fertility improvement

In agroecosystems, soil organic carbon (SOC) is a significant determinant of soil fertility (Kamau *et al.*, 2020). The combination of trees and crop components in agroforestry enhances SOC concentration by adding increased quantities of litter, both above and below ground, compared with sole-crop systems. Total SOC stocks are thus higher in agroforestry systems in tropical areas than in sole-crop cultivation under comparable conditions (Chatterjee *et al.*, 2018). In addition, agroforestry practices can be highly successful in increasing SOC stocks to a depth of 100 cm and the contribution of agroforestry practices to improving SOC increases over time (Chatterjee *et al.*, 2018).

Leguminous trees such as *Leucaena* spp. (leucaena), *Gliricidia sepium* (gliricidia), *Flemingia congesta*, *Erythrina* spp., *Sesbania sesban* or *Senna spectabilis* are often planted in agroforestry systems for their ability to fix atmospheric $N_2$. They can generate more biomass than other species in a N-deficient soil. In addition, this N becomes available to other components of the agroforestry system over time, eventually leading to increased biomass production overall (Jose, 2009).

Another significant benefit of agroforestry is its potential to increase nutrient cycling through perennial shrubs and trees, which can absorb nutrients from deeper layers of the soil, thus contributing to soil improvement (Bambo *et al.*, 2009; Pardon *et al.*, 2017; Dollinger & Jose, 2018).

Decomposition of litter (dead leaves, twigs and branches and living material from pruning) provides nutrients that help improve tree/crop yield (Henriksen *et al.*, 2002; Dollinger & Jose, 2018). The litter decomposition process also contributes significantly to the formation of soil organic matter and improves nutrient cycling in agroforestry systems (Quinkenstein *et al.*, 2009; Youkhana & Idol, 2009). The rate of litter decomposition and nutrient release differs depending on the tree species, the nutrient content in the litter and the climate.

## 2.5 Spatial variation in tree/crop performance and soil fertility in agroforestry

Depending on the tree/crop components used, the system design and management practices, agroforestry systems naturally exhibit variability in terms of the productivity of the constituent trees and crops, the fertility of the soil and the available plant nutrients. According to Nyaga *et al.* (2019), system design, tree/crop components and their spatial arrangement directly affect system performance and tree-crop interactions and also play a significant role in determining the resource use efficiency of agroforestry systems. In overall evaluations of agroforestry performance and of the complex interactions between trees and associated crops, it is crucial to consider spatial variability in tree/crop performance and soil fertility within agroforestry systems (Wengert *et al.*, 2021). Awareness of spatial variability is also important among agroforestry managers, since it has a direct impact on system productivity, ability to provide ecosystem services, and capacity to mitigate and adapt to climate change (Roupsard *et al.*, 2020). Understanding the spatial variability in soil properties is thus essential to support land management decisions (Takoutsing *et al.*, 2017; Santos *et al.*, 2023).

Point measurements along transects are often used in studies on the spatial distribution of tree/crop performance and yield-related tree/crop parameters in agroforestry (Kanzler *et al.*, 2019; Nyaga *et al.*, 2019; Seserman *et al.*, 2019; Swieter *et al.*, 2019). They can also be useful in studies on the spatial distribution of soil properties within agroforestry. Emerging methods for mapping plant features with high spatial resolution and coverage based on remote sensing by unmanned aerial vehicles (UAVs) are increasingly being used to examine the spatial variability in tree/crop performance in agroforestry (Iwasaki *et al.*, 2019; Leroux *et al.*, 2020; Roupsard *et al.*, 2020; Wengert *et al.*, 2021). Spatial variability in crop performance and resource distribution can also be assessed in simulations using modelling techniques. The modelling tools that have been applied to date include Hi-sAFe (A 3D Agroforestry Model for Integrating Dynamic Tree-Crop Interactions) (Dupraz *et al.*, 2019), APSIM (model Agricultural Production Systems Simulator) (Huth *et al.*, 2002; Dilla *et al.*, 2018) and WanulCAS (Water, Nutrient and Light Capture in Agroforestry Systems) (van Noordwijk & Lusiana, 2001).

Because of the impact of slope on soil erosion, surface run-off and plant-available water and sunlight, the variability in resource supply can be greater in agroforestry on steep slopes than on flat terrain (Garrity, 1996). Several studies on this issue have been conducted in alley systems, in which annual crops are planted along the contour of steep slopes with trees and/or grass strips. Topsoil movement from the upper to lower parts of the alley has been found to be the primary cause of spatial variation in soil nutrients, soil water availability and crop production down the slope direction (Garrity, 1996, 1999; Niang *et al.*, 1997; Dercon *et al.*, 2006; Guto *et al.*, 2012).

However, the degree of resource variability in agroforestry on steep slopes is also highly dependent on the type of tree/crops and system management, and becomes more complex as systems incorporate more tree/crop components. Analysis of the spatial arrangement in agroforestry systems where trees, crops and grasses are planted along contours and the impact on tree/crop performance and soil nutrients is needed in order to identify how resources can be used more effectively in such systems on steep slopes.

## 2.6 Weed management in agroforestry

Weed plants are a constitutive component of agroecosystems and can cause significant economic losses. Weeds compete for key resources such as water, light, nutrients and space, reducing agricultural production and resulting in low economic returns for farmers due to yield losses and high investment costs for weed management in terms of labour or herbicides (Zimdahl, 2007).

Weeds are likely to have different effects on growth and productivity in agroforestry than in sole-crop systems, due to the greater resource heterogeneity in agroforestry (Deiss *et al.*, 2017). There is a possibility of some weeds spreading from under-row areas of a tree plantation in agroforestry to the intercropped crop area, resulting in crop yield losses (Burgess *et al.*, 2003; Meziere *et al.*, 2016; Boinot *et al.*, 2019). Weeds also have the potential to impair the performance of tree components in newly established agroforestry, since they prevent optimal growth and survival of many tree species due to competition (Schroeder, 1988; Lauer & Glover, 1999; Schroeder & Naeem, 2017). In agroforestry, weeds compete directly with tree and crop components for nutrients, light and water. They can also serve as alternate habitats for pests that target agroforestry species (Sileshi *et al.*, 2007). Agroforestry has been shown to be capable of reducing weed abundance through competition for resources (light, water, nutrients) between tree/crops and weeds (Sileshi *et al.*, 2007; Malézieux *et al.*, 2009; Pumariño *et al.*, 2015). For example, shading by trees can be a factor in weed suppression in agroforestry systems (Jama *et al.*, 1991; Macdicken *et al.*, 1996; Tscharntke *et al.*, 2011). Furthermore, some tree species can release allelopathic substances into the environment, such as weed germination or growth inhibitors (Liebman & Dyck, 1993). For example, some phytotoxic substances that affect weed germination can be released into the soil under teak trees (*Tectona grandis*) through leaf leachate and litter decomposition (Kato-Noguchi, 2021).

Conventional weed management approaches, such as chemical (herbicides) and mechanical (*e.g*. tillage, hand hoeing, weed harrowing), are widely used and are known to be efficient in reducing weed abundance. The use of herbicides is attractive to farmers because of their effectiveness in weed suppression and low labour demand, but abuse of herbicides for weed control has detrimental environmental consequences (*e.g*. contamination of soils, groundwater, rivers and lakes) (Fernandes *et al*., 2020). It can also affect the health of farm workers (Bajwa *et al.*, 2015).

Herbicide use can result in strong selection for features linked with tolerance, increasing the chances of weed populations acquiring herbicide resistance. Even without resistance, species similar to the crop are more difficult to kill with herbicides and therefore there is a great risk that they will propagate and be the first to develop herbicide resistance (MacLaren *et al.*, 2020). Mechanical weed control methods can be successful in reducing weeds, but they can be costly in terms of time (labour) and harm to nearby non-target plants.

Weed management is more complex in agroforestry systems with several tree/crop components. In addition, each type of tree or crop used has a different degree of weed competition and requires a different weed management approach. To reduce weed abundance and selection pressure on weeds, it may be necessary to use mixed methods of weed control and balance this against short-term economic returns. For example, combining good tree-crop planting geometry with appropriate weed control strategies increases crop production, which is critical for the viability of agroforestry-based cropping systems (Parija *et al.*, 2023). Appropriate weed control strategies for agroforestry systems still need to be identified.

## 2.7 Constraints on wider adoption of agroforestry

Adoption of agroforestry as a sustainable farming system is influenced by a variety of factors. For example, in terms of economic efficiency, agroforestry is a costly undertaking that involves high establishment costs, including labour costs (Mwase *et al.*, 2015; Wolz *et al.*, 2018). It may also result in net losses during the first few years (Do *et al.*, 2020). Other barriers to agroforestry adoption include unstable output markets, as well as price and yield uncertainties associated with tree and crop products (Do *et al.*, 2020; Sollen-Norrlin *et al.*, 2020). In addition, farmers may face challenges in converting their existing crop fields to agroforestry due to a lack of expertise, finance and time, as well as the inherent risks associated with adoption of a new practice (Zamora & Udawatta, 2016; Tschora & Cherubini, 2020). Moreover, the volatile weather conditions at high altitude create high risks for agroforestry implementation, with climate conditions varying depending on the particular local context (Lee *et al.*, 2020). Ultimately, government definitions of ‘good farming practices’ need to include agroforestry in order to increase acceptance and transparency for sustainable farming, but knowledge of context-specific best practice options is still restricted (Zinngrebe *et al.*, 2020). Land scarcity and insecure tenure are other barriers to scaling up agroforestry practices (Catacutan *et al.*, 2017; Gordon *et al.*, 2018).

## 2.8 Agroforestry in Vietnam

Agroforestry has been documented in Vietnam since the 1960s and the evolution from 1960 to present can be separated into four major periods: 1960-1990, 1990-2000, 2000-2004 and 2004-present (Nguyen & Catacutan, 2012).

During the period 1960-1990, there were two forms of agroforestry combining different farming systems, namely garden-fish-pond-livestock (VAC) and forest-garden-fish pond-livestock (RVAC). The VAC system was widely adopted by farmers and quickly spread throughout lowland areas of the country. VAC was regarded as the ultimate subsistence farming system, with effective resource allocation among system components. The RVAC system was introduced following large-scale migration of people from the lowlands to the central highlands and mountainous regions in the 1980s, as part of the government’s goal to establish new economic zones (Simelton *et al.*, 2017).

The period 1990-2000 was strongly influenced by the Vietnamese government’s reform programme "Doi Moi" (started in 1986), which aimed at de-collectivising cultivated land and converting subsistence farming to commodity production. Farmers invested more in their allocated land and small-scale fruit trees and home gardens developed in the country between 1990 and 2000. In addition, in the 1990s the Vietnamese government made a significant push for reforestation, following a rapid decrease in forest in mountainous areas in the period 1960-1980. According to Nguyen &

Catacutan (2012), *taungya* (intercropping of crops and trees in the first years after tree planting, see definition in Table 1) was one of the most commonly used agroforestry systems in government reforestation programmes.

In the period 2000-2004, there were more widespread fruit gardens throughout the nation, forest gardens in the north and a growing tendency for adoption of *taungya* systems in the north and south central regions, with the aid of a reforestation programme.

Since 2004, the northern uplands and south central areas have seen an increase in small woodlots, alley cropping and *taungya* systems with a diverse variety of species, as well as intercropping of different tree species (mainly in the north). In the decades since the Doi Moi programme, there has been a rapid increase in intensified cultivation on steep slopes in northwest Vietnam, with crops such as maize, cassava, paddy and upland rice, coffee and tea grown with the aim of increasing farmers' income (Hoang *et al.*, 2017). However, intensified cultivation with unsustainable farming techniques has impaired livelihoods and caused environmental issues in the region. More recent studies have shown that local farmers lack the financial resources to shift from conventional intensified crop production to novel sustainable practices such as agroforestry (Zimmer *et al.*, 2018). The unstable market and uncertainties in yield and prices for tree and crop products in northern Vietnam are other constraints on agroforestry adoption (Thang *et al.*, 2015; Do *et al.*, 2020). Finally, segregation of policy into agriculture and forestry has promoted sole-crop cultivation and discouraged integration of trees and annual crops in the region (Simelton *et al.*, 2017). Therefore, agroforestry is not yet an attractive option for local stakeholders.

## 2.9 AFLI projects in northwest Vietnam

To overcome the main livelihood and environmental issues in the northwest region, World Agroforestry (ICRAF) in Vietnam, in collaboration with local partners, has been carrying out research and development activities on agroforestry in upland areas in three northwest provinces (Dien Bien, Yen Bai, Son La) since 2011. The "Agroforestry for Livelihoods of Smallholder Farmers in Northwest Vietnam" (AFLI_1) was a five-year project (2011-2016) with the overall goal of using agroforestry to improve the performance of smallholder farming systems in the target region (La *et al.*, 2019a). The project offered techniques, seedlings, farmer training and on-farm experiments to help farmers establish more sustainable agriculture systems using agroforestry than their present practices of annual sole crops. The initiative aimed to raise the productivity of connected tree/crops and livestock systems, for example by producing fodder and fruit in the systems together with annual crops, resulting in more diverse and sustainable production systems and greater income.

From 2017 to 2021, the project “Developing and Promoting Market-Based Agroforestry and Forest Rehabilitation Options for Northwest Vietnam” (AFLI_2) was active. Its aim was to create and promote market-based agroforestry options in order to improve livelihoods and forest and landscape management (La *et al.*, 2022). Significant potential for agroforestry adoption in the region was identified (Nguyen, 2020). For instance, biophysical suitability research revealed that agroforestry would be feasible on roughly 85% of cropland areas in the region with slope >27%. The main ethnic groups in the area, such as the Kinh, Thai and H'mong, have a positive attitude to the advantages of agroforestry and, despite their limited resources, farmers in the area are eager to undertake agroforestry.

The first years of the work reported in this thesis were carried out as part of the AFLI projects.

# 3. Materials and methods

## 3.1 Study sites

Field research was conducted in the northwest uplands of Vietnam (21°-23°N; 103°-105°E), in the provinces of Dien Bien, Son La and Yen Bai (Figure 1). Dien Bien is a mountainous province bordering Lao PDR and China, with more than 50% of its land area at elevation greater than 1000 m above sea level (asl). The elevation of Son La province ranges from 100 to 2900 m asl, with slope ranging from 46 to 57%. Yen Bai province is situated between Vietnam's northwest and northeast regions. The western part of Yen Bai (also known as the highlands, >600 m asl) is similar to the other northwest provinces, while the eastern part (lowlands, <600 m asl) is more like the northeast (Nguyen, 2020).

Most areas in the region are characterised by a sub-humid tropical climate, with a rainy season from April to October and a dry season from November to March. Mean annual temperature is 21°C and annual rainfall ranges between 1200 and 1600 mm in Dien Bien and Son La, and 1700 and 2000 mm in Yen Bai. Around 90% of annual rainfall is concentrated in the period April-September. Most agricultural production, in either annual or perennial cropping systems, is on slopes less than 57% (Hoang *et al.*, 2017).

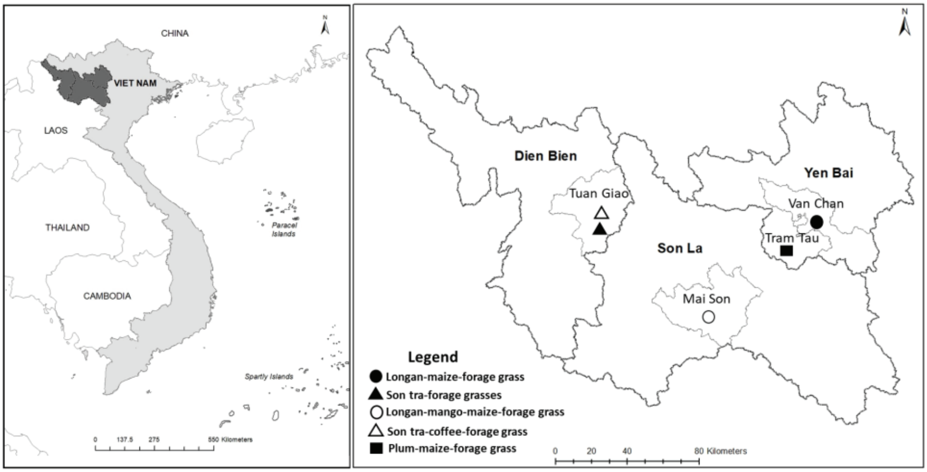


*Figure 1*. Location of the agroforestry experimental fields in Dien Bien, Son La and Yen Bai provinces in northwest Vietnam.

*Figure 2.* Typical landscape in upland areas of northwest Vietnam.

Field experiments (see Table 2) were established on farms in Tuan Giao District in Dien Bien province, Mai Son District in Son La province, and Van Chan and Tram Tau Districts in Yen Bai province (Figure 1).

Table 2. *Details of the field experiments in Tuan Giao District in Dien Bien province, Mai Son District in Son La province, and Van Chan and Tram Tau Districts in Yen Bai province*

| Experiment | Longitude, latitude | Slope (%) | Elevation (m asl) | Location (district-province) |
|---|---|---|---|---|
| Longan-maize-AF | 21.56°N, 104.56°E | 27 | 374 | Van Chan-Yen Bai |
| Son tra-grasses-AF | 21.56°N, 103.50°E | 27 | 1267 | Tuan Giao-Dien Bien |
| Longan-mango-AF | 21.10°N, 104.06°E | 37 | 566 | Mai Son-Son La |
| Son tra-coffee-AF | 21.33°N, 103.30°E | 56 | 1104 | Tuan Giao-Dien Bien |
| Plum-maize-AF | 21.31°N, 104.21°E | 65 | 938 | Tram Tau-Yen Bai |

Longan-maize-forage grass agroforestry (longan-maize-AF), son tra-forage grasses (guinea and mulato) agroforestry (son tra-grasses-AF), longan-mango-maize-forage grass agroforestry (longan-mango-AF), son tra-coffee-forage grass agroforestry (son tra-coffee-AF), plum-maize-forage grass agroforestry (plum-maize-AF).

Characterisation of soil physical and chemical properties, including plant nutrient concentrations, was carried out at the five field sites before the start of the experiments (Table 3). Soil profile descriptions for the longan-maize-AF and son tra-grasses (guinea and mulato)-AF trial sites are presented in Appendix 1 and 2 to this thesis, and for the longan-mango-AF, son tra-coffee-AF and plum-maize-AF trial sites in Appendix 3.

Table 3. *Topsoil (Ap-horizon) characteristics at the different experimental sites*

| Experiment | Topsoil | Bulk density | pH[a] | SOC[a] | Total N, P, K[a] [%] | | | Available P, K[a] [mg $100g^{-1}$] | | CEC[a] | Texture [%] | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | [cm] | [g $cm^{-3}$] | [$H_2O$] | [%] | N | P | K | P | K[b] | [cmol (+) $kg^{-1}$] | <0.002 mm | 0.002-0.02 mm | 0.02-0.2 mm | 0.2-2 mm |
| Longan-maize-AF (n=3) | 0-18 | 1.15 | 4.7 | 1.74 | 0.12 | 0.02 | 0.5 | 0.50 | | 15.6 | 29 | 26 | 35 | 10 |
| Son tra-grasses-AF (n=3) | 0-18 | 1.05 | 4.6 | 3.8 | 0.24 | 0.02 | 0.85 | 0.92 | | 28.3 | 42 | 13 | 44 | 1 |
| Longan-mango-AF (n=1) | 0-17 | 1.37 | 5.5 | 1.78 | 0.15 | 0.03 | 0.31 | 0.64 | 7.6 | 15 | 18 | 40 | 36 | 6 |
| Son tra-coffee-AF (n=1) | 0-23 | 1.15 | 4.0 | 2.21 | 0.16 | 0.04 | 0.63 | 0.61 | 5.6 | 11.8 | 17 | 39 | 40 | 4 |
| Plum-maize-AF (n=1) | 0-18 | 1.18 | 4.4 | 1.76 | 0.15 | 0.07 | 0.10 | 0.14 | 2.6 | 13 | 16 | 33 | 45 | 6 |

Longan-maize-forage grass agroforestry (longan-maize-AF), son tra-forage grasses (guinea and mulato) agroforestry (son tra-grasses-AF), longan-mango-maize-forage grass agroforestry (longan-mango-AF), son tra-coffee-forage grass agroforestry (son tra-coffee-AF), plum-maize-forage grass agroforestry (plum-maize-AF).

[a]Soil pH ($H_2O$) was tested by mixing soil and water in a 1:5 ratio (TCVN: 5979, 2007). The Walkley-Black method (TCVN: 8941, 2011), Kjeldahl method (TCVN: 6498, 1999), and digestion with mixed strong acids method (TCVN: 8940, 2011 and TCVN: 8660, 2011) were used to determine SOC and total N, P and K. The Bray II method (TCVN: 8942, 2011) and the ammonium acetate method (TCVN: 8662, 2011) were used to determine available P and K. The ammonium acetate method (TCVN: 8568, 2010) was used to determine CEC (cation exchange capacity).

[b]Available K was not determined in longan-maize-AF and son tra-grasses (guinea and mulato)-AF.

.

## 3.2 Field trials and experimental design (Papers I-IV)

### 3.2.1 Field trials

The field work was carried out in two series of field trials, established 2012/2013 and 2017/2018, respectively (Table 4). The trials established in 2012/2013 compared longan (*Dimocarpus longan* L.)-maize (*Zea mays* L.)-guinea grass (*Panicum maximum* Jacq.) agroforestry (longan-maize-AF) with sole-crop maize (sole-maize) and sole-crop longan (sole-longan); and son tra (*Docynia indica* (Wall.) Decne.)-guinea grass agroforestry (son tra-guinea-AF) and son tra-mulato (*Brachiaria* sp.) grass agroforestry (son tra-mulato-AF) with sole-crop son tra (sole-son tra) (Figure 3).

Table 4. *Details of the agroforestry (AF) and sole-crop treatments*

| Agroforestry | Control | Replicates | Period | Paper |
|---|---|---|---|---|
| Longan-maize-AF | Sole-maize<br>Sole-longan | 3<br>3 | 2012-2018 | I |
| Son tra-guinea-AF<br>Son tra-mulato-AF | Sole-son tra | 3 | 2013-2018 | I |
| Longan-mango-AF | Sole-maize | 4 | 2017-2021 | II, III |
| Son tra-coffee-AF | Sole-coffee | 4 | 2017-2021 | II |
| Plum-maize-AF | Sole-maize | 4 | 2018-2021 | III, IV |

Longan-maize-forage grass agroforestry (longan-maize-AF), son tra-guinea grass agroforestry (son tra-guinea-AF), son tra-mulato grass agroforestry (son tra-mulato-AF), longan-mango-maize-forage grass agroforestry (longan-mango-AF), son tra-coffee-forage grass agroforestry (son tra-coffee-AF), plum-maize-forage grass agroforestry (plum-maize-AF), sole-crop maize (sole-maize), sole-crop longan (sole-longan), sole-crop son tra (sole-son tra), sole-crop coffee (sole-coffee).

The trials established in 2017/2018 compared longan-mango (*Mangifera indica* L.)-maize-guinea grass agroforestry (longan-mango-AF) with sole-maize, son tra-coffee-guinea grass agroforestry (son tra-coffee-AF) with sole-crop coffee (sole-coffee), and plum (*Prunus salicina* L.)-maize-guinea grass agroforestry (plum-maize-AF) with sole-maize (Figure 3).

A grafted late-maturing longan variety (PHM-99-1-1), grafted son tra seedlings (H'Mong apple), a grafted mango seedling variety (GL4), a grafted plum variety (Tam Hoa), coffee (cv. Catimor), forage guinea grass (Mombasa) and mulato grass (Mulato II) were used in the field trials. The hybrid PAC 999 maize variety was used in all treatments involving maize. All trees/crops/grasses were planted along contour lines.


*Figure 3.* Sites of the agroforestry trials. (a) Longan-maize-forage grass agroforestry (longan-maize-AF). (b) Son tra-forage grasses agroforestry (guinea and mulato)-AF. (c) Longan-mango-maize-forage grass agroforestry (longan-mango-AF). (d) Son tra-coffee-forage grass agroforestry (son tra-coffee-AF). (e) Plum-maize-forage grass agroforestry (plum-maize-AF).

### 3.2.2 Experimental design and management

The longan-maize-AF, son tra-guinea-AF and son tra-mulato-AF trials were designed as randomised complete block experiments replicated on three different farms (Figure 4). In longan-maize-AF, longan was planted at 5 m spacing in double rows along contour lines, with 15 m between two double rows (240 trees $ha^{-1}$) (Figure 4a). Guinea grass was planted in double rows 0.5 m from the trees, and the distance between two rows was 0.5 m. The seed rate, row spacing and distance between plants in sole-crop maize was 15 kg ha$^{-1}$, 0.65 m and 0.3 m, respectively. Maize plants were sown with the same row spacing and plant distance in the agroforestry system, but on a 10-20% smaller area as it was not sown in the grass strips or within 0.5 m from the canopy of longan. Sole-longan trees were planted with 5 m between-row and 5 m within-row spacing (400 trees ha$^{-1}$).

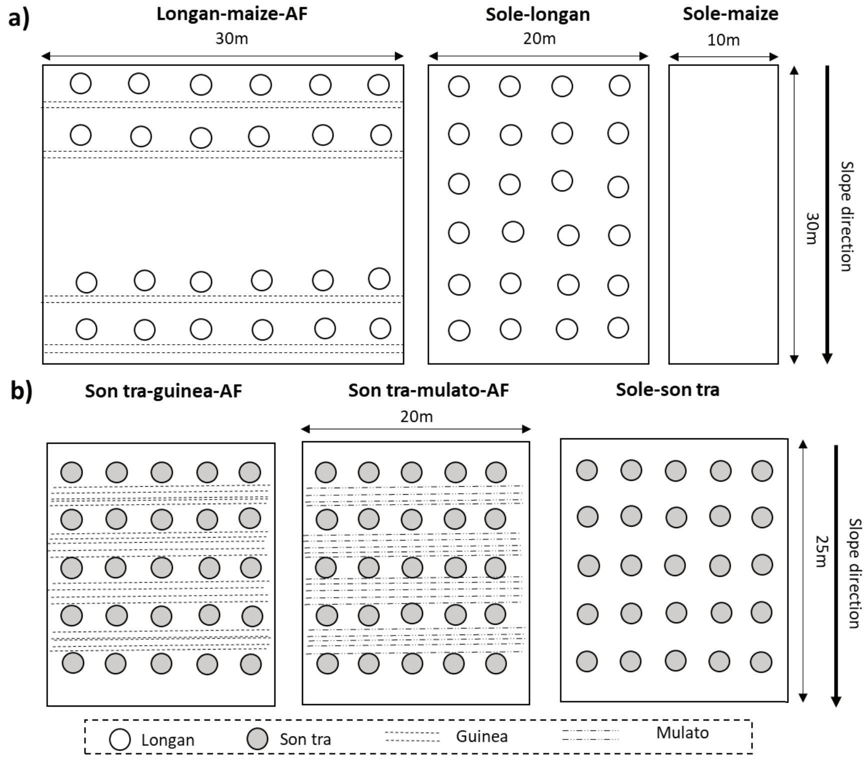


*Figure 4*. Design of trials established 2012-2013 comparing (a) longan-maize-forage grass agroforestry (longan-maize-AF, plot area 900 m$^2$), sole-crop longan (sole-longan, 600 m$^2$) and sole-crop maize (sole-maize, 300 m$^2$) and (b) son tra-guinea grass agroforestry (son tra-guinea-AF), son tra-mulato grass agroforestry (son tra-mulato-AF) and sole-crop son tra (sole-son tra) (plot area 500 m$^2$).

In the trial with son tra, the trees were planted with 5 m spacing between rows and 4 m spacing between trees within rows (500 trees ha$^{-1}$) (Figure 4b). Seven rows of guinea grass or mulato grass were planted between two rows of son tra. The distance between the grass rows was 0.5 m and the strips were 1 m from the son tra rows.

The experiments with longan-mango-AF, son tra-coffee-AF and plum-maize-AF were also laid out in a randomised complete block design with two treatments, agroforestry versus continuous sole crop, and four replicates. The four replicates were established on one fairly uniform field (Figure 5). In longan-mango-AF, trees were planted in single-species rows, with 4.0 m spacing within rows, and 10 m between tree rows (125 trees species$^{-1}$ ha$^{-1}$) (Figure 5a). Guinea grass was planted in double rows 1 m below the trees, with a spacing of 0.5 m between the 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 and plant spacing in both treatments, but on a smaller area in longan-mango-AF. The distance to above the grass strips and outside the canopy of the fruit trees was kept to 0.8 m and 0.5 m, respectively. Thus, the area of maize reduced as the tree canopy expanded, so that maize was grown on 15% less land in agroforestry in the first year and on 22% less land than in sole-maize in year 5.

In son tra-coffee-AF, trees were planted with 10 m spacing between rows and 4.0 m spacing between trees within rows (250 tree ha$^{-1}$) (Figure 5b). A double row of guinea grass was planted 1 m downhill from the son tra, 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 (2857 shrubs ha$^{-1}$). In sole-coffee, the shrubs were planted across the whole plots, with the same distance between and within rows as in son tra-coffee-AF (3571 shrubs ha$^{-1}$), resulting in 20% more shrubs than in son tra-coffee-AF.

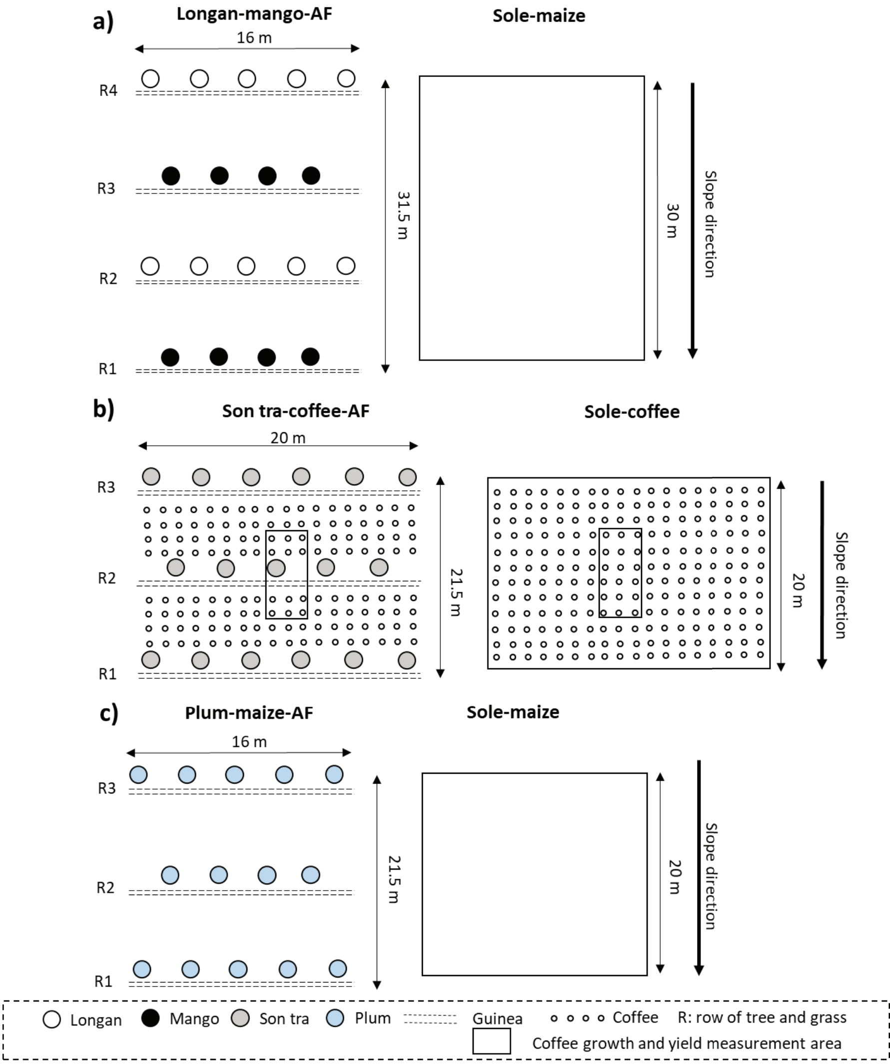


*Figure 5.* Design of field experiments established in 2017-2018 comparing (a) longan-mango-maize-forage grass agroforestry (longan-mango-AF, plot area 504 $m^2$) and sole-crop maize (sole-maize, 480 $m^2$), (b) son tra-coffee-forage grass agroforestry (son tra-coffee-AF, 430 $m^2$) and sole-crop coffee (sole-coffee, 400 $m^2$) and (c) plum-maize-forage grass agroforestry (plum-maize-AF, 344 $m^2$) and sole-crop maize (sole-maize, 320 $m^2$).

In plum-maize-AF, the trees were planted with 10 m spacing between rows and 4.0 m spacing between trees within rows (250 tree $ha^{-1}$) (Figure 5c). Guinea grass was planted in double rows 1 m below the plum trees, with a spacing of 0.5 m between the 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. The distance to above the grass strips and outside the canopy of the fruit trees was kept to 0.8 m and 0.5 m, respectively. In plum-maize-AF, the trial was established late in the growing season 2018, and hence maize was planted from year 2 onwards, on 15% and 24% less land in plum-maize-AF than in sole-maize in year 2 and 4, respectively.

Detailed information on the fertilisation regime applied in the longan-maize-AF, son tra-guinea-AF and son tra-mulato-AF plots can be found in Table S1 in Paper I, while the fertilisation regime in the longan-mango-AF and son tra-coffee-AF trials is described in Table S1 in Paper II and that in the plum-maize-AF trials in Table S2 in Paper III. In all experiments, the purpose of planting grass strips was to utilise nutrients in runoff, and therefore no nutrients were applied to the forage grasses.

Weed control for tree/crops in agroforestry and sole-tree/crop treatments is described in Table 5. In longan-maize-AF (Paper I), one herbicide atrazine (active ingredient: atrazine 800 g kg$^{-1}$ + additives: 200 g kg$^{-1}$, dose 2 kg ha$^{-1}$) application was made in both agroforestry and the sole-maize treatment before sowing maize in all years. In longan-mango-AF (Papers II-III) and plum-maize-AF (Paper III), weeds were manually hoed before sowing maize in all years. In son tra-coffee-AF and sole-coffee (Paper II), weed control was carried out at the same time as fertiliser application to the coffee shrubs, at the beginning (April), middle (July) and end (October) of the rainy season.

Table 5. *Weed control practices used in experimental fields (Papers I-III)*

| Tree/ crop | Treatment | Weed control |
|---|---|---|
| Maize | Sole-maize | One herbicide spraying when the maize had 3-4 fully expanded leaves |
| | Longan-maize-AF | One herbicide spraying when the maize had 3-4 fully expanded leaves in year 1, hand hoeing when the maize had 3-4 and 10-11 fully expanded leaves in years 2-7 |
| | Longan-mango-AF | One herbicide spraying when the maize had 3-4 fully expanded leaves in year 1, hand hoeing when the maize had 3-4 and 10-11 fully expanded leaves in years 2-5 |
| | Plum-maize-AF | Hand hoeing when the maize had 3-4 and 10-11 fully expanded leaves in years 2-4 |
| Coffee | Sole-coffee<br>Son tra-coffee-AF | Hand hoeing once in year 1, hoeing three times in years 2-3, three weed strimmings in years 4-5 |
| Fruit trees | All agroforestry and sole-fruit tree | Hand weeding around all fruit trees in longan-maize-AF, son tra-grasses (guinea and mulato)-AF, longan-mango-AF, son tra-coffee-AF, plum-maize-AF, sole-longan and sole-son tra |

Longan-maize-forage grass agroforestry (longan-maize-AF), son tra-guinea grass agroforestry (son tra-guinea-AF), son tra-mulato grass agroforestry (son tra-mulato-AF), longan-mango-maize-forage grass agroforestry (longan-mango-AF), son tra-coffee-forage grass agroforestry (son tra-coffee-AF), plum-maize-forage grass agroforestry (plum-maize-AF), sole-crop maize (sole-maize), sole-crop longan (sole-longan), sole-crop son tra (sole-son tra), sole-crop coffee (sole-coffee).

In Paper IV, weed control treatments were applied in longan-mango-AF in the maize growing season 2018-2021 and in plum-maize-AF in the maize growing season 2019-2021. The different treatments were assigned to sub-plots in all agroforestry plots. Randomisation was constrained by an installation to measure erosion that required the 2xHAND treatment (explained below) to be assigned to that area. They comprised: i) two hand hoeings when maize had 3-4 and 10-11 fully expanded leaves (2xHAND); ii) one herbicide application when maize had 3-4 fully expanded leaves and one hand hoeing when maize had 10-11 fully expanded leaves (HERB+HAND); and iii) herbicide application (control) when maize had 3-4 fully expanded leaves (HERB). Weed management in the sole-maize reference plot consisted of one herbicide application when maize had 3-4 fully expanded leaves. The area of each weed treatment plot and corresponding sole-maize reference plot was 4.0 m x 31.5 m and 4.0 m x 30 m, respectively, in the longan-mango-AF trial and 4.0 m x 21.5 m and 4.0 x 20 m, respectively, in the plum-maize-AF trial. The herbicide used in HERB+HAND, HERB and SM was atrazine (active ingredient: atrazine 800 g $kg^{-1}$ + additives: 200 g $kg^{-1}$, dose 2 kg $ha^{-1}$). At both sites and in all years, weeds were hoed by hand before sowing of maize in the agroforestry and sole-maize plots.

## 3.3 Research methods used for data collection

### 3.3.1 Tree/crop measurements and sampling (Papers I-IV)

Non-destructive measurements were applied at several growth stages over the growing season, while destructive measurements such as tree/crop biomass sampling were performed at physiological maturity (Table 6).

The growth of fruit trees and coffee plants was measured every three months over the whole experimental period, to determine base diameter, canopy diameter and height. The measurements made on longan, son tra (in the son tra-grasses-AF trial), mango and plum are described in detail in Papers I, III and IV. In the son tra-coffee-AF trial, all son tra trees in each plot were used for growth measurement, while coffee growth measurements were carried out in a 40 $m^2$ sub-area in each agroforestry and sole-coffee plot (Figure 5b).

Table 6. *Summary of different measurements performed in experimental fields*

| *Non-destructive* | Measurement | Paper |
|---|---|---|
| Tree growth[1] | Every three months | I, III, IV |
| Maize growth (height) | Four vegetative stages[2] | I, III, IV |
| Forage grass growth (height) | Monthly in growing season[3] | I and III |
| Longan leaf N concentrations[4] | At beginning and after maize season in year 7 | I |
| Maize plant N concentrations[4] | Four vegetative stages[2] | I, III, IV |
| Forage grass N concentrations[4] | Monthly in growing season[3] | I and III |
| *Destructive* | | |
| Tree fruit yield | At harvest | I, IV |
| Maize grain and stover | At harvest | I, III, IV |
| Forage grass biomass | Monthly in growing season | I, III, IV |
| Coffee yield | At harvest | This thesis |
| Weed biomass | After maize harvesting | IV |

[1]Tree and coffee growth (base diameter, canopy diameter and height). Son tra, coffee growth and yield in son tra-coffee-forage grass trial only reported in this Thesis. [2]Four vegetative stages of the maize crop (3-4, 6-7 and 10-11 fully expanded leaves, and silking), in longan-maize-forage grass at year 7, longan-mango-maize-forage grass in years 2-5 and plum-maize-forage grass in years 2-4. [3]Applied for guinea grass in longan-maize-forage grass at year 7, longan-mango-maize-forage grass in years 2-5 and plum-maize-forage grass in years 2-4. [4]SPAD measurements were used to estimate leaf N concentrations.

Measurement of maize height in all trials was carried out at four vegetative stages of the maize crop (3-4, 6-7, 10-11 fully expanded leaves, and silking) during the growing season. In the longan-maize-AF trial, maize height was only measured in year 7, as described in Paper I. In Papers I, III and IV, maize height measurements in the longan-mango-AF and plum-maize-AF trials were carried out in years 2-5 and 2-4, respectively.

Grass height (guinea grass) was measured every month during the growing season and just before harvesting the grass (Table 6). Ten guinea grass plants in each grass strip per plot were measured along a 4-m section in the longan-mango-AF and plum-maize-AF trials (Papers III) and along a 5-m section in longan-maize-AF (Paper I). No measurements were made for guinea and mulato in son tra-grasses (guinea and mulato)-AF (Paper I).

Plant (leaf) N concentration in longan, maize and guinea forage grass was monitored indirectly by using a soil plant analysis development (SPAD) 502 Plus chlorophyll meter to determine the amount of chlorophyll present in plant leaves (Minolta, 1989). The method used for measuring leaf N concentration in longan (Sritontip *et al.*, 2011) is described in Paper I, that used for maize at four vegetative stages (Argenta *et al.*, 2004) is described in Papers I, III and IV, and that used for guinea grass (Viana *et al.*, 2014) is described in Papers I and III.

Fruit yield in the longan-mango-AF and plum-maize-AF trials was determined separately for each weed control treatment (Paper IV). Fruit yield in the weed treatment involving two hand hoeings (2xHAND) is reported in this thesis. In longan-maize-AF, son tra-guinea-AF and son tra-mulato-AF (Paper I), fruit yield was determined by harvesting and weighing all fruits per trial unit. Coffee yield in the son tra-coffee-AF trial was determined by harvesting an area of 40 $m^2$ (Figure 5b) in each plot, while son tra fruit yield was determined based on all trees in each plot.

Maize grain and stover (stems, leaves, cobs, and covers) were harvested at physiological maturity and weighed to determine their fresh weight. Fresh sub-samples 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. Maize grain and stover yield was measured in a 100 $m^2$ area in the longan-maize-AF trial, 120 $m^2$ in the longan-mango-AF trial (120 $m^2$ per weed control treatment) and 80 $m^2$ in the plum-maize trial (80 $m^2$ per weed control treatment), while a similar area of each corresponding sole-maize reference treatment was harvested. Maize yield in the weed treatment with two hand hoeings is reported in this thesis.

Fresh weight biomass production of forage grasses was measured monthly by harvesting a 4-m section of each grass strip in longan-mango-AF and plum-maize-AF and their weed control treatment (Papers III and IV), while forage grass biomass in the weed treatment applying two hand hoeings is reported in this thesis. A 5-m section of each grass strip was measured in longan-maize-AF, son tra-guinea-AF and son tra-mulato-AF (Paper I).

In Paper IV, weed biomass was collected annually in each weed control treatment in the longan-mango-AF and plum-maize-AF plots and in the sole maize plots. The weed biomass was collected within zones in positions relative to the tree and grass rows (as described in section 3.3.7). There were nine sampling zones in the sole-maize plots of longan-mango-AF and six in the sole-maize plots of plum-maize-AF. Weed collection was performed in a 1 $m^2$ area per sampling zone, in the maize areas after maize harvest. Fresh sub-samples of weed biomass were weighed and dried to constant weight. The ratio of fresh to dry weight was used to calculate the total harvested dry weight of weed biomass.

### 3.3.2 Land equivalent ratio (LER), partial LER and harvest index

Land equivalent ratio (LER) was used to compare yields in the different treatments, with LER values >1.0 indicating that the mixed system (intercrop) was more advantageous than the sole crop (Paper I). LER was calculated according to Mead & Willey (1980) (see section 2.3 of this thesis). The LER of individual crops in intercropping compared with their sole-crop yields (pLER) was calculated according to Himmelstein *et al.* (2017) (see section 2.3) and was used to assess how maize in longan-mango-AF and plum-maize-AF (Paper IV, this thesis) and coffee in son tra-coffee-AF (this thesis) crops responded to intercropping. Harvest index (Papers III-IV), *i.e.* the ratio of grain yield to total above-ground biomass at physiological maturity (Kawano 1990), was calculated as:

$$HI = Y/B \qquad \text{(Eq. 1)}$$

where HI is harvest index, Y is maize grain yield and B is aboveground biomass including maize grain and stover (stems, leaves, covers and maize cobs).

### 3.3.3 Farmer interviews (Paper I)

To identify possibilities for improvement and wider-scale development of agroforestry, farmers' perceptions and aspirations were documented in group discussions carried out in January 2020. The systems discussed were longan-maize-AF and son tra-grasses (son tra-guinea-AF and son tra-mulato-AF).

Selection of participants for farmer group discussions is described in Paper I. For each agroforestry practice, two villages were selected: one village that hosted an experiment (experiment-hosting village) and a nearby village (non-hosting village) (Table S3 in Paper I). In each village, farmers who were familiar with or had observed the agroforestry system in the field experiment were selected and divided into three groups based on resource endowment and gender (poor female, poor male, non-poor mixed female and male). Farmers hosting the experiments were interviewed individually, using the same open-ended questions as in the group discussions. The Vietnamese government's poverty scale was used to capture responses from farmers experiencing different levels of poverty (Vietnamese Government, 2015). The discussions were facilitated by an interview team of three researchers from World Agroforestry (ICRAF) in Vietnam (one in each group) and were recorded, transcribed and translated to English. The questions guiding the discussion are presented in Table S4 in Paper I.

### 3.3.4 Sediment movement and terrace formation measurements (Paper II)

For evaluation of sediment movement within agroforestry plots, 30 cm long erosion pins were inserted 15 cm into the soil at points close downslope of the grass strips, midway between the grass strips, and close upslope of the grass strips in each agroforestry plot (Hart *et al.*, 2017). Soil loss/accumulation was estimated annually as the difference between measured pin height above the ground and initial pin height (15 cm above the ground).

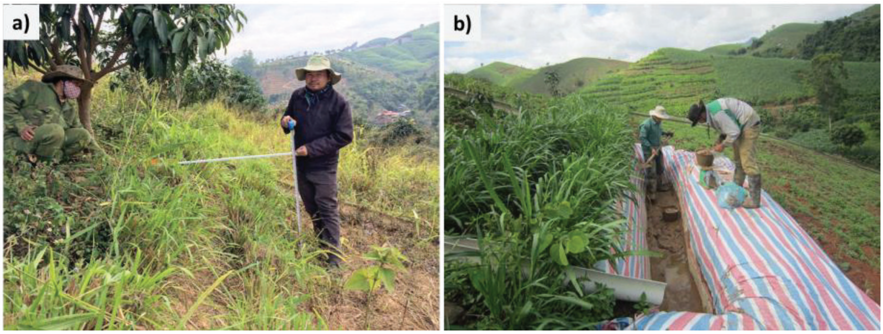


*Figure 6*. Field measurements of (a) terrace formation and (b) annual soil loss in erosion soil traps (4 m long, 0.5 m wide and 0.8 m deep) during the rainy season. Images taken in the longan-mango-maize-forage grass experiment in Mai Son District, Son La province.

The volume of terrace formed by the trees and grass strips within the agroforestry treatments was estimated according to Sjödell & Thelberg (2020) in the fifth growing season after establishment of the experiments (*i.e.* at the end of 2021) (Figure 6a). The methods used for evaluation of sediment movement and terrace formation are described in detail in Paper II.

### 3.3.5 Soil and related nutrient loss determination (Paper II)

Soil and nutrient losses from agroforestry and sole-crop plots were quantified using soil traps. In longan-mango-AF and sole-maize, soil erosion and soil loss were determined using traps measuring 4.0 m x 31.5 m and 4.0 m x 30 m, respectively, while in son tra-coffee-AF and sole-coffee trap dimensions were 4.0 m x 21.5 m and 4.0 m x 20 m, respectively. At the bottom of each area, a soil trap was established and covered with a permeable fabric to allow water infiltration. To prevent soil from entering the trap from outside the area of soil loss quantification, 30 cm high pro-cement sheet frames were used to surround the area. The material that fell into soil traps during the rainy season was collected and weighed (Figure 6b). A sub-sample of 300 g of fresh soil was collected and dried, and the ratio of fresh to dry weight was used to calculate the total mass of lost soil. The dried samples were analysed to determine the soil concentrations of total SOC, N, P and potassium (K).

### 3.3.6 Vegetation cover measurements and rainfall data (Paper II)

Vegetation cover was measured to evaluate the impact of rainfall and vegetation cover on soil loss. Photos were taken 3.5 m above the ground using a digital camera (Canon SX280 HS). The images were taken on the left and right sides of the soil erosion measurement areas in longan-mango-AF and son tra-coffee-AF and their corresponding sole-crop. Vegetation cover was calculated using ImageJ version 1.52 (Xiong *et al.*, 2019). The method used for vegetation cover determination is described in detail in Paper II.

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 Dien Bien (21.34°N, 103.31°E; 1.2 km north of the Tuan Giao site).

### 3.3.7 Spatial variation within agroforestry (Paper III)

Spatial variations in crop growth, yield and soil fertility within the agroforestry plots of longan-mango-AF (2018-2021) and plum-maize-AF were determined (2019-2021).

Maize height and leaf N concentration (SPAD) were measured in zones at three positions relative to the tree and grass rows: above tree and grass rows (up to 3.0 m upslope of the upper grass rows); below tree and grass rows (up to 3.0 m downslope of the lower grass rows); and between two tree rows (the area between the 'above' and 'below' zones) (Figure 7). Maize yield (grain and stover) was measured in the same zones as were used for maize height and plant N concentration measurement. Maize yield was determined both by whole plot area and by maize area.

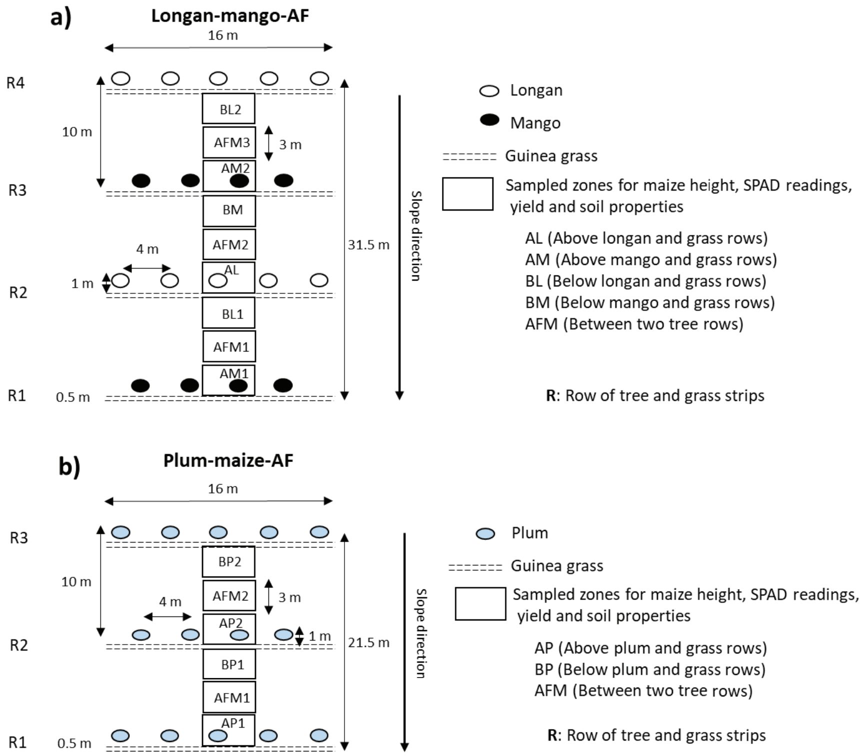


*Figure 7.* Sampling zones (each 12 m$^2$) within agroforestry. (a) longan-mango-maize-forage grass agroforestry (longan-mango-AF) (three at positions between two tree rows (AFM), two above mango and grass rows (AM), one below mango and grass rows (BM), one above longan and grass rows (AL) and two below longan and grass rows (BL)). (b) plum-maize-forage grass agroforestry (plum-maize-AF) (two at each position between two tree rows (AFM), above plum and grass rows (AP) and below plum and grass rows (BP), respectively).

Forage grass growth and leaf N concentration under different fruit tree species were evaluated during four growing seasons in longan-mango-AF (2018-2021), and grass biomass yield was quantified in five growing seasons (2017-2021). In plum-maize-AF, grass growth, leaf N concentration and biomass yield were quantified during three growing seasons (2019-2021).

Soil samples were collected in the designated zones (Figure 7) on two occasions at the end of maize growing season in both systems (longan-mango-AF in 2018 and 2021; plum-maize-AF 2019 and 2021). The soil samples were taken in the same zones in which the maize measurements were carried out, except for the zones above tree row 1 and below grass row 4 in longan-mango-AF (Figure 7a) and row 3 in plum-maize-AF (Figure 7b). Topsoil was sampled at two depths: 0-10 and 10-20 cm. In each sampling zone, one composite soil sample representing each soil depth was taken from 11 sampling points. To reduce the number of soil samples for analysis, those from zones between two tree rows (AFM) were pooled into one sample per plot representing the AFM position in both longan-mango-AF and plum-maize-AF. The soil samples were analysed for SOC, total N, P and K, and available P and K.

### 3.3.8 Profitability (Papers I and IV)

Cost-benefit analysis was performed for agroforestry (longan-maize-AF, son tra-guinea-AF and son tra-mulato-AF) and the corresponding sole-crop treatment (sole-maize, sole-longan and sole-son tra) in Paper I and each weed control treatment in agroforestry (longan-mango-AF and plum-maize-AF) and corresponding sole-maize treatment in Paper IV.

The analysis was based on investment costs, maintenance costs and revenue from products sold across monitoring years. Annual inputs included fertiliser, pesticide, labour, planting materials *etc*. Total annual income was calculated based on yield and the price obtained for the different products at harvest.

Net profit was calculated by subtracting all input costs from gross income, while excluding the value of bank interest or taxes:

$$Np = T - I \qquad \text{(Eq. 2)}$$

where Np is net profit, T is total income and I is total cost of all inputs, all in USD $ha^{-1}$ $year^{-1}$.

## 3.4 Statistical analyses

The software R (version 3.6.1) was used for all statistical analyses. In all model analyses (Table 7), log-transformation was used to normalize the data where necessary. In all repeated measures ANOVA with the mixed models was used. When a significant difference was indicated in F-tests, least squares means (lsmeans) or estimated marginal means (emmeans) were used to identify significant ($p$<0.05) differences between means. In all ANOVA models, Tukey's HSD test was used to find means that were significantly different from each other.

Table 7. *Statistical analysis carried out in R, where (+) separates between main effects of different factors and (*) indicates that all possible interactions between the respective factors were considered.*

| Paper | Statistical model | Factors | Response variables |
|---|---|---|---|
| I | Repeated measures ANOVA with the mixed model | *Fixed:* cropping system + year + copping system*year<br>*Random:* block | Tree growth (base diameter, canopy diameter and height), tree/crops yield and profitability |
| I | Repeated measures ANOVA with the mixed model | *Fixed:* cropping system + maize growth stage + position to grass strips + cropping system*maize growth stage + cropping system* position to grass strips + cropping system*maize growth stage*position to grass strips<br>*Random:* block, sampling zone and measured maize plant | Maize growth and plant N concentrations in longan-maize-AF and sole-maize in year 7 |
| I | ANOVA | Cropping system + position to grass strips | Yield of maize at different positions relative to the grass strips within longan-maize-AF and sole-maize in year 7 |
| II | Repeated measures ANOVA with the mixed model | *Fixed:* site + cropping system + year + site*copping system + site*year + cropping system*year + site*cropping system*year<br>*Random:* block and plot | Soil and related nutrient losses |
| II | Repeated measures ANOVA with the mixed model | *Fixed:* cropping system + year + measurement period + cropping system*year + cropping system* measurement period + year* measurement period + cropping system*year *measurement period<br>*Random:* block and plot | Vegetation cover |
| II | ANOVA | Row of tree and grass strips | The volume of terrace formed over five years in |

| Paper | Statistical model | Factors | Response variables |
|---|---|---|---|
| | | | the agroforestry systems |
| III | Repeated measures ANOVA with the mixed model | *Fixed:* Position to grass strip + year + maize growth stage + position to grass strip*year + position to grass strip*maize growth stage + year*maize growth stage + position to grass strips*year*maize growth stage *Random:* block, plot, sampling zone and measured maize plant | Maize growth and plant N concentrations |
| III | Repeated measures ANOVA with the mixed model | *Fixed:* position to grass strips + year + position to grass strip*year *Random:* block, plot and sampling zone | Maize yield and maize harvest index (HI) |
| III | Repeated measures ANOVA with the mixed model | *Fixed:* Forage grass under tree species + measurement/harvesting occasion + forage grass tree species *measurement/harvesting occasion *Random:* block, plot, grass row and measured grass plant | Growth, plant N concentration, and biomass yield of forage grass |
| III | Repeated measures ANOVA with the mixed model | *Fixed:* different tree species + year + different tree species *year *Random:* block, plot and tree row | Growth of tree (base diameter, canopy diameter and height) |
| III | Repeated measures ANOVA with the mixed model | *Fixed:* position to grass strips + year + soil depth + position to grass strip*year + position to grass strips*soil depth + year*soil depth + position to grass strips*year*soil depth *Random:* block, plot and sampling zone | Soil parameters (SOC, total (N, P and K), available (P and K) |
| IV | Repeated measures ANOVA with the mixed model | *Fixed:* weed treatment + year + weed treatment*year *Random:* block, plot and sampling zone | Weed biomass |

| Paper | Statistical model | Factors | Response variables |
|---|---|---|---|
| IV | Repeated measures ANOVA with the mixed model | *Fixed:* weed treatment + year + maize growth stage + weed treatment*year + weed treatment*maize growth stage + year*maize growth stage + weed treatment*year*maize growth stage<br>*Random:* block, plot, sampling zone and measured maize plant | Maize height and leaf N concentration |
| IV | Repeated measures ANOVA with the mixed model | *Fixed:* weed treatment + year + weed treatment*year<br>*Random:* block and plot | Growth of trees; yield of maize, forage grass and fruits; maize HI and maize pLER; profitability and labour use |
| This thesis | Repeated measures ANOVA with the mixed model | *Fixed:* cropping system + year + cropping system*year<br>*Random:* block and plot | Tree growth (base diameter, canopy diameter and height), tree/crops yield and crop pLER |
| This thesis | Repeated measures ANOVA with the mixed model | *Fixed:* cropping system + year maize growth stage + cropping system*maize growth stage + cropping system* year + cropping system*maize growth stage*year<br>*Random:* block, plot, sampling zone and measured maize plant | Maize height and leaf N concentration |

# 4. Results

## 4.1 Tree/crop performance and profitability of agroforestry from establishment to early maturity (4-7 years)

### 4.1.1 Growth of trees

There was a significant effect of agroforestry cropping system on growth of fruit trees compared with sole trees in the first set of trials (Paper I). Tree base diameter ($p<0.001$), canopy diameter ($p<0.001$) and height ($p<0.001$) were significantly greater in the sole-longan and sole-son tra plots than in the longan-maize-AF, son tra-guinea-AF and son tra-mulato-AF plots (Figures 8a, 8b). In the second set of trials there were no sole tree plots to compare with (Papers II-IV), but fruit tree growth was monitored in the agroforestry treatments involving longan, mango, plum and son tra (Figures 8c-8e). In longan-mango-AF, mango trees had larger base diameter, canopy diameter and height than longan trees ($p<0.001$).

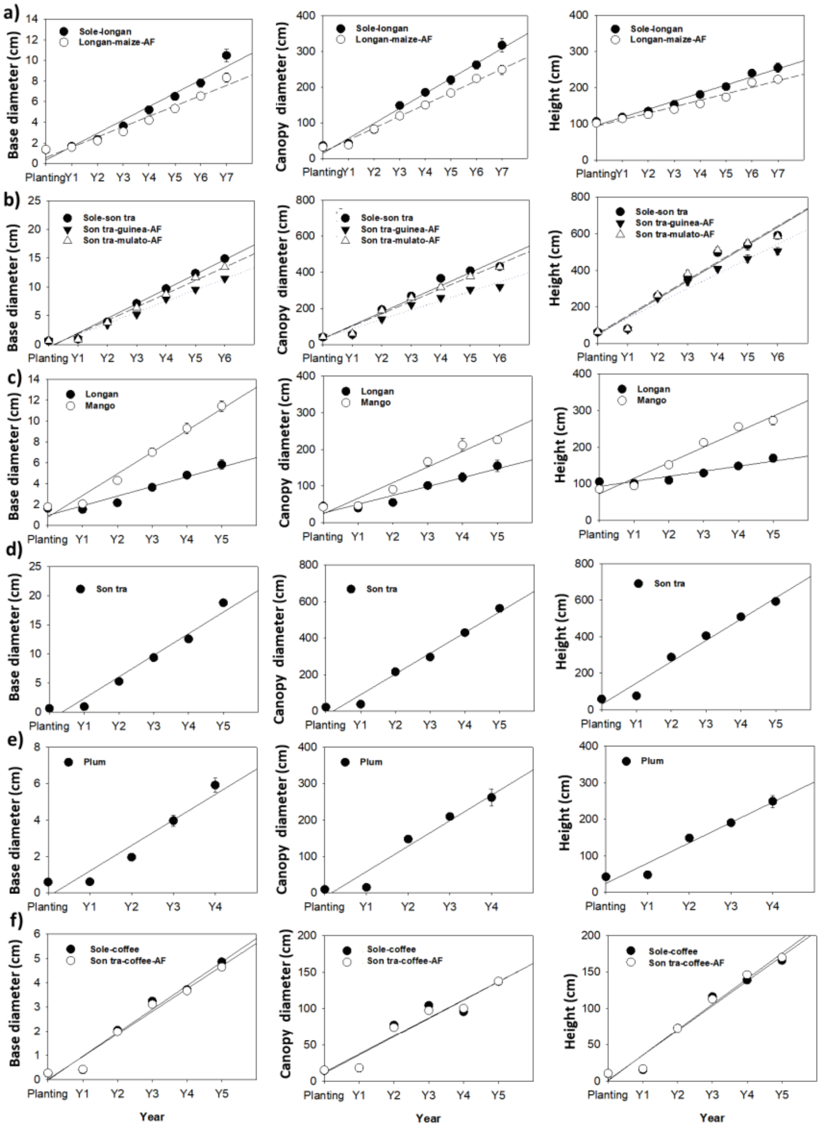


*Figure 8*. Regression lines of tree growth (mean ± standard error). (a) Longan in sole-crop longan (sole-longan) and longan-maize-forage grass agroforestry (longan-maize-AF) (Paper I). (b) Son tra in sole-crop son tra (sole-son tra), son tra-guinea grass agroforestry (son tra-guinea-AF) and son tra-mulato grass agroforestry (son tra-mulato-AF) (Paper I). (c) Longan and mango in longan-mango-maize-forage grass agroforestry. (d) Son tra in son tra-coffee-forage grass agroforestry (son tra-coffee-AF). (e) Plum in plum-maize-forage grass agroforestry. (f) Coffee in sole-crop coffee (sole-coffee) and son tra-coffee-AF.

### 4.1.2 Growth of crops

In year 7 (the only year of measurements), maize height and SPAD values were greater in sole-maize than in longan-maize-AF (Table 2 in Paper I). There was an interaction between cropping system and maize growth stage, with greater maize height and SPAD values in sole-maize than agroforestry after 3-4 fully expanded leaves stage ($p<0.001$).

In longan-mango-AF, maize height and SPAD values were also greater in sole-maize than in agroforestry (Figure 9a). There were interactions between cropping system x year, cropping system x maize growth stage, and cropping system x year x maize growth stage, where the SPAD values decreased before the first topdressing with N. There was variation between the years, but no clear trend.

In plum-maize-AF, maize height and SPAD values were significantly greater in sole-maize than in the agroforestry treatment (Figure 9b). There were interactions between cropping system x year, cropping system x maize growth stage, and cropping system x year x maize growth stage, reflecting effects of topdressing on SPAD values, which varied between the years.

In son tra-coffee AF, there was no significant effect of cropping system on growth of coffee (Figure 8f). Five years after planting, base diameter, canopy diameter and height of coffee in both son tra-coffee-AF and sole-coffee was around 4.6, 138 and 167 cm, respectively.

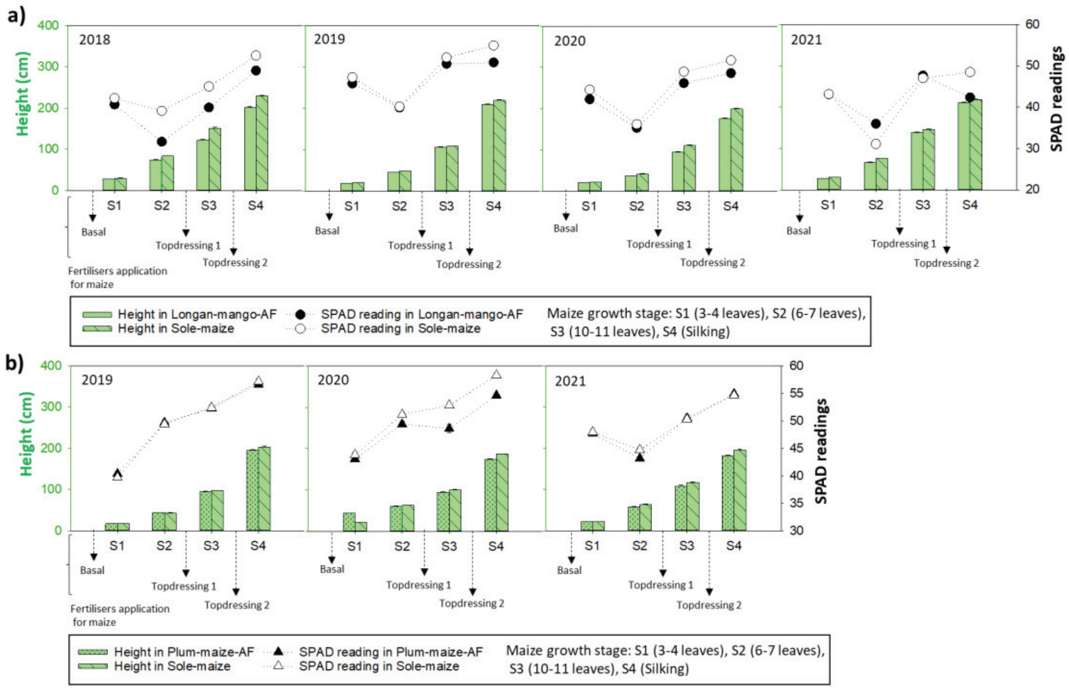


*Figure 9*. Growth of maize (height) and SPAD readings in agroforestry and sole-maize systems (mean ± standard error) in (a) longan-mango-maize-forage grass agroforestry (longan-mango-AF) and sole-crop maize (sole-maize) and (b) plum-maize-forage grass agroforestry (plum-maize-AF) and sole-crop maize (sole-maize).

### 4.1.3 Yield, land equivalent ratio (LER) and partial LER

In the longan-maize-AF trials, there was no significant effect of cropping system, or interaction between treatment and year, on maize yield (Figure 10a). The grass started yielding from year 2 and the system's products became more diversified from year 4, when longan started to bear fruit, and yield increased during subsequent years. Yield of longan was significantly higher in sole-longan than in longan-maize-AF. There was a significant interaction between treatment and year, where fruit yield tended to increase more over time for sole trees than in AF.

In son tra-guinea-AF and son tra-mulato-AF, the guinea grass and mulato grass were harvested from year 2, with high yield (Figure 10b). The agroforestry treatments had more products from year 3, when son tra started to bear fruit. However, there was a significant effect of cropping system on the productivity of son tra, with fruit yield being significantly lower in the son tra-guinea-AF and son tra-mulato AF systems than in sole-son tra.

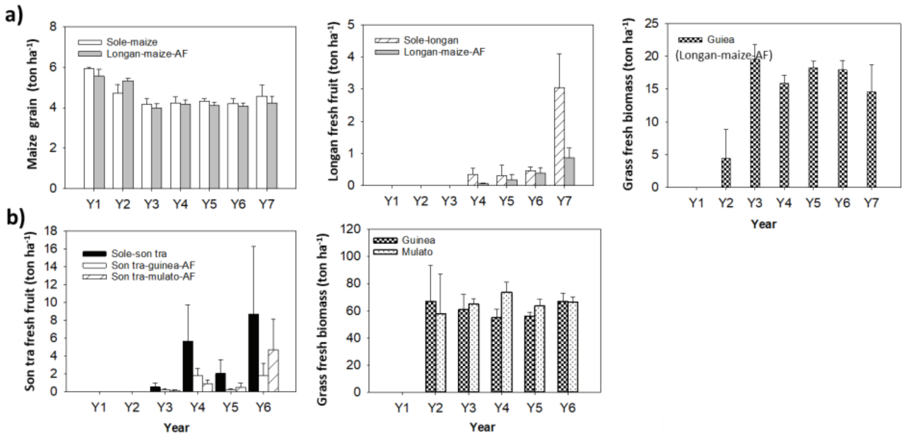


*Figure 10*. Maize (dry grain), forage grass and fruit yield (mean ± standard error) in (a) longan-maize-forage grass agroforestry (longan-maize-AF) compared with sole-crop maize (sole-maize) and sole-crop longan (sole-longan) and (b) son tra-forage grasses agroforestry (son tra-guinea-AF and son tra-mulato-AF) compared with sole-crop son tra (sole-son tra) (Paper I).

During the first two years, the products in longan-mango-AF were primarily maize cobs and forage-grass biomass (Figure 11a). The products became more diversified when mango and longan started to bear fruit in year 3 and 4, respectively, and yield increased during subsequent years. Significantly higher maize grain yield was recorded in sole maize than in agroforestry, but the maize yield in both systems showed a tendency to decrease in years 4 and 5.

In plum-maize-AF, there was no significant effect of cropping system and no interaction between treatment and year on maize grain yield (Figure 11b). Guinea grass started giving biomass yield from year 2, but the plum trees did not produce fruit until year 4.

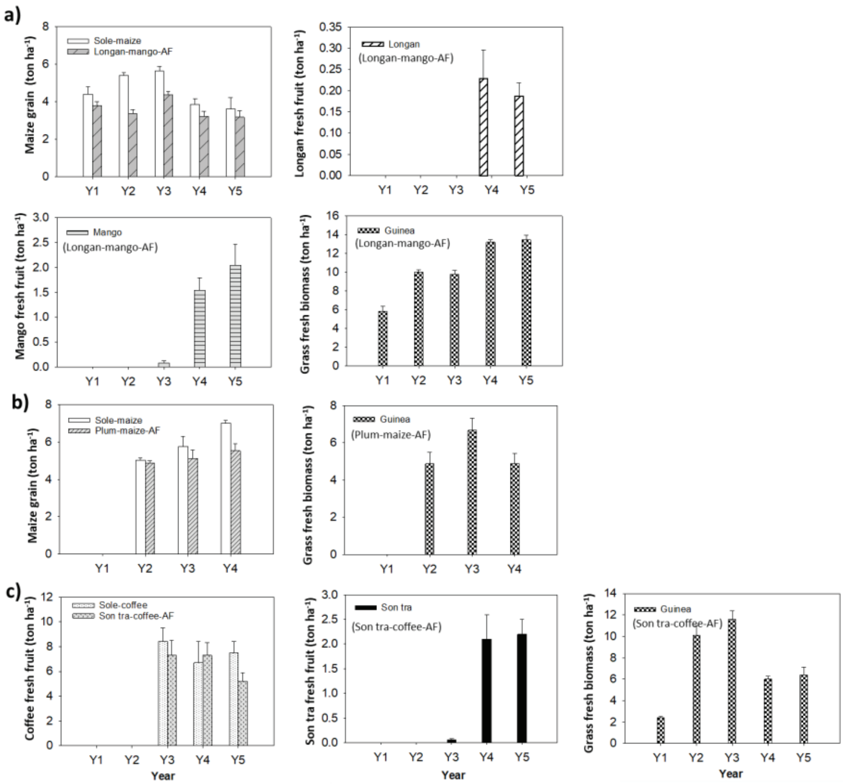


*Figure 11*. Maize (dry grain), forage grass, coffee and fruit yield (mean ± standard error) in (a) longan-mango-maize-forage grass agroforestry (longan-mango-AF) compared with sole-crop maize (sole-maize), (b) plum-maize-forage grass agroforestry (plum-maize-AF) compared with sole-crop maize (sole-maize) and (c) son tra-coffee-forage grass agroforestry (son tra-coffee-AF) and sole-crop coffee (sole-coffee).

During the first two years, the products in son tra-coffee-AF were primarily from forage grass biomass (Figure 11c). The products of the system became more diversified when son tra and coffee started to bear fruit in year 3, and yield increased during subsequent years. There was no significant effect of cropping system and no interaction between treatment and year on coffee yield in sole-coffee and son tra-coffee-AF.

From years 2 to 7, LER of the longan-maize-AF system ranged from 1.1 to 1.9 (Figure 12a), while LER of son tra-guinea-AF and son tra-mulato-AF ranged from 0.5 to 1.1 and 0.6 to 1.8, respectively, during year 2 to 6 (Figure 12b).

The pLER of maize was 0.62-0.96 and 0.79-0.97 in longan-mango-AF and plum-maize-AF, respectively, and there was no significant difference between years (Figures 12c, 12d).). In son tra-coffee-AF, pLER of coffee ranged from 0.69 to 0.86 during years 3-5 (Figure 12e).

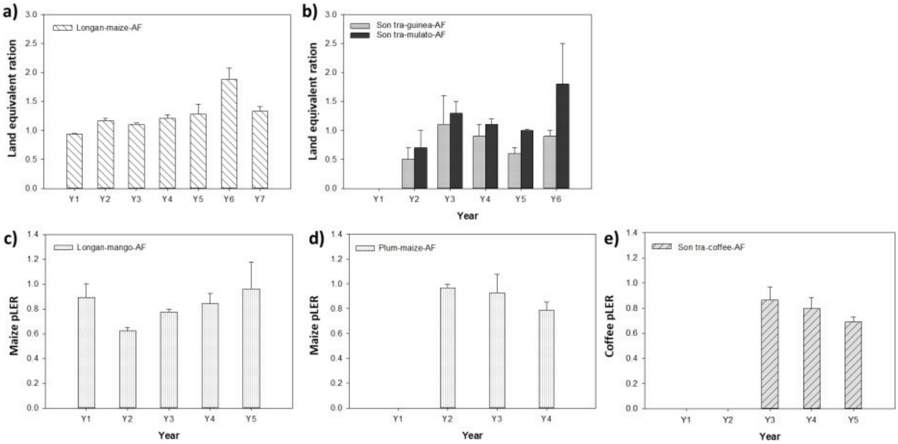


*Figure 12.* Land equivalent ratio (LER) and partial LER (pLER) values (mean and standard error (bars)). (a) LER of longan-maize-forage grass agroforestry (longan-maize-AF) (Paper I). (b) LER of son tra-guinea grass agroforestry (son tra-guinea-AF) and son tra-mulato grass agroforestry (son tra-mulato-AF) (Paper I). (c) Maize pLER of longan-mango-maize-forage grass agroforestry (longan-mango-AF). (d) Maize pLER of plum-maize-forage grass agroforestry (plum-maize-AF). (e) Coffee pLER of son tra-coffee-forage grass agroforestry (son tra-coffee-AF).

### 4.1.4 Profitability (Paper I)

The investment cost of sole-longan and longan-maize-AF was 3.7-fold and 3.2-fold higher, respectively, than that of sole-maize (Figure 13a). The mean net profit of longan-maize-AF was 2.4-fold higher ($p<0.001$) than that of sole-maize, while sole-longan only achieved a positive profit from year 6 (Table 3 in Paper I).

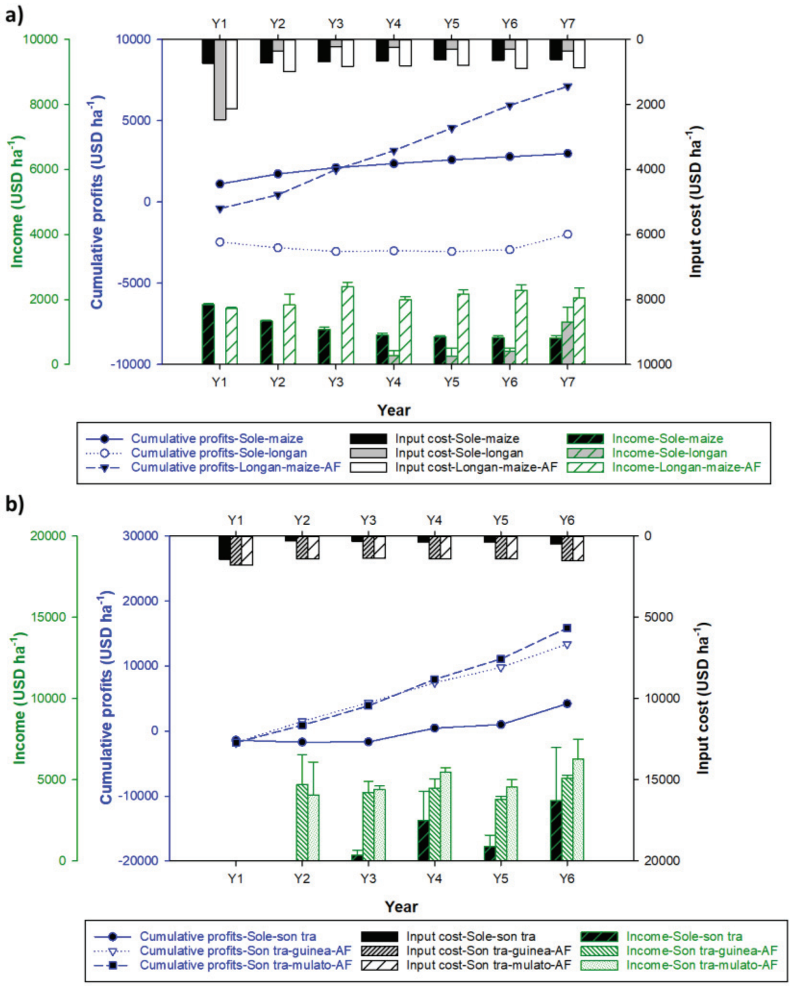


*Figure 13.* Input costs, income and cumulative profit of (a) longan-maize-forage grass agroforestry (longan-maize-AF) compared with sole-crop maize (sole-maize) and sole-crop longan (sole-longan) and (b) son tra-guinea grass agroforestry (son tra-guinea-AF) and son tra-mulato grass agroforestry (son tra-mulato-AF) compared with sole-crop son tra (sole-son tra) (Paper I).

In addition, the cumulative profit from longan-maize-AF was positive from year 2 and higher than for sole-maize from year 4 (Figure 13a). In contrast, the cumulative profit from sole-longan was still negative in year 7. The break-even point of longan-maize-AF was from year 2.

In the year of establishment, the total input costs in both son tra-guinea-AF and son tra-mulato-AF were higher than in sole-son tra. In the following years, son tra-guinea-AF and son tra-mulato-AF required higher investment than sole-son tra, mainly deriving from labour costs for forage grass harvesting (Figure 13b). There was a significant effect ($p$=0.005) on net profit, with mean profit in son tra-guinea-AF and son tra-mulato-AF being 3.2- and 3.7-fold higher, respectively, than in sole-son tra (Table 3 in Paper I). Sole-son tra gave a positive net profit from year 3, but the cumulative profit from son tra-guinea-AF and son tra-mulato-AF was positive and higher than in sole-son tra from year 2 (Figure 13b). The break-even point for son tra-guinea-AF and son tra-mulato-AF was from year 2.

## 4.2 Farmers' perceptions (Paper I)

### 4.2.1 Benefits of the agroforestry systems

The perceptions and aspirations of farmers about benefits of agroforestry were documented through farmer group discussions in and around the villages where the longan-maize-AF, son tra-grasses (guinea and mulato)-AF trials were hosted.

The farmers reported that they achieved early and more diverse products and higher economic benefit from the agroforestry systems compared with the sole crops (Figure 8 in Paper I). In addition, they conveyed that agroforestry enhanced ecosystem services by controlling erosion and surface runoff, increasing soil fertility and improving resilience to extreme weather. The grass strips contributed to these ecological functions within agroforestry, and were also used to feed livestock, produce green manure and provide earlier income for local farmers. Growing fodder grass reduced the labour requirement for finding/collecting feedstuffs and played a significant function in terrace formation on the sloping uplands in the area.

### 4.2.2 Performance of agroforestry systems and possibilities for improvements

Most farmers were fully aware of possible effects of competition for resources (light, water, nutrients) on the performance of tree and crop components within the agroforestry systems (Figure 7 in Paper I). They reported that growth and yield of trees and crops in agroforestry were lower than when trees and crops were grown separately. Most groups attributed this to close distance between trees, crops and grass leading to competition in agroforestry.

The farmer groups also suggested that the agroforestry systems could be optimised through better management of trees and crops (Figure 7 in Paper I). They proposed different solutions to improve the efficiency, such as adding more fertilisers to plants suffering from nutrient deficiency in areas where trees, crops and grass affected each other's nutrient availability, reducing tree density and increasing pruning to reduce shading. In addition, modifying the planting distance between trees and grass was suggested by groups from both sites. The farmers interviewed also suggested use of less competitive crops, *e.g.* legume species with biological N fixation, such as soybean and groundnut, instead of maize in longan-maize-AF, and upland rice or cucumber instead of guinea and mulato grass in son tra-guinea-AF and son tra-mulato-AF.

### 4.2.3 Constraints and solutions for wider-scale development of agroforestry

Most of the farmer groups recognised and listed constraints to uptake of agroforestry and proposed possible solutions to improve uptake in the region (Figure 14).

All groups indicated that the investment costs were higher for agroforestry than for sole-crop cultivation, making it difficult for poor households to adopt agroforestry. Management of pests and diseases in agroforestry was also perceived to be more complicated, with more tree and crop components. An unstable market and low prices for products were also seen as constraints to uptake of agroforestry in the region.

Harsh weather events, such as drought or frost, lack of technologies and low awareness among farmers of the benefits of agroforestry were other main drawbacks to uptake of agroforestry. At one site, all farmer groups perceived that it would be difficult to combine traditional free grazing of crop residues with agroforestry. The forage grass was not considered valuable, since in the free-grazing area farmers are not accustomed to collecting fodder.

The local farmers proposed some possible solutions such as reducing investment costs by *e.g.* planting alternative crops to replace maize and forage grass, producing their own fruit tree seedlings or reducing plant density (Figure 14). Financial support or access to loans/credits with low interest to start implementing agroforestry practices was perceived to be a necessary incentive, as were interventions in plant protection to control pests and weeds. Farmers saw a need to promote and develop livestock production to utilise the forage grasses in the trial systems, *i.e.* to shift from free grazing to captive grazing. Development of market links for agroforestry products and creation of a stable market were key factors for agroforestry adoption according to the farmers interviewed (Figure 14).

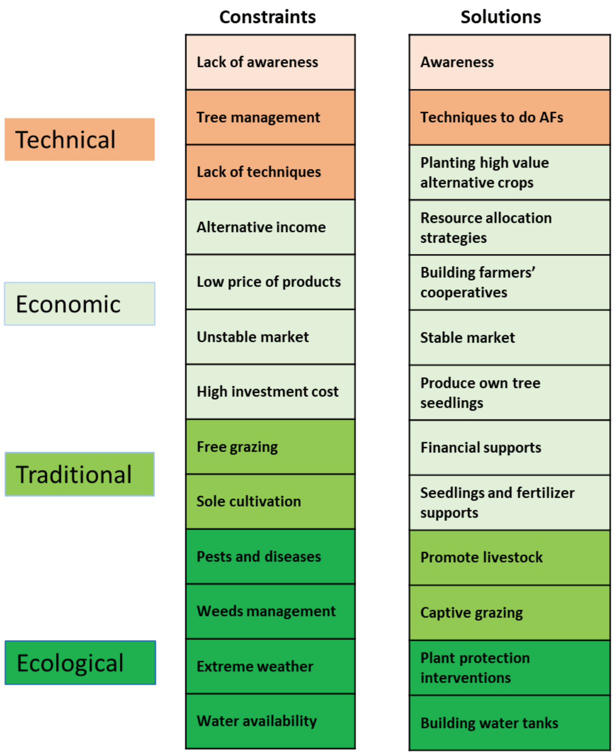


*Figure 14.* Farmers' perceptions of constraints (left) and solutions (right) to the uptake of agroforestry in their local district (Paper I).

## 4.3 Impact of agroforestry on soil and nutrient conservation (Paper II)

### 4.3.1 Sediment movement and terrace formation

Measurements of soil movement along the slope over four growing seasons (2018-2021) in longan-mango-AF and son tra-coffee-AF, using erosion pins, showed accumulation of soil upslope of the grass strips (Figure 15). In contrast, soil was lost from positions downslope of, and midway between, the grass strips.

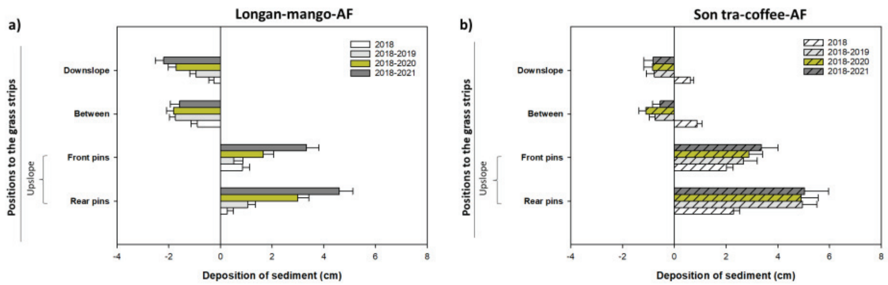


*Figure 15.* Sediment movement downslope over time (2018-2021) based on changes measured at erosion pins, where negative values of the x-axis indicate soil losses and positive values indicate accumulation (error bars indicate standard error), in (a) longan-mango-maize-forage grass agroforestry (longan-mango-AF) and (b) son tra-coffee-forage grass agroforestry (son tra-coffee-AF) (Paper II).

There were no significant differences in terrace formation after five growing seasons between uphill and downhill tree and grass strips within plots (Figure 16). The average volume of terrace formed was 0.26 $m^3$ per m in longan-mango-AF and 0.43 $m^3$ per m terrace in son tra-coffee-AF. Since the control systems (sole-maize, sole-coffee) did not form terraces, no comparison was made between agroforestry and sole-crops.

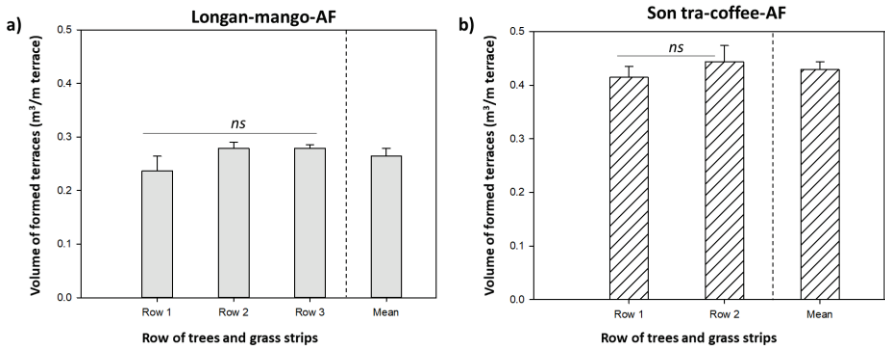


*Figure 16.* Mean volume of terrace formed by tree and grass strips after five growing seasons (error bars indicate standard error) in (a) longan-mango-maize-forage grass agroforestry (longan-mango-AF) and (b) son tra-coffee-forage grass agroforestry (son tra-coffee-AF) (Paper II).

### 4.3.2 Impact of agroforestry on soil loss mitigation

Soil loss reduced significantly in the agroforestry systems as compared with the sole crops in year 2, while the impacts were even greater in years 3-4, resulting in a significant interaction between cropping system and year (Figure 17).

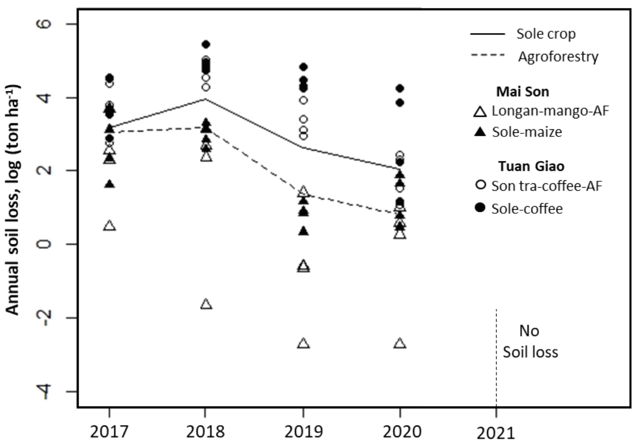


*Figure 17.* Interaction plot of annual soil loss in the longan-mango-maize-forage grass agroforestry (longan-mango-AF) and son tra-coffee-forage grass agroforestry (son tra-coffee-AF) and their corresponding sole-crop. Soil loss data were log-transformed (Paper II).

During years 2-4, the longan-mango-AF and son tra-coffee-AF systems reduced soil loss by 27-76% compared with the sole-crop systems (sole-maize and sole-coffee) (Figure 17).

Soil losses were substantially greater at the steeper son tra-coffee-AF trial site than at the longan-mango-maize-AF site over the five growing seasons (Figure 17).

### 4.3.3 Impact of rainfall and vegetation cover on soil loss

There was no significant difference in vegetation cover between longan-mango-AF and sole-maize, and the majority of soil erosion occurred between maize crop planting (when the soil surface was bare due to tillage operations) and maize silking (when vegetation cover was less than 50%) (Figure 18a). No soil loss was observed from silking to the end of the rainy season when the average vegetation cover was greater than 50% in all treatments (2018-2021).

In son tra-coffee-AF, there was considerably greater vegetation cover than in sole-coffee, indicating a significant effect of cropping system (Figure 18b). Furthermore, there was a significant interaction between cropping system and year, and between cropping system and measurement period, on vegetation cover. In year 1, neither system had an average vegetation cover of more than 10% (Figure 18b). From year 2 onwards, the vegetation cover increased in both systems, with son tra-coffee-AF having more vegetation cover than sole-coffee (Figure 18b). However, soil loss continued even during the periods of greatest vegetation.

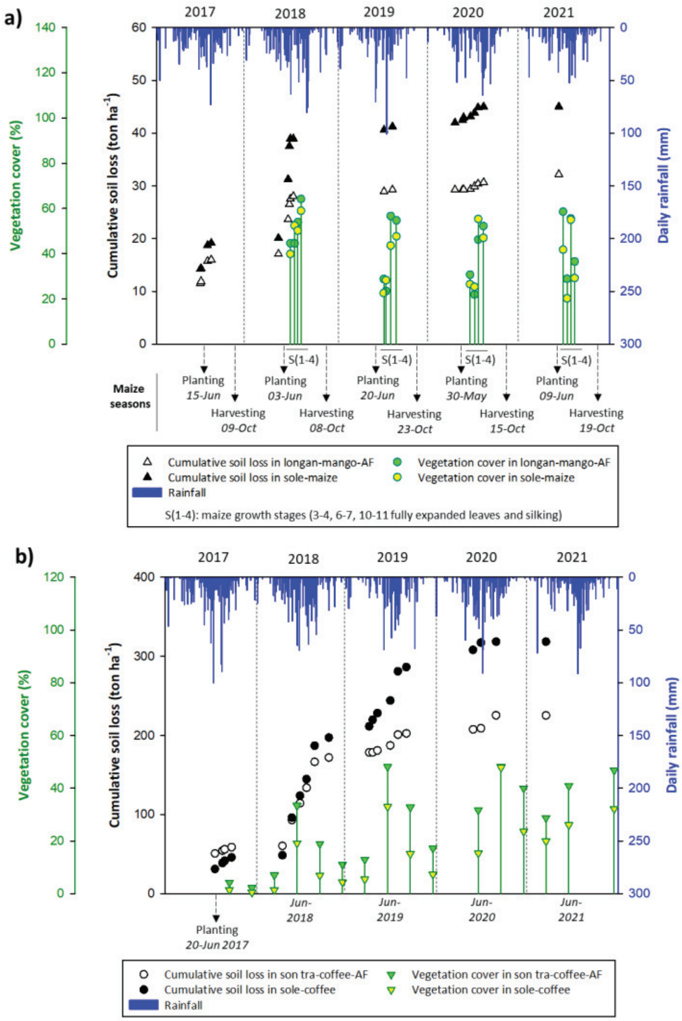


*Figure 18.* Cumulative soil loss over the five-year study period, daily rainfall and percentage vegetation cover over time in (a) longan-mango-maize-forage grass agroforestry (longan-mango-AF) and sole-crop maize (sole-maize) and (b) son tra-coffee-forage grass agroforestry (son tra-coffee-AF) and sole-crop coffee (sole-coffee) (Paper II).

### 4.3.4 Impact of agroforestry on SOC and nutrient losses

There was a significant interaction between cropping system and year on losses of SOC and nutrients (N, P, K) (Figure 19). During years 2-4, longan-mango-AF and son tra-coffee-AF showed losses of SOC, N, P and K that were 21-78%, 20-82%, 24-82% and 22-84% lower, respectively, than those in the corresponding sole-crop system (sole-maize and sole-coffee) (Figure 19).

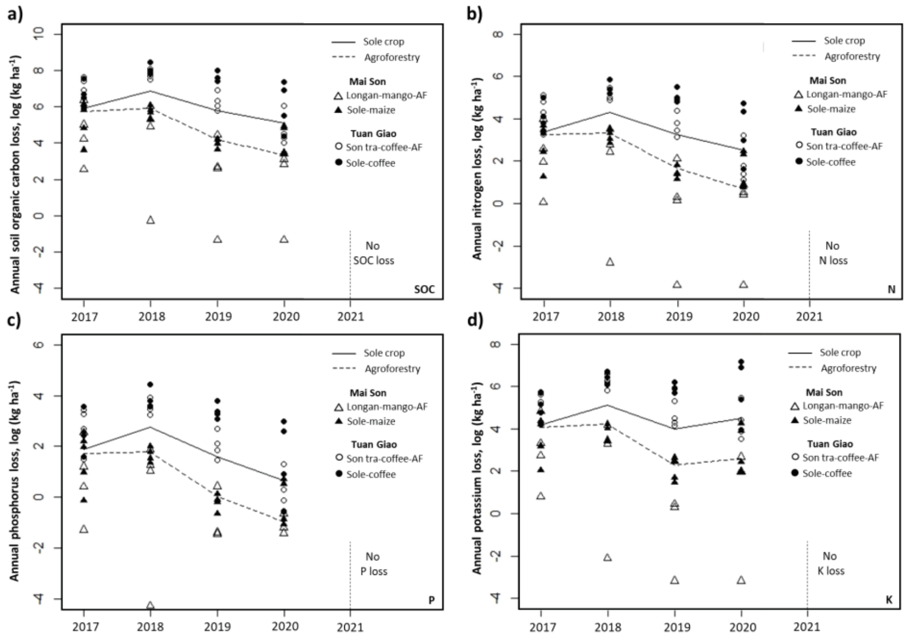


*Figure 19.* Interaction plot for annual losses of (a) soil organic carbon (SOC), (b) nitrogen (N), (c) phosphorus (P) and (d) potassium (K) via soil erosion in longan-mango-maize-forage grass agroforestry (longan-mango-AF) and son tra-coffee-forage grass agroforestry (son tra-coffee-AF) compared with the corresponding sole-crop system (sole-maize and sole-coffee). SOC and nutrient loss data were log-transformed (Paper II).

The son tra-coffee-AF trial was located on a steeper slope and had much greater losses of SOC (P=0.007) and nutrients (N, P, K) ($p$=0.01, $p$=0.01, $p$=0.005, respectively) than longan-mango-maize-AF (Figure 19), reflecting the greater losses of bulk soil and also higher soil concentrations of SOC and soil K at that site. Over the period 2017-2020, accumulated SOC, N, P and K losses at the son tra-coffee-AF site were 10-, 9-, 8- and 13-fold higher, respectively, than those at the longan-mango-maize-AF site.

## 4.4 Spatial variation within agroforestry (Paper III)

### 4.4.1 Maize height and leaf N concentration

In longan-maize-AF, maize height was similar in positions above the longan and mango tree-grass rows (AL, AM) and between two tree rows (AFM), and higher ($p<0.001$) at those positions than below longan and mango tree-grass rows (BL, BM) (Figure 20a). Maize SPAD values were also similar in positions above tree-grass rows (AL, AM) and between (AFM) tree rows, and lower ($p<0.001$) below tree-grass rows (BL, BM).

In the last two years of the experiment, maize height and SPAD values in the areas between two tree rows (AFM) and above tree-grass rows (AL and AM) were higher than those in the areas below tree-grass rows (BL, BM), causing an interactive effect between position relative to tree-grass rows and year ($p<0.001$). In the longan-mango-AF system, a difference in plant height above and below longan tree-grass rows was apparent already when maize had 3-4 fully expanded leaves, but for the mango trees did not emerge until maize had 6-7 fully expanded leaves, causing an interaction ($p<0.001$) (Figure 20a). At silking, only maize plants between two tree rows were significantly higher than those below tree-grass rows. When maize had 6-7 fully expanded leaves, SPAD values were higher between two tree rows than below tree-grass rows. At silking, maize height was significantly greater above tree-grass rows of both tree species than below longan and grass, but not above longan compared with below mango and grass.

In plum-maize-AF, maize height was similar above and below plum tree-grass rows (AP, BP), but greater ($p<0.001$) between two tree rows (AFM). The SPAD values were highest between two tree rows (AFM), followed by above tree-grass rows (AP), and lowest below tree-grass rows (BP) (Figure 20b). For maize SPAD values, there was an interactive relationship between position in relation to tree-grass rows and year ($p<0.001$). In the first two years of the experiment, maize plants above tree-grass rows (AP) and between two tree rows (AFM) had higher SPAD values than those below tree-grass rows (BP). There was an interactive effect of maize growth stage and position relative to tree-grass rows on maize height and SPAD values ($p<0.001$). Maize height and SPAD values were similar above tree-grass rows (AP) and between tree rows (AFM), but lower below tree-grass rows (BP) at stages 10-11 fully expanded leaves and silking.

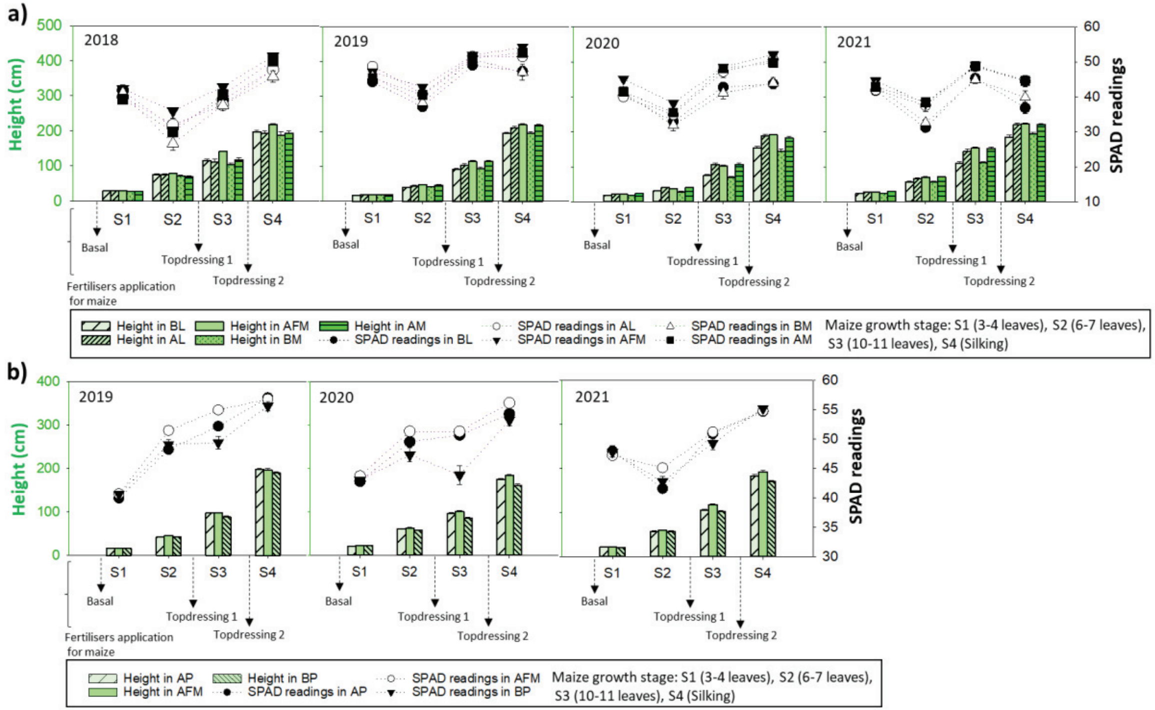


*Figure 20*. Growth of maize (height) and SPAD readings (mean ± standard error) (a) below longan (BL), above longan (AL), between two tree rows (AFM), below mango (BM) and above mango (AM) in longan-mango-maize-forage grass agroforestry (longan-mango-AF) and (b) above plum (AP), between two tree rows (AFM) and below plum (BP) in plum-maize-forage grass agroforestry (plum-maize-AF).

### 4.4.2 Maize yield and harvest index

In longan-mango-AF, maize grain and stover yields were significantly higher between the two tree rows (AFM) than in positions above or below tree-grass rows (AL, AM, BL, BM) (Figures 21a, 21c). By whole system area, average maize grain and stover yield in AFM was around 4.6 and 4.1 tons $ha^{-1}$, respectively, while it was around 2.7 and 2.6 tons $ha^{-1}$, respectively, in all positions just above or below tree-grass rows (AL, AM, BL, BM).

In plum-maize-AF, yield of both maize grain and stover was affected by position relative to grass and tree rows (Figures 21e, 21g). Maize grain yield was similar at positions between two tree rows (AFM) and below tree-grass rows (BP), and lower above tree-grass rows (AP), while maize stover yield was higher at positions between two tree rows (AFM) than above tree-grass rows (AP). By whole system area, average maize grain and stover yield between two tree rows (AFM) and below tree-grass rows (BP) was around 5.4 and 5.5 tons $ha^{-1}$, respectively, while it was around 3.6 and 3.9 tons $ha^{-1}$, respectively, above tree-grass rows (AP).

There was an interaction between position relative to grass and tree rows and year on maize grain and stover yield, but no clear trend was observed.

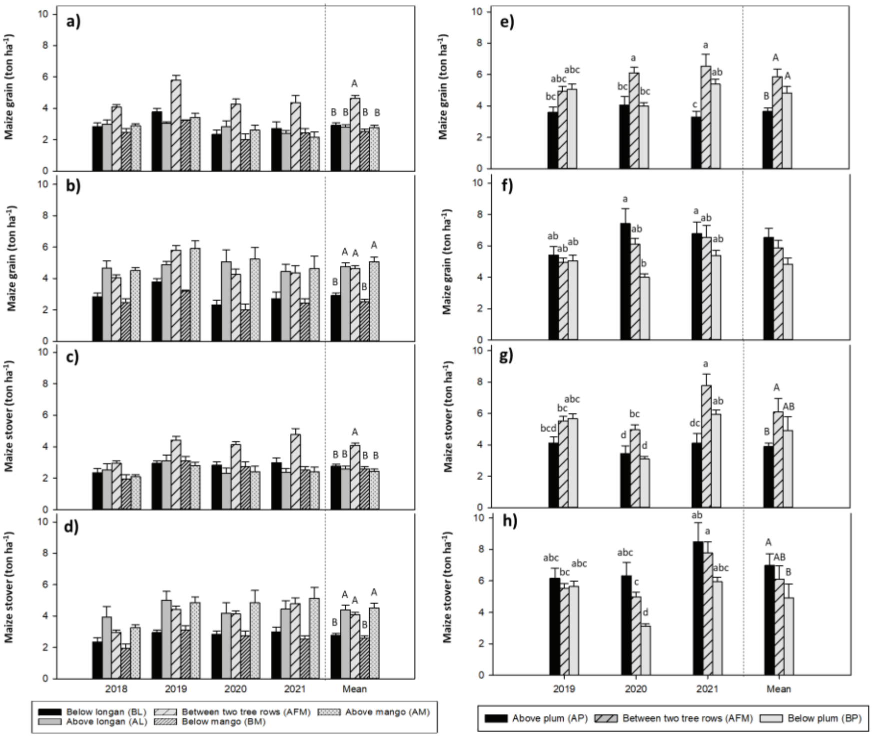


*Figure 21.* Yield of maize (dry grain and stover), calculated by whole system area and by maize crop area (mean ± standard error). (a) Maize grain by whole area in longan-mango-maize-forage grass agroforestry (longan-mango-AF). (b) Maize grain by maize area in longan-mango-AF. (c) Maize stover by whole area in longan-mango-AF. (d) Maize stover by maize area in longan-mango-AF. (e) Maize grain by whole area in plum-maize-forage grass agroforestry (plum-maize-AF). (f) Maize grain by maize area in plum-maize-AF. (g) Maize stover by whole area in plum-maize-AF. (h) Maize stover by maize area in plum-maize-AF. Different upper-case and lower-case letters indicate significant differences ($p$<0.05) in the main effect of position within agroforestry (A-B) and interactive effect of position and year on maize yield (a-d).

In longan-mango-AF, maize HI was similar in 2018 and 2019 (around 0.55) and decreased over time to around 0.48 in 2020-2021 (Figure 22a). In 2018-2019, maize HI was equivalent in all positions, while in 2020 maize HI below longan and mango tree-grass rows (BL and BM) was lower than above longan and mango tree-grass rows (AL and AM). In the period 2020-2021, maize HI decreased at positions AM and AFM. Above longan tree-grass rows, HI remained consistent.

In plum-maize-AF, the greatest maize HI was recorded in 2020 (0.55), followed by 2019 (0.47) and 2021 (0.49) (Figure 22b).

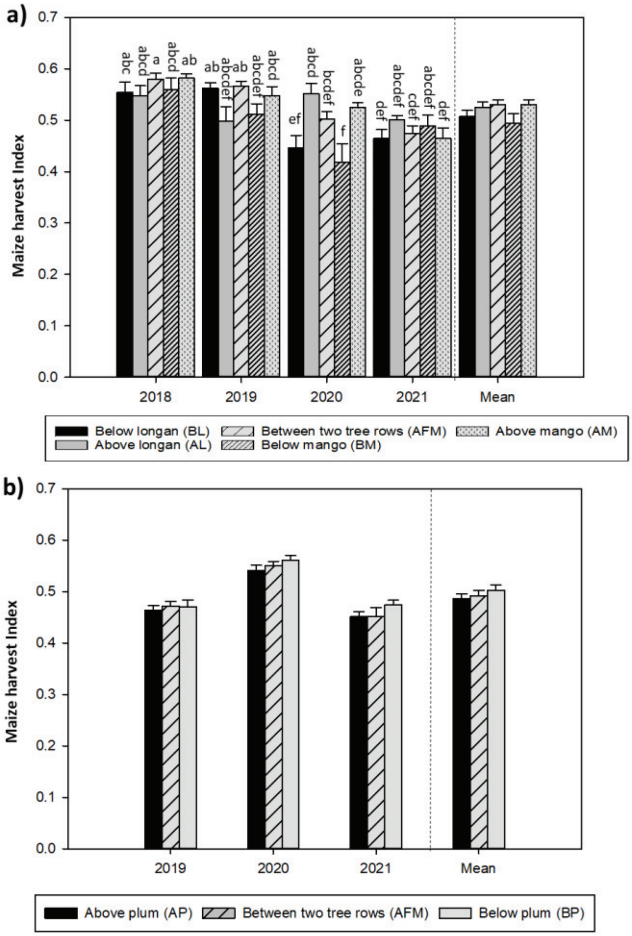


*Figure 22.* Maize harvest index (HI) (mean ± standard error) (a) below longan (BL), above longan (AL), between two tree rows (AFM), below mango (BM) and above mango (AM) in longan-mango-maize-forage grass agroforestry (longan-mango-AF) and (b) above plum (AP), between two tree rows (AFM) and below plum (BP) in plum-maize-forage grass agroforestry (plum-maize-AF). Different lower-case letters indicate significant differences ($p<0.05$) interactive effect of position and year on maize harvest index (a-f).

### 4.4.3 Height, leaf N concentration and biomass yield of forage grass

In both experiments, forage grass height varied depending on when during the growing season the grass was harvested. In general, forage grass height was greatest in the middle of the maize season. The SPAD readings for forage grass increased after maize was planted and fertilised, and peaked in the middle of the maize season, before declining by maize harvest time (Figures 23a, 23b). There was an interaction between forage grass below trees (longan and mango) and year (2019 and 2021, 2018 and 2021) on height and SPAD values, respectively.

In the first year of longan-mango-AF, the forage grass produced biomass two months after planting and there was no significant difference in harvested fresh grass biomass below longan and mango trees (Figure 24a). Except in the first year, fresh grass biomass yield varied depending on the time of harvest (Figure 24a). The amount increased from planting of maize and peaked in the middle of the maize season, then decreased by maize harvesting time.

In plum-maize-AF, harvesting of fresh grass biomass started in the beginning of the maize season in 2019 (Figure 24b). Fresh grass biomass yield increased from planting and fertilisation of maize and reached its highest value in the middle of the maize season, then decreased by maize harvesting time.

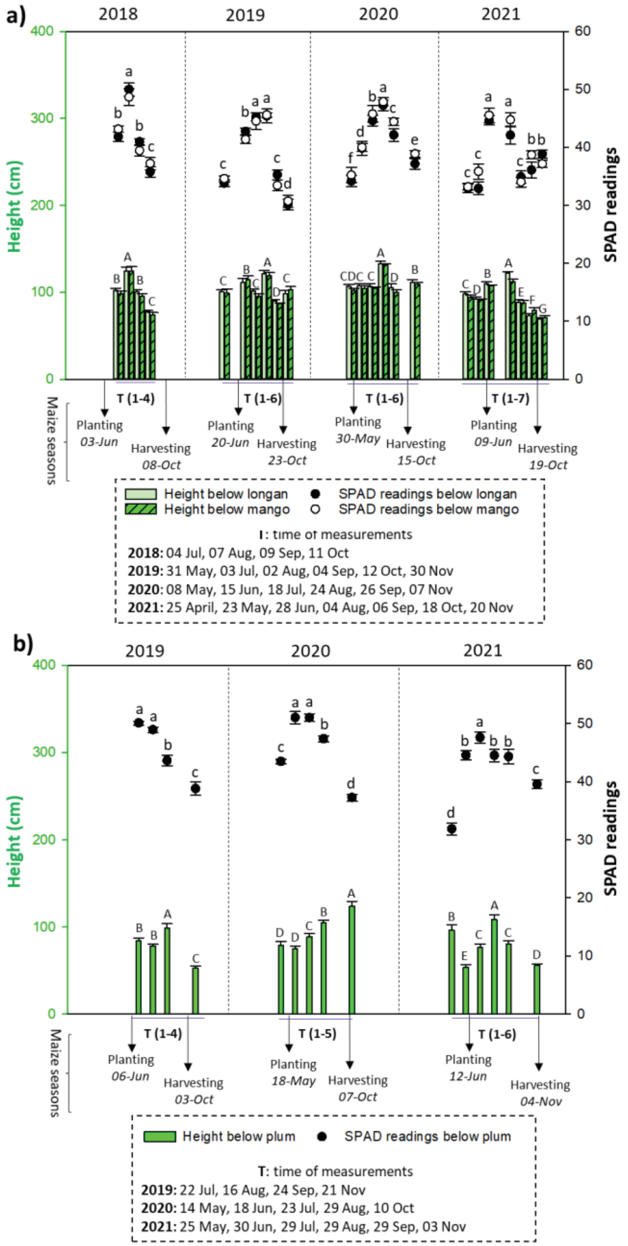


*Figure 23*. Growth and SPAD readings of forage grass (mean and standard error) in (a) longan-mango-maize-forage grass agroforestry and (b) plum-maize-forage grass agroforestry. Different upper-case (growth) and lower-case (SPAD readings) letters on bars indicate significant differences ($p$<0.05) between measurement occasions.

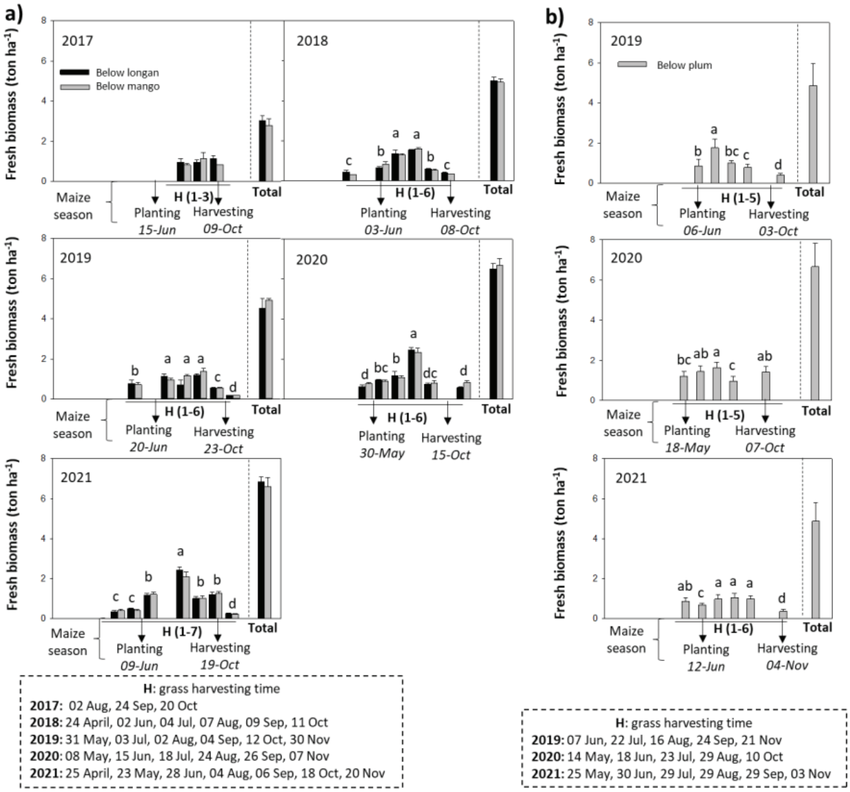


*Figure 24*. Yield of forage grass (fresh biomass, mean and standard error) harvested in (a) longan-mango-maize-forage grass agroforestry and (b) plum-maize-forage grass agroforestry. Different lower-case letters on bars indicate significant differences ($p$<0.05) between harvesting times.

### 4.4.4 SOC and nutrient concentrations

Across years and soil depths, the concentrations of available P and available K in the longan-mango-AF system were significantly influenced by position in relation to the tree and grass strips (Figures 25a5, 25a6). The concentrations were significantly lower below the longan (BL) and mango (BM) tree-grass rows than above the grass-tree rows (AL, AM). There was an interaction between position relative to the tree and grass strips and year on SOC, total-P and available P, where SOC declined over time below the longan tree-grass rows (BL), while there was no change at the other positions (Figure 25a1). Total-P concentration was similar in all positions in 2018, but it was higher above longan tree-grass rows (AL) than below mango tree-grass row (BM) in 2021 (Figure 25a3). Available P concentration decreased below the tree-grass rows (BL, BM) over time, and was higher above than below tree-grass rows in 2021 (Figure 25a5).

Across years and soil depths, in plum-maize-AF there was a significant main effect of position relative to tree and grass strips on SOC (Figure 25b1) and total-N (Figure 25b2), where SOC was significantly higher above plum tree-grass rows (AP) than between two tree rows (AFM) and below plum tree-grass rows (BP). The SOC content was lower below tree-grass rows (BP) than between two tree rows (AFM). Total-N concentration was similar above tree-grass rows (AP) and between two tree rows (AFM), but significantly lower below tree-grass rows (BP). There was an interactive effect of position and year on SOC, which decreased over time between two tree rows (AFM) and below tree-grass rows (BP).

Overall, the concentrations of SOC and related 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.

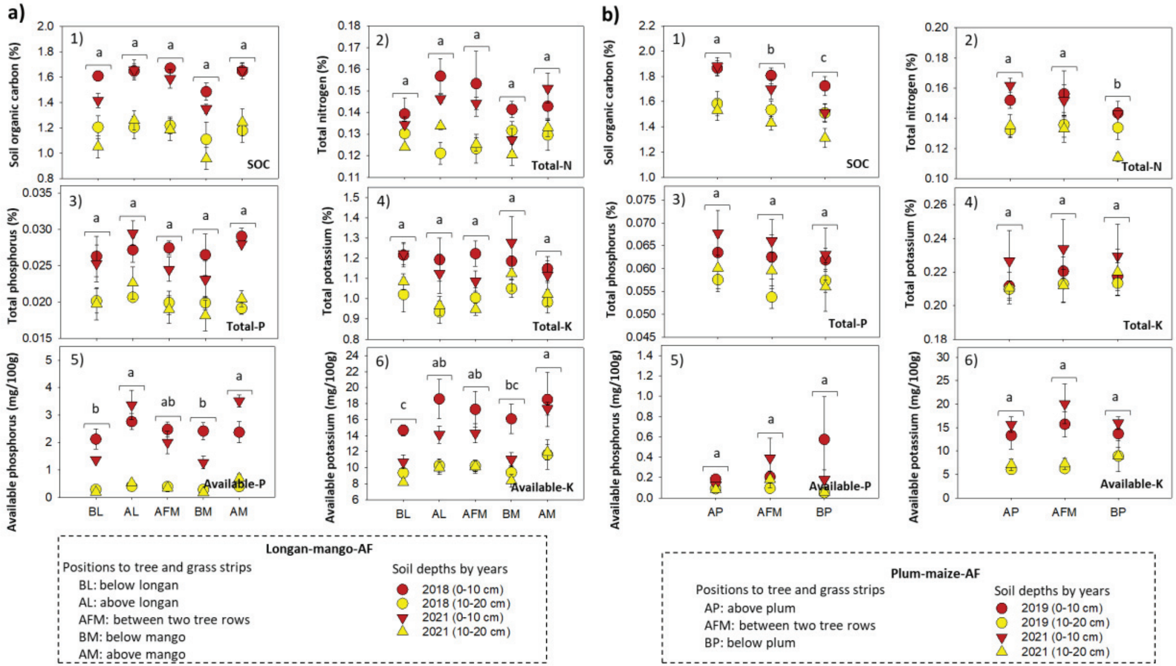


*Figure 25*. Soil nutrient concentrations (mean ± standard error) in (a) longan-mango-maize-forage grass agroforestry (longan-mango-AF): 1) soil organic carbon (SOC), 2) total nitrogen, 3) total phosphorus, 4) total potassium, 5) available phosphorus, and 6) available potassium, and (b) plum-maize-forage grass agroforestry (plum-maize-AF): 1) SOC, 2) total nitrogen, 3) total phosphorus, 4) total potassium, 5) available phosphorus, and 6) available potassium. 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 SOC and nutrients.

## 4.5 Impact of weed management practices (Paper IV)

### 4.5.1 Weed biomass

In longan-mango-AF, weed biomass was generally lower with two hand hoeings (2xHAND) and with one herbicide application and one hand hoeing (HERB+HAND) than in the herbicide-only treatment (HERB) (Figure 26a). The effect of weed control treatment changed over time and showed an interaction between weed biomass and year. In the first year, HERB plots had similar amounts of weeds as 2xHAND and HERB+HAND plots, but in the second year weed biomass was much higher in HERB than in 2xHAND and HERB+HAND (Figure 26a).

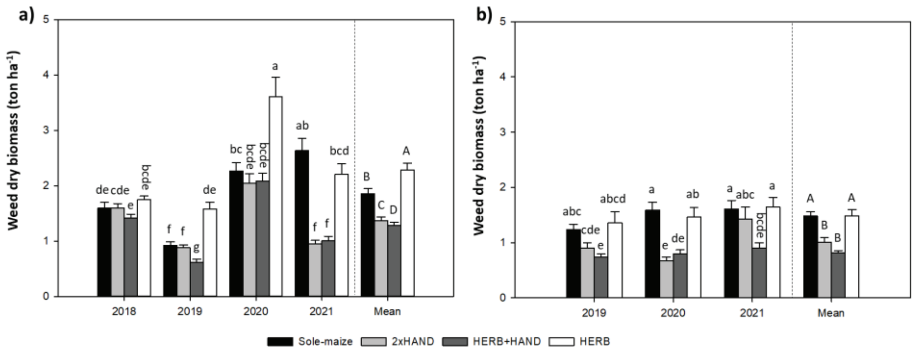


*Figure 26*. Weed biomass in different weed control treatments (mean ± standard error, sole-crop maize as reference) in (a) longan-mango-maize-forage grass agroforestry and (b) plum-maize-forage grass agroforestry. The weed treatments were: two hand hoeings, at maize stage 3-4 and 10-11 fully expanded leaves (2xHAND); one herbicide application at maize stage 3-4 fully expanded leaves + one hand hoeing at maize stage 10-11 fully expanded leaves (HERB+HAND); and one herbicide application at maize stage 3-4 fully expanded leaves (HERB). One herbicide application at maize stage 3-4 fully expanded leaves was applied in sole-crop maize (sole-maize). Different upper-case and lower-case letters indicate significant differences ($p<0.05$) in the main effect of weed control treatment (A-D) and interactive effect of weed control treatment and year on weed biomass (a-g).

In plum-maize-AF, weed biomass was generally similar in HERB and sole-maize and significantly lower in 2xHAND and HERB+HAND. The weed control treatments showed an interaction with year, but no clear trend (Figure 26b).

### 4.5.2 Maize growth and plant leaf N concentration

In longan-mango-AF, there was a main effect of weed control treatment on maize growth (height) and SPAD values, with interactive effects of weed treatment x year, weed treatment x maize growth stage, and weed treatment x year x maize growth stage (Figure 27a). On average, maize height and SPAD values were similar in 2xHAND, HERB+HAND and HERB. Differences in SPAD values between treatments started to emerge when maize had 6-7 leaves (Figure 27a), and SPAD was then higher in 2xHAND than in the other treatments. In later maize development stages, SPAD was higher in HERB+HAND than in 2xHAND.

In plum-maize-AF, all weed control treatments had a significant impact on maize height and SPAD values, which were higher in 2xHAND than in HERB (Figure 27b). There were interactive effects of weed treatment x year and weed treatment x year x maize growth stage, but no clear patterns (Figure 27b).

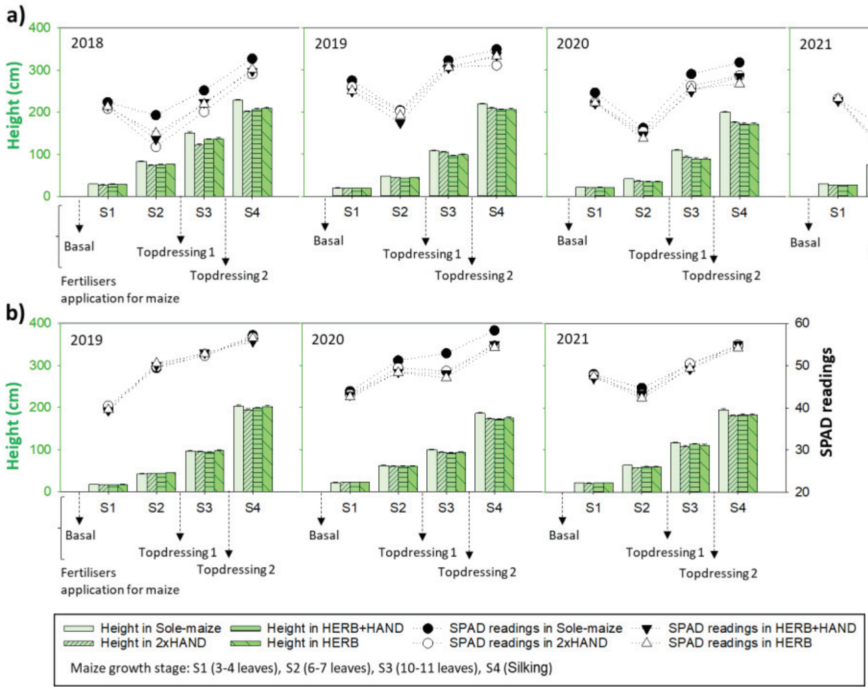


*Figure 27*. Maize height and SPAD values recorded in the different weed control treatments (mean ± standard error, sole-crop maize as reference) in (a) longan-mango-maize-forage grass agroforestry 2018-2021 and (b) plum-maize-forage grass agroforestry 2019-2021. For description of treatments, see Figure 26.

### 4.5.3 Yield of maize, forage grass and fruit trees

In longan-mango-AF, there was an effect of weed control treatment on maize grain yield, which was higher in 2xHAND and HERB+HAND than in HERB (Figure 28a1). There was an interactive effect of weed treatment and year on maize grain yield, which likely reflected the declining maize yield in HERB+HAND and HERB (and in the reference sole-maize) starting in 2020, while it remained stable in 2xHAND in 2018-2021.

In plum-maize-AF, there was no significant effect of weed control treatment on maize grain yield and no interaction between weed treatment and year (Figure 28b1).

In longan-mango-AF, fresh biomass of forage grass was significantly lower in 2xHAND than in HERB+HAND and HERB (Figure 28a2). In plum-maize-AF, fresh grass biomass was similar in 2xHAND and HERB+HAND, but lower in HERB (Figure 28b2).

The mango and longan trees started to bear fruit in year 3 and 4, respectively. Fruit yield of longan was similar in all weed control treatments (Figure 28a3), but mango yield was significantly higher in the treatment that did not involve herbicides (2xHAND) (Figure 28a4). The plum trees did not produce any fruit during the experimental period.

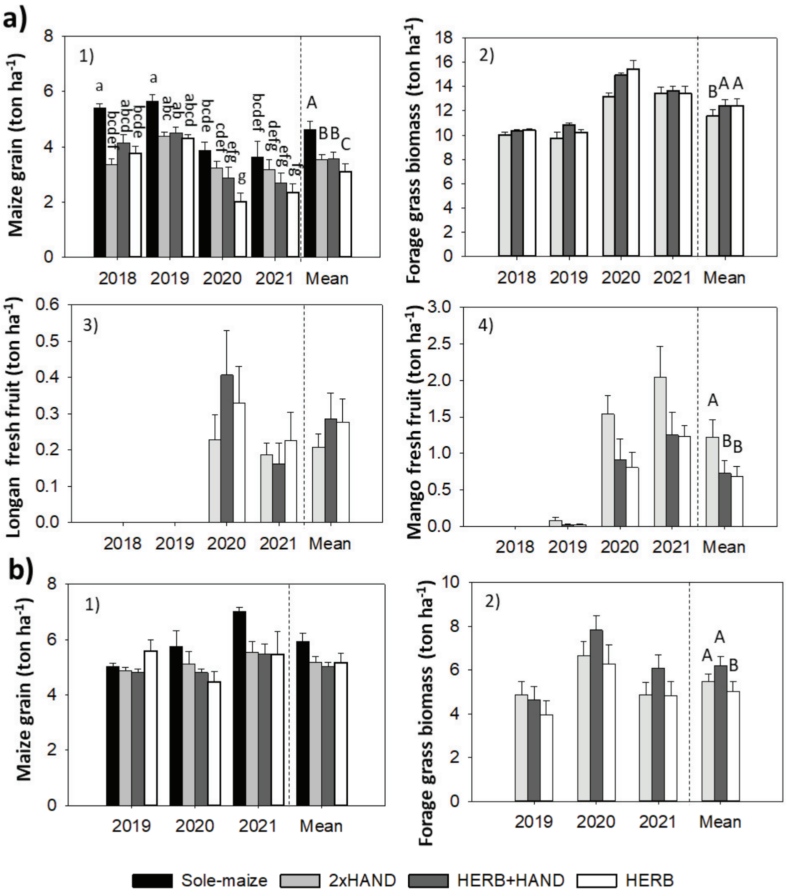


*Figure 28.* Yield of maize (dry grain), fresh forage grass and fruits in different weed control treatments (mean ± standard error, sole-crop maize as reference) in (a) longan-mango-maize-forage grass agroforestry: 1) maize grain, 2) fresh forage grass biomass, 3) longan fruit and 4) mango fruit, and (b) plum-maize-forage grass agroforestry: 1) maize grain and 2) fresh forage grass biomass. Different upper-case and lower-case letters indicate significant differences ($p$<0.05) in the main effect of weed control treatment (A-C) and interactive effect of weed control treatment and year on yield of maize, forage grass and fruit (a-g). For description of weed control treatments, see Figure 26.

### 4.5.4 Maize harvest index (HI) and partial land equivalent ratio (pLER)

There was no significant difference in maize HI between the weed control treatments at either site. The HI values ranged from 0.48 to 0.57 in longan-mango-AF and 0.46 to 0.55 in plum-maize-AF (Figure 29). In longan-mango-AF, the pLER of maize in 2xHAND and HERB+HAND was significantly higher than in HERB (Figure 29c). There were interactive effects of weed treatment x year on maize pLER, but no clear patterns (Figure 29c). The pLER of maize was 0.62-0.84, 0.74-0.81 and 0.51-0.77 in 2xHAND, HERB+HAND and HERB, respectively. In plum-maize-AF, there was no significant difference in pLER of maize between the weed treatments (0.79-0.97, 0.78-0.96 and 0.79-1.11 in 2xHAND, HERB+HAND and HERB, respectively) (Figure 29d).

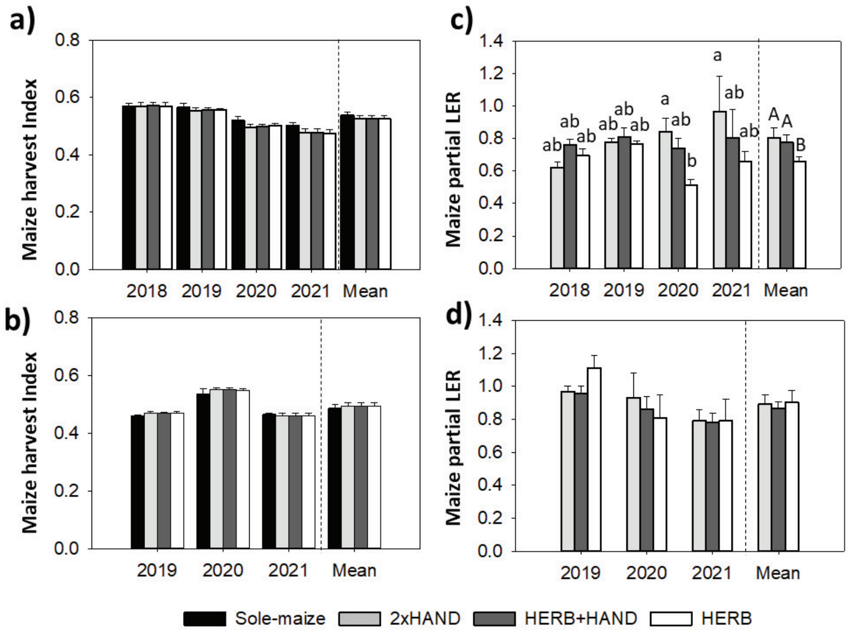


*Figure 29.* Maize harvest index (HI) and partial land equivalent ratio (pLER) (both mean ± standard error, sole-crop maize as reference) in different weed control treatments in the agroforestry systems. (a) HI in longan-mango-maize-forage grass agroforestry (longan-mango-AF). (b) HI in plum-maize-forage grass agroforestry (plum-maize-AF). (c) pLER in longan-mango-AF. (d) pLER in plum-maize-AF. Different upper-case and lower-case letters indicate significant differences ($p$<0.05) in the main effect of weed control treatment (A-B) and interactive effect of weed control treatment and year on maize HI and pLER (a-b). For description of weed control treatments, see Figure 26.

### 4.5.5 Tree growth in the agroforestry systems

Longan growth was not significantly affected by weed control treatment (Figure 30a), but mango tree base diameter, canopy width and height were smaller in HERB than in the other treatments (Figure 30b). Plum tree base diameter ($p$=0.01), canopy diameter ($p$=0.04) and tree height ($p$=0.009) were significantly greater in 2xHAND than in HERB (Figure 30c).

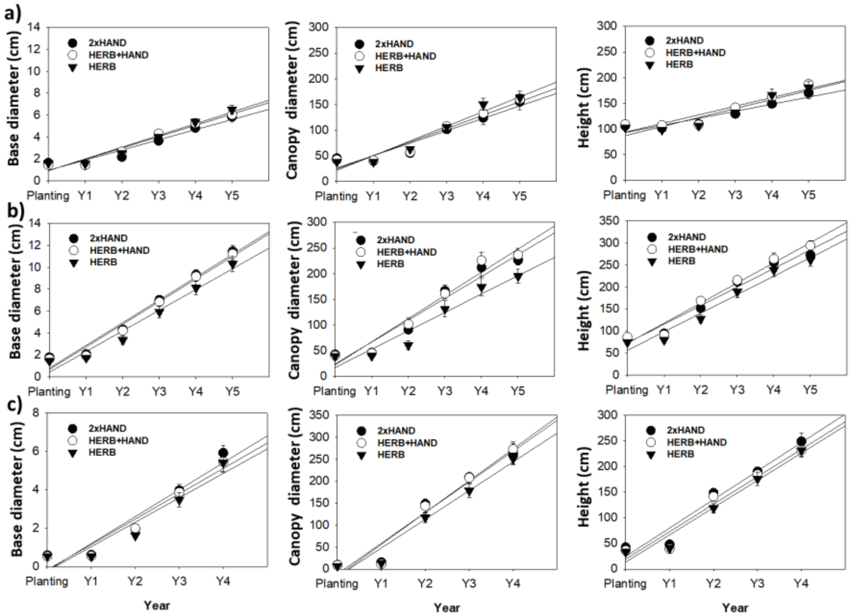


*Figure 30.* Regression lines describing tree growth (mean ± standard error) in different weed control treatments in (a) longan and (b) mango in longan-mango-maize-forage grass agroforestry and (c) plum in plum-maize-forage grass agroforestry. For description of weed control treatments, see Figure 26.

### 4.5.6 Labour use

Labour use in sole-maize (reference) was similar across years at both sites, while it increased in the agroforestry systems, causing a significant interaction between weed control treatment and year (Figure 31).

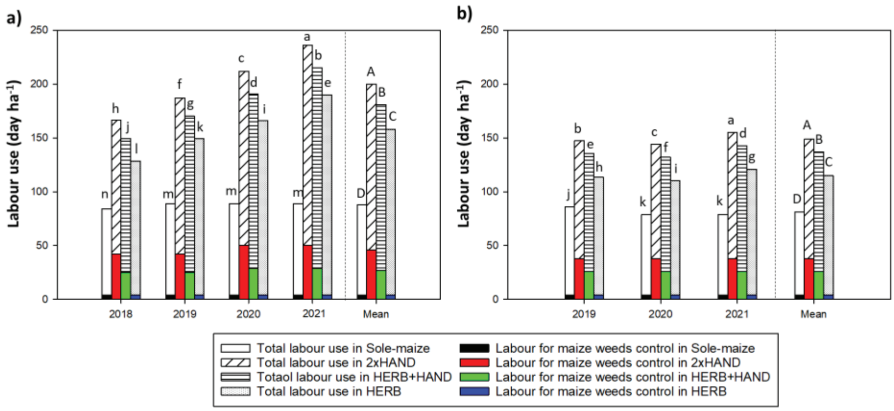


*Figure 31*. Total labour use in the different weed control treatments and labour use for maize weeds control (values are means, sole-crop maize as reference) in (a) longan-mango-maize-forage grass agroforestry and (b) plum-maize-forage grass agroforestry. Different upper-case and lower-case letters indicate significant differences ($p$<0.05) in the main effect of weed control treatment (A-D) and interactive effect of weed control treatment and year on labour use (a-n). For description of weed control treatments, see Figure 26.

In agroforestry, labour use for maize weed control was highest in 2xHAND, followed by HERB+HAND, and lowest in HERB (Figure 31). In 2xHAND, weed control comprised 21-25% of total labour use in longan-mango-AF and 25-26% in plum-maize-AF, in HERB+HAND it comprised 14-17% of total labour use in longan-mango-AF and 18-20% in plum-maize-AF, and in HERB it comprised only 2-3% and 3-4% of total labour use longan-mango-AF and plum-maize-AF, respectively.

### 4.5.7 Profitability

In longan-mango-AF, during the period 2018-2021, sole-maize had a mean annual total investment cost of 967 USD ha$^{-1}$, while that of 2xHAND, HERB+HAND and HERB was 1.8-, 1.7- and 1.6-fold higher, respectively (Figure 32a). However, mean annual total income in 2xHAND, HERB+HAND and HERB was 1.6-, 1.6- and 1.4-fold higher, respectively, than in sole-maize (1286 USD ha$^{-1}$). The profitability (net profit) of 2xHAND, HERB+HAND and HERB did not differ significantly in any of the years.

In plum-maize-AF, during the period 2019-2021 mean total annual investment cost of sole-maize was 989 USD ha$^{-1}$, while it was 1.5-, 1.5- and

1.3-fold higher in 2xHAND, HERB+HAND and HERB, respectively (Figure 32b). There were no significant differences in terms of annual total income between the weed control treatments (Figure 32b). There was an interactive effect of weed treatment and year on net profit, which increased over time in 2xHAND, HERB+HAND and HERB, but was similar in all treatments within years.

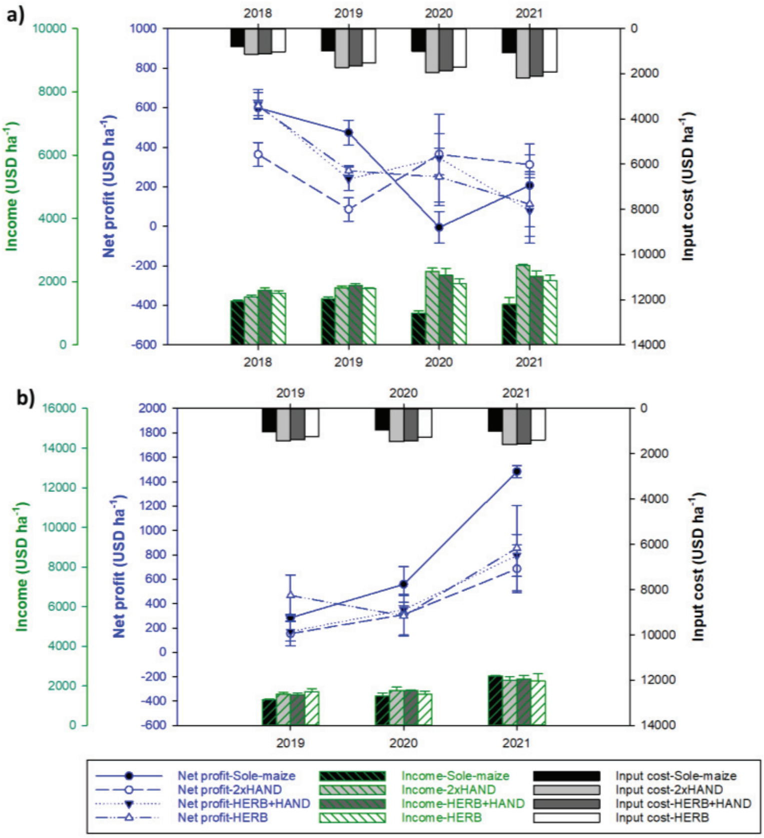


*Figure 32*. Profitability of different weed control treatments (mean ± standard error, sole-crop maize as reference) in (a) longan-mango-maize-forage grass agroforestry and (b) plum-maize-forage grass agroforestry. For description of weed control treatments, see Figure 26.

# 5. Discussion

## 5.1 Tree-crop performance

Longan and son tra trees in agroforestry systems with longan-maize and son tra-grasses (guinea and mulato) had slower growth and lower yield than when they were grown as sole-trees (Paper I). According to Malézieux *et al.* (2009), aboveground interactions and competition between tree/crop components in agroforestry systems are mostly due to shadowing, while belowground interactions and competition are due to the distribution of tree/crop roots relative to soil water and nutrient availability. Competition between trees, crops and grass growing adjacent to each other resulted in reduced growth and yield of longan and son tra in the agroforestry systems assessed in this thesis. Previous studies have shown that forage grasses such as guinea grass form a deep, robust, dense and fibrous root system (Humphreys & Patridge, 1995), which may have inhibited lateral root development by longan and son tra trees in the trials. Furthermore, soil water competition can occur when trees and forage grass are planted adjacent to one another (Sarto *et al.*, 2022). As a result, when trees are planted close to grass strips, they experience intense competition that has an adverse effect on growth and yield (Schaller *et al.*, 2003). This was most likely also the case in the systems assessed in this thesis, although soil water measurements were not performed. At the same time, the maize in longan-maize-AF likely affected the longan trees by reducing tree root development in the cropping zone, as previously been observed by Livesley *et al.* (2000).

Sole-fruit tree plots were not available for comparison in longan-mango-AF, plum-maize-AF and son tra-coffee-AF. However, in the older longan-maize-AF trial (established 2012) the forage grass was found to have a negative impact on the longan trees planted nearby (*e.g.* 0.5 m away), which led to lower growth and fruit yield than in sole-longan (Paper I). Although longan, mango, plum and son tra were planted 1.0 m away from the guinea grass strips in the trials established 2017/2018, there was probably still competition between the forage grass and the fruit trees. This is similar to findings that guinea grass can have a negative impact on *Eucalyptus deglupta* (Schaller *et al.*, 2003) or son tra (Paper I) trees planted 0.9 and 1.0 m, respectively, away from the grass strips.

Maize height and plant leaf N concentration were greater in sole-crop maize than in longan-mango-AF and plum-maize-AF over a five- and four-year period, respectively (Paper III), and this was also found in longan-maize-AF at year 7 (the only year of measurements) (Paper I). This was likely caused by competition between tree/crop components and spatial variability in resource distribution within the agroforestry systems. Paper III in this thesis revealed spatial variability in maize growth, leaf N concentration and yield along slopes in longan-mango-AF and plum-maize-AF. Previous research on alley systems has found that tree roots compete for water and that shading by trees reduces solar radiation in rows of maize adjacent to the tree rows, resulting in lower maize performance (Jose *et al.*, 2000; Miller & Pallardy, 2001; Friday & Fownes, 2002; Swieter *et al.*, 2022). Tuan *et al.* (2016) found that in a system where maize was planted with contour planting of grass strips, competition with maize occurred, resulting in reductions in maize growth, leaf N concentration and yield, particularly in rows close to grass barriers. However, in Paper III competition only occurred at the downslope side of the tree-grass rows. Competition for N and water between trees, maize and grass most likely caused lower growth and a yield reduction in maize in the downslope positions. In contrast, maize performed better between and above the tree-grass rows than on the downslope side of the grass strips in terms of height, plant N concentration and yield (net area). This spatial variation in maize crop performance may have been caused by differences (or changes) in resource distribution, particularly with regard to soil water and nutrient availability (Dercon *et al.*, 2006; Guto *et al.*, 2012; Lenka *et al.*, 2012). Along the descending slope, soil nutrients and water were probably transferred from positions downslope of a grass strip to positions above the next tree-grass row. As a result, maize grew better in positions above tree-grass rows than in positions below the grass strips and had better yield. Some previous studies have also reported higher yields of crops such as potato, maize and cabbage on the upslope side than on the downslope side of grass strips (Poudel *et al.*, 1999; Kagabo *et al.*, 2013). In contrast, other studies have found lower yield of *e.g.* maize and wheat on the upslope side of grass strips, caused by competition for soil nutrients and moisture (Dercon *et al.*, 2006; Guto *et al.*, 2012).

In this thesis, maize yield (whole area) was lower in longan-mango-AF than in sole-maize, while maize yield in longan-maize-AF and plum-maize-AF systems was comparable to that in sole-maize. Water is most likely the limiting factor throughout the growing season on steeply sloping land in northwest Vietnam, where maize growth is entirely dependent on rainfall (Ha *et al.*, 2004). Total rainfall during the study period was lower in Son La, where the longan-mango-maize-AF trial was located, than in Yen Bai, where the longan-maize-AF and plum-maize-AF trials were situated. Thus, at both research sites, competition for water resources between maize, trees, forage grass and weeds was probably an important factor influencing maize yield. Higher rainfall during the growing season probably compensated to some extent for water competition between maize and trees, fodder grass and weeds in agroforestry at the Yen Bai site. The results obtained for plum-maize-AF indicated that even in positions below tree-grass rows, maize yields were comparable to those in between tree rows over the experimental period (Paper III). In longan-maize-AF, data obtained in year 7 revealed that maize yield between two tree rows was 24% higher than in sole-maize (Paper I). On the contrary, overall maize HI in longan-mango-AF declined over time. Maize HI also decreased above mango tree-grass rows, but remained constant above longan tree-grass rows. Mango trees had a larger canopy and greater height during the study period than longan trees. As a result, mango trees were likely more resource-competitive with maize than longan trees, which affected maize yield in the longan-mango-AF system.

Growth and yield of coffee in son tra-coffee-AF were equivalent to those in sole-coffee. Incorporation of shade trees into coffee plantations can enhance yield in various cropping systems (Munroe *et al.*, 2015). The presence of shade trees has been shown to significantly alter the microclimate for the coffee crop, by lowering air temperature in the summer and increasing the relative humidity (Araújo *et al.*, 2016), which helps the coffee to grow better. Under the canopy of shade trees, coffee is shielded from wind and frost and, in addition, mulch is provided (Nguyen *et al.*, 2020). Furthermore, shade trees prevent soil erosion, increase carbon sequestration and improve system resilience to climate change (Jha *et al.*, 2011). The son tra-coffee-AF system assessed in this thesis was just five years old and the ecological benefits of the system would likely become more visible in the mature system, when the son tra trees can provide greater shade for coffee development. However, during the study period there were no competitive or beneficial effects of trees on the coffee plants.

There were no sole-guinea grass plots available for comparison in this thesis. Guinea grass is a C4 photosynthesis forage crop (Carvalho *et al.*, 2020) and the shade from tree canopies in agroforestry affects its biomass production (Kumar *et al.*, 2001; Pandey *et al.*, 2011; Dibala *et al.*, 2021). However, Paper III showed that under the different fruit tree species in longan-mango-AF and plum-maize-AF, the height, plant N concentration and biomass yield of guinea grass were comparable. It also showed that the performance of the grass was likely unaffected by trees in terms of competition for light resources during the early stage of agroforestry (4-5 years). In mature agroforestry, when the trees have a bigger canopy cover and fully shade the grass strips, a greater reduction in forage grass biomass yield can be expected.

## 5.2 Productivity and profitability

The agroforestry systems evaluated in this thesis delivered earlier and more diverse products than the sole-tree and sole-crop systems. From the second year onwards, they also provided higher total production for farmers. Total production derived primarily from forage grasses and crops over the first three years, with forage-grass biomass bringing farmers benefits from years 1-2. When the trees began to yield fruit in years 3-4, the products became more diverse, with production increasing in subsequent years.

A LER value greater than 1.0 indicates that mixed systems are advantageous (Mead & Willey, 1980). Numerous researchers have discovered that although agroforestry may decrease crop and/or tree yield as a result of competition, its LER remains greater than 1.0 (Fadl & Sheikh, 2010; Bai *et al.*, 2016; Miah *et al.*, 2018; Xu *et al.*, 2019; Njira *et al.*, 2021; Temani *et al.*, 2021). This was confirmed for the longan-maize-AF in this thesis, where the mixed system was more productive than the sole-maize and sole-longan from year 2 onwards, as indicated by LER ranging from 1.1 to 1.9. The LER of son tra-mulato-AF exceeded 1.0 from year 3, when son tra started to bear fruit, while son tra-guinea-AF had LER <1.0 due to strong competition from the grass hindering the growth of the son tra trees.

Since sole fruit-tree plots were not available for comparison with longan-mango-AF, plum-maize-AF and son tra-coffee-AF, pLER was calculated for maize and coffee. The results showed that pLER for maize was 0.62-0.98 and 0.79-0.97 in longan-mango-AF and plum-maize-AF, respectively, and pLER for coffee was 0.69-0.86 in son tra-coffee-AF. The high pLER in most years suggests that companion crops, in this case fruit trees and forage grass strips, had moderate negative effect on the crops in the agroforestry systems during the first 4-5 years after establishment.

From year 2 onward, cost-benefit analysis for longan-maize-AF and son tra-grasses (guinea and mulato)-AF revealed that these systems were more profitable than the corresponding sole-crop systems. In addition, the payback period of the loan/credit to farmers for these agroforestry systems was around two years. However, agroforestry required a larger initial investment than sole-crops. In addition, trees take several years to bear fruit and planting trees is a long-term investment (Caviglia-Harris *et al.*, 2003; Bohra *et al.*, 2018). Therefore, when comparing production and profitability, a cycle of some years must be considered because the time to establish perennial trees is always longer than for annual crops and the economic input is higher in agroforestry systems (Do *et al.*, 2020).

## 5.3 Terrace formation, soil and nutrient losses

Five years after transition from sole cropping of annual crops to AF, there was evidence that soil had moved from the downslope side of grass strips and accumulated at the upslope side of the next grass strip, leading to formation of terraces in the longan-mango-AF and son tra-coffee-AF systems. These movements of soil on steep slopes were probably associated with soil tillage practices such as ploughing, hoeing and mechanical weed control and water flows entering the field from above (Rymshaw *et al.*, 1997; Ziegler *et al.*, 2007). Soil surface tillage associated with weed management by repeated hand hoeing and slope gradient had a significant impact on the rate of soil deposition above the grass strips in longan-mango-AF and son tra-coffee-AF (Paper II). Grass strips delay the downhill movement of soil by retaining sediment (Kagabo *et al.*, 2013), facilitating terrace formation on steep slopes (Paper II). The grass strips (and tree rows) in the different 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 contour lines over time. In addition, the trees in agroforestry have been shown to stabilise terrace structure through their deep and wide root systems (Rutebuka *et al.*, 2021). Trees also increase soil cover through the contribution of the canopy and litter layer and supply soil organic matter from dead leaves, twigs, and branches, as well as living material from pruning that falls to the ground (Atangana *et al.*, 2014).

Well-established effective barriers in the different agroforestry systems, such as natural terrace formation by grass strips and tree rows, played a significant role in minimising soil movement and SOC and nutrient losses, even at an early stage after transitioning from sole annual crops to agroforestry (Paper II). Effective barriers play a direct role in erosion control and reduce surface runoff of water and associated losses of soil, SOC and nutrients by minimising slope length and inclination, and modifying the passage of overland flow (Kagabo *et al.*, 2013; Atangana *et al.*, 2014; Are *et al.*, 2018). The findings in this thesis are in line with those of Muchane *et al.* (2020), who conducted a meta-analysis on the effect of agroforestry systems on soil loss due to soil erosion in the humid and sub-humid tropics. According to that study, agroforestry reduces soil erosion rates by 50% compared with sole-crop cultivation. In addition, studies world-wide have demonstrated that different agroforestry practices can have a significant impact in reducing SOC and nutrient losses compared with sole-crop cultivation (Lenka *et al.*, 2012; Hombegowda *et al.*, 2020; Zhu *et al.*, 2020). This thesis confirmed that planting grass strips, trees and crops along contour lines resulted in natural terrace formation on steeply sloping land (37-56%), thus reducing SOC and nutrient losses by 20-84% compared with sole crops.

## 5.4 Spatial variation in soil properties

As mentioned in section 5.1, maize height, leaf N concentration and yield were higher upslope than downslope of tree-grass strips in the longan-mango-AF and plum-maize-AF systems. Within the soil, spatial variation in available P and K developed within the longan-mango-AF system, whereas in plum-maize-AF spatial variation in SOC and total-N distribution developed (Paper III). Lower concentrations of SOC and other soil parameters were then observed in positions downslope of grass strips compared with upslope of tree-grass rows. In addition, SOC tended to decrease downslope of grass strips in both plum-maize-AF and longan-mango-AF during the experimental period. In the latter system, total-P and available P concentrations also decreased, while they remained at the same levels on the upslope side of tree-grass rows. The reason for this was probably that disturbed sediment gradually moved from the downslope side of grass strips and accumulated at the upslope side of the tree-grass rows farther down (Dercon *et al.*, 2006; Paper II). Competition for nutrients between tree/crop/grass components may also have contributed to the decline in soil fertility downslope of grass strips.

In this thesis, nutrient concentrations only decreased downslope of grass strips, and did not change upslope of the tree-grass rows and between two tree rows over the experimental period. The forage grass seemed to utilise the excess nutrients upslope of tree-grass strips when fertiliser was applied to maize and fruit trees during the growing season. This was evident from the height, plant N concentration and biomass production of the grass strips, which increased when maize was planted and peaked in the middle of the maize season before falling at maize harvest. These changes occurred concurrently with the times of fertiliser application to maize. The impact of position on soil water availability was not investigated, but other studies have indicated that in slope cultivation, grass strips play a significant role in slowing runoff velocity, spreading out 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, trees and maize growing above the grass strips. Even if nutrient availability is already adequate, this could result in higher fertiliser doses above the grass strips.

## 5.5 Functions of grass strips

When trees and crops were planted close to grass strips, they suffered intense competition, which had an adverse effect on growth and yield (as discussed in section 5.1). However, forage grass was considered one of the main components of the agroforestry systems in this thesis, as it brought early income to farmers already from year 1-2. Forage grass biomass can be used on-farm for feeding livestock and fish (Cook *et al.*, 2005) or can be sold or used as green manure. In addition, growing forage grasses can be an incentive for smallholder livestock production by improving the daily weight gain of cattle and reducing labour in finding feedstuffs (Bush *et al.*, 2014; Tuan *et al.*, 2014; Paper I).

Guinea grass has a deep, strong, dense and fibrous root system (Humphreys & Partridge, 1995) which has the ability to penetrate and bind soil particles, reinforcing the soil by increasing shear strength and soil surface roughness (Welle *et al.*, 2006). As a result, guinea grass strips can play a significant function in trapping sediment, contributing to terrace formation on steep slopes. Paper II demonstrated that the grass strips significantly reduced soil and nutrient losses, even in the early season of annual crops when the soil surface was bare due to tillage operations and the soil surface was disturbed after weed management by hand hoeing. Furthermore, the forage grass strips played an important role in trapping N during the growth season, enhancing nutrient use efficiency within agroforestry on steep slopes (Paper III).

Guinea grass is a forage grass with high agronomic value that is extensively distributed in the tropics and subtropics and has a strong tolerance to biotic and abiotic stresses. However, guinea grass has been observed to be highly invasive and to pose a major danger to native biodiversity and crops in agricultural landscapes (Soti & Thomas, 2022). Therefore, effective management is required when guinea grass is grown in agricultural fields, to avoid it spreading to natural habitats.

## 5.6 Effect of different weed control practices

Compared with HERB, the 2xHAND and HERB+HAND weed control strategies had lower weed abundance and higher maize yield in agroforestry. The results indicated that the frequency of treatment was more significant for weed control than the method used. This supports findings in previous studies where two weedings by hand and herbicides followed by one or two manual weedings efficiently controlled weeds, thus ensuring better maize yield at the end of the season (Muoni *et al.*, 2013; Fonteyne *et al.*, 2022). Hand hoeing can improve gas exchange in the soil and support root growth by eliminating soil crusts, while opening the soil surface boosts its ability to absorb water. As a result, the soil is better aerated and water may reach plant roots more quickly. However, soil tillage can also increase erosion. For the three different weed management techniques compared in the longan-mango-AF and plum-maize-AF trials, maize growth and maize leaf N concentration were comparable in all treatments. This suggests that at the experimental sites, competition between weeds and maize for available soil water was probably a major factor affecting maize yield rather than competition for N. Using HERB as a single approach is typically insufficient for long-term weed management (Ronald *et al.*, 2011). Furthermore, frequent application of herbicides with the same mode of action may lead to the emergence of herbicide-resistant weed populations (Heap, 2010). Therefore, repeated manual hand hoeing or herbicide application followed by hand hoeing for weed control may aid in preventing the development of herbicide resistance in weeds.

Compared with the 2xHAND treatment, HERB had a negative impact on the growth of mango and plum trees and on mango yield in the longan-mango and plum-maize-AF trials (Paper IV). Atrazine suppresses photosynthesis in some grasses and broadleaved plants (Chalifour & Juneau, 2011), and after application it can remain in the soil for 4-8 weeks, during which time it is taken up by plant roots and leaves and moves upward in the plant to areas of new growth (Rohde *et al.*, 1981; Houjayfa *et al.*, 2020). This might explain the negative effect on tree growth seen in the HERB treatment, while in HERB+HAND manual weeding after the early herbicide application might have compensated for the impact of herbicide on tree growth. Repeated hand hoeing (2xHAND treatment) enhanced the migration of sediment from below grass strips, resulting in build-up of a terrace above the next tree-grass strip (Paper II). Furthermore, during the sediment movement process, runoff and water erosion transferred SOC and nutrients applied to maize downhill, to be retained on the upslope side of tree-grass rows. This probably helped the trees in the 2xHAND treatment to grow better and give higher yield.

Paper IV confirmed that when herbicide was replaced with manual weeding (hand hoeing) in agroforestry, much more labour time was required. However, the net profit of the three weed management practices was not significantly different, despite the fact that 2xHAND and HERB+HAND used more labour to control weeds than HERB. The results demonstrated that the increased tree/crop yield in 2xHAND and HERB+HAND compensated for the higher labour cost associated with these weed management strategies.

To encourage farmers to produce high-quality agroforestry products in environmentally sustainable ways, *e.g.* using manual hand hoeing for weed control, a clear distribution route to market for agroforestry products is required. In order to add value to the products and compensate for higher investment and labour costs, agroforestry commodities must also be specifically certified or labelled (Simelton *et al.*, 2015).

## 5.7 Possibilities for system improvement

To increase the efficiency of the different agroforestry systems studied in this thesis, some potential improvements can be made. Competition would be reduced by increasing the planting distance between grass strips, crops and trees (Bazié *et al.*, 2012; Zhao *et al.*, 2012; Gao *et al.*, 2013; Paper I). Pruning trees to improve root distribution patterns and crown architecture can weaken aboveground and belowground competition between trees and crops (Peter & Lehmann, 2000; Bayala *et al.*, 2015; Dilla *et al.*, 2019; Nyaga *et al.*, 2019; Paper I). Planting legumes such as soybean and peanuts instead of maize is another option (Paper I). Supplying more fertiliser to plants suffering from nutrient deficiency in competition zones has also been suggested to increase production (Mercado & Reyes, 2012; Wolka *et al.*, 2021) and improve spatial resource availability. To reduce sediment loss on the downslope side of tree-grass strips, alternatives to traditional soil tillage techniques are needed, such as using minimum tillage and a cover crop or minimum tillage and a relay crop for maize (Tuan *et al.*, 2014). In addition, in the agroforestry systems studied in this thesis, forage grass competed for resources with tree/crop components, indicating that it would be necessary to fertilise forage grass in order to increase the amount of fodder for livestock, while also reducing competition with the tree and crop components in the system.

Management of trees and crops in agroforestry systems also needs to be adapted over time, from establishment to more mature agroforestry systems, so that farmers can overcome competition effects and optimise the efficiency of land use (Xu *et al.*, 2019). In the fruit tree-based agroforestry systems, the farmers prioritised the annual crop and forage grass during the first three years, when the trees had not yet produced fruit, but they began to pay more attention to the trees once they started to bear fruit. To maintain the long-term advantages of the fruit trees, the farmers required the short-term income from the annual crops (Paper I).

## 5.8 Possibilities for widespread adoption of fruit tree agroforestry in northwest Vietnam

Fruit tree-based agroforestry systems showed higher production levels and profitability than sole-crop cultivation and earlier returns on investment than sole-tree cultivation (Paper I). In addition, the agroforestry systems played a significant role in reducing soil and nutrient losses caused by soil erosion on steep slopes compared with sole-crops (Paper II). However, fruit-tree based agroforestry is viewed as a costly undertaking by local farmers, since it involves high establishment and labour costs. Local farmers were also concerned about the current low price of agroforestry products and the uncertain future market. In addition, farmers and extension workers often lack knowledge and expertise in implementing agroforestry (Simelton *et al.*, 2015; Nguyen *et al*., 2021).

Initial investment funding, subsidies or loans would be required to compensate for the high investment and maintenance costs in the first few years of agroforestry (Do *et al.*, 2020; Paper I). A stable market and the development of market links for agroforestry products are other important factors for agroforestry adoption in the region (Do *et al.*, 2020; Paper I). In addition, the capacity of farmers and extension workers to implement fruit tree-based agroforestry needs to be further developed. Detailed guidelines on the principles and design of agroforestry with contour planting on sloping uplands already exists (*e.g*. Xu *et al.*, 2013; La *et al.*, 2016). There are also guidelines on supporting agroforestry development for stakeholders, including authorities and decision makers (Catacutan *et al.*, 2018). In addition, some technical extension material on implementing different agroforestry options on sloping land (La *et al.*, 2019b, 2019c, 2019d, 2019e, 2019f, 2019g, 2019h) and on producing different tree seedlings that are suitable for local conditions (La *et al.*, 2019a) has been released. This technical information could be useful for extension workers and farmers in northwest Vietnam who are considering implementing agroforestry. However, the expansion of fruit tree-based agroforestry needs to be integrated into agricultural and forestry land use plans and policies, and into agricultural support programmes in the region (Simelton *et al.*, 2015). Finally, promoting use of forage grass biomass in livestock production would make agroforestry involving forage grass strips more viable in the region.

# 6. Conclusions, recommendations and future research

## 6.1 Conclusions

- Fruit tree agroforestry was more productive and profitable than sole cropping, but high investment costs and an uncertain market are barriers to uptake of agroforestry.
- Competition reduced production of the individual component crops, but increased total production and income over time. The impact of competition also increased over time and needs to be managed properly as the trees grow larger.
- Terraces were naturally formed by planting fruit trees and grass strips along contour lines, with gradual deposition of soil sediment and terrace formation above the tree-grass rows over time.
- Contour planting with fruit trees and fodder grass decreased losses of soil and nutrients by 20-84% compared with sole maize and coffee. Slope, rainfall intensity within and across years, degree of vegetation cover and tillage operations (particularly weed control technique) all had an impact on soil erosion rates.
- Spatial variation in crop performance and soil characteristics developed over time downslope of the tree-grass strips in agroforestry, most likely due to changes in soil nutrient distribution along the slope and nutrient competition between grass and tree/crop components. Within longan-mango and plum-maize agroforestry, maize performance and yield were higher above the tree-grass strips than below, whereas SOC and nutrient concentrations tended to decrease at positions downslope of the tree-grass strips.

- There was no difference in forage grass performance when grown below different fruit tree species (4-5 years since establishment). Grass strips were important in trapping N during the growing season and in improving nutrient utilisation in agroforestry on steep slopes. However, the forage grass probably competed for nutrients with the tree/crop components.
- In fruit tree agroforestry, repeated hand hoeing or herbicide application followed by one hand hoeing was better than the common local practice of one herbicide application. Higher tree/crop yield compensated for the higher labour requirement and cost of manual weeding.

## 6.2 Recommendations

- In order to optimise production in fruit tree agroforestry, competitive effects must be considered when designing agroforestry practices and developing management regimes. Future fruit tree-based agroforestry systems should apply adaptive management tailored to the needs arising when the agroforestry system is maturing, taking into account measures such as increasing the planting distance between trees, crops and grass, providing fertiliser for nutrient-deficient system components and pruning trees in competition zones. To further optimise the benefits of agroforestry, other high-value crops and/or biological N-fixing species can be introduced to reduce competition and support tree growth.
- To reduce soil and nutrient losses and maintain soil fertility and productivity, agroforestry establishment and contour planting to support natural terrace formation, as a nature-based solution to soil conservation, must be encouraged in steeply sloping areas. Adaptive management may be needed to improve spatial resource availability over time, such as fertilising nutrient-deficient components and areas within agroforestry systems.
- To gain economic and environmental benefits from manual weed control or a combination of manual weed control and herbicide, in fruit tree agroforestry and to increase farmer acceptance of these weed management strategies, adding value to agroforestry products in market value chains is critical to compensate for high investment

and labour costs. In order to reduce manual work and labour cost, different options for weed control need to be developed and evaluated, such as strimming weeds or covering the ground with understorey plants that also can be used as forage or green manure.

- To enable farmers in northwest Vietnam to adopt and expand agroforestry, financial support to assist with the higher investment costs, better market value chains and good market stability are required. Promoting use of forage grass in livestock production would make agroforestry involving forage grass strips more viable in the region. Fruit tree-based agroforestry with grass strips should be flexibly incorporated by local governments into land use plans for forestry and agriculture and into agricultural support programmes in the region. For practitioners (farmers and extension workers), capacity building in establishing and managing fruit tree-based agroforestry is required.

## 6.3 Future research

Future research needs to properly address the issue of competition for resources both above (for light) and below ground (for soil nutrients and water) between all tree/crop components. The results should be applied in the design, establishment and modelling of fruit tree-based agroforestry on steeply sloping land. Management factors, such as tree and crop species and cultivar selection, fertiliser type and rate, manure and other organic amendments, tree pruning, pest and weed control, and handling of tree/crop residues, must also be assessed. The aim of future research should be to advance the basis for recommendations on suitable design options and adaptive management practices, taking into account all tree, crop and grass components of the system to reduce competition and optimise resource use. Future studies should also seek to measure and quantify the contribution of agroforestry to soil and water protection, carbon storage and climate adaptation and mitigation. Finally, work is needed to enhance the quality of agroforestry goods (such as fruits), in order to have high-quality products with high market value, and to develop value chains and marketing systems.

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# Popular science summary

Cultivation on sloping land is a key characteristic of upland agriculture. The topographical characteristics of hilly regions, irregular rainfall events and ineffective agricultural management all contribute to severe soil erosion and associated nutrient losses, reduced crop yields and a decline in smallholder income over time. This threatens environmental sustainability and food security, especially in uplands dominated by poor communities and ethnic minorities. Agroforestry can be a more sustainable way to produce food and other products and services on sloping land than agriculture based on sole-crop cultivation of annual crops. This thesis examined whether fruit tree-based agroforestry on smallholder farms on sloping uplands can have a positive impact on sustainability. Production, potential soil conservation, profitability, tree and crop performance, spatial variation in resource distribution and impacts of weed control practices in agroforestry systems comprised of fruit trees, crops and fodder grasses were compared at sites on sloping uplands in northwest Vietnam. Sole-crop trees and crops were used as controls.

The various fruit tree-based agroforestry systems evaluated (including mango, longan, plum, son tra, coffee, maize, guinea grass or mulato grass) provided more diverse products and higher profitability than sole-crop systems. From the second year onwards, they also provided higher total productivity (higher total yield per area of land) for farmers. This total productivity derived primarily from forage grasses and crops over the first three years. When the trees began to yield fruit in years 3-4, the products became more diverse, with production increasing in subsequent years. In addition, the fruit tree-based agroforestry systems with contour planting of grass resulted in build-up of terraces, acting as a nature-based solution to soil erosion on upland farms. The terraces formed in fruit tree-based agroforestry

contributed significantly to soil conservation by reducing soil, organic carbon and related nutrient losses by 20-84% compared with sole-crop cultivation. Forage grass was one of main components in the agroforestry and can be used for feeding livestock and fish, reducing the labour requirement for finding feedstuffs, or can be sold or used as green manure, bringing earlier income for farmers. The forage grass strips also played a significant role in trapping nitrogen during the growing season and improving nutrient use efficiency in agroforestry on steep slopes. Spatial variation in crop performance and soil characteristics developed over time in fruit tree-based agroforestry on steeply sloping land. Maize height, leaf nitrogen concentration and yield (net area) were significantly higher at positions upslope of tree-grass rows than at positions downslope from grass strips. Soil organic carbon, total nitrogen, total phosphorus, available phosphorus and available potassium tended to decrease on the downslope side of tree-grass strips, most likely owing to transportation of soil and nutrients distribution down the slope and nutrient competition between grass and tree/crop components.

Today farmers often use herbicides to control weeds. The results showed that repeated hand hoeing or one herbicide application followed by one hand hoeing for weed control improved tree growth, increased crop and fruit yield, reduced weed abundance and partly compensated for the high cost of manual weed control in fruit tree-based agroforestry.

However, fruit tree-based agroforestry involved higher initial investment costs than sole-crop systems. Challenges such as higher investment cost and an unstable market for agroforestry products are barriers to promotion and wider adoption of agroforestry.

In addition, individual crop components generally grew more slowly and gave lower yield in agroforestry systems than in sole-crop/tree systems, most likely due to competition for light, water and nutrients.

Fruit tree-based agroforestry systems should use adaptive management while the system is maturing. Measures such as increasing the planting distance between trees, crops and grass, supplying fertiliser to nutrient-deficient tree/crop components and areas, and pruning trees in competition zones could maximise productivity and reduce competition between all components. Introducing other suitable high-value crops or biological nitrogen-fixing species to reduce competition and support the growth of trees could also help optimise the system. However, the replacement crop depends on farmers' needs and market demands. To gain both economic and environmental benefits from manual weed control in fruit tree agroforestry and to increase farmer acceptance of this practice, value must be added to agroforestry products in market value chains to compensate for the higher costs. External financial support, loans and/or supporting policy may be needed to cover the higher investment costs and to improve market value chains, particularly market stability. Promoting use of forage grass in livestock production would also make agroforestry involving forage grass strips more viable.

# Populärvetenskaplig sammanfattning

Odling på starkt sluttande mark är karaktäristiskt för jordbruk i högläntа områden. De topografiska egenskaperna hos kuperade områden, oregelbunden nederbörd och mindre effektiva odlingsmetoder kan bidra till allvarlig jorderosion med tillhörande näringsförluster, minskade skördar och en minskning av småbrukarnas inkomster över tid. Detta hotar både miljömässig hållbarhet och livsmedelssäkerhet, särskilt i bergsområden som domineras av fattig befolkning och etniska minoriteter. Agroforestry (trädjordbruk med samodling av träd, fleråriga och/eller ettåriga grödor) kan vara ett mer hållbart sätt att producera mat och andra produkter och tjänster på sluttande mark än jordbruk baserat på odling av ettåriga grödor i renbestånd.

I denna avhandling undersökte jag om fruktträdsbaserat trädjordbruk kan ha en positiv inverkan på olika aspekter av hållbarhet på små gårdar som ligger i sluttande högländer i nordvästra Vietnam. Produktion, potentiellt markbevarande, lönsamhet, utvecklingen av träd och grödor, rumslig variation i resursfördelning (t.ex. näring) och effekterna av ogräsbekämpningsmetoder i trädjordbruk som bestod av fruktträd, grödor och fodergräs jämfördes på olika platser. Renbestånd av träd och grödor användes som kontroll.

Olika typer av fruktträdsbaserade odlingssystem med träd (mango, longan, plommon, H’mong-äpple), grödor (majs, kaffe) och fodergräs (guinea och mulatu gräs) utvärderades och forskningen visade att de gav mer mångsidiga produkter och högre lönsamhet än odling av enskilda träd eller grödor i renbestånd. Från det andra året och framåt ledde trädjordbruk till högre total produktivitet för bönderna, d.v.s. högre totalskörd per markyta. Denna totala produktivitet härrörde främst från fodergräs och grödor under de första tre åren. När träden började ge frukt (tredje eller fjärde året) blev produkterna mer mångsidiga och den totala mängden produkter ökade sedan under de efterföljande åren. Dessutom resulterade konturplanteringen av fodergräs och fruktträd i uppbyggandet av terrasser av eroderad jord, dvs den fungerade som en naturbaserad lösning på jorderosion på gårdar i områden med branta sluttningar. Terrasserna som bildades bidrog avsevärt till markvården genom att minska förlusterna av jord, organiskt kol och växtnäringsämnen med 20 till 84 % jämfört med odling av grödor i renbestånd.

Fodergräs var en av huvudkomponenterna i trädjordbruket och det kan användas för att utfodra boskap och fisk, vilket minskar arbetsbehovet för att samla foder, och det kan även säljas eller användas som gröngödsel, vilket ger inkomster för jordbrukarna. Fodergräsremsorna spelade också en betydande roll för att fånga upp kväve under växtsäsongen och för att förbättra näringseffektiviteten inom trädjordbruket på branta sluttningar. Rumslig variation i majsens tillväxt och i markegenskaper såsom organiskt material och näring utvecklades på de starkt sluttande fälten under försöksperioden. Jord och näring samlades ovanför gräs- och trädraderna där majsen växte bra och gav högre skörd än nedanför dessa rader där matjordslagret tunnades ut och näringen försvann. Majsens höjd, kvävekoncentration i bladen och skörd var signifikant högre vid positioner ovanför träd- och gräsrader än vid positioner nedför dessa remsor. Organiskt material (kol), totalt kväve, total fosfor, tillgänglig fosfor och tillgängligt kalium tenderade att minska på den nedre sidan av träd- och gräsremsorna, troligen på grund av förändringar i markens näringsfördelning nedför sluttningen och näringskonkurrens mellan gräset och träd/grödor.

Bönderna använder ofta kemiska bekämpningsmedel för att minska mängden ogräs. Resultaten visar att upprepad handhackning, eller en ogräsmedelsapplicering följt av handhackning för att kontrollera ogräs förbättrade trädtillväxten, ökade skörden av grödor och frukt, minskade ogräsförekomsten och kompenserade delvis för den högre kostnaden för manuell ogräsbekämpning inom trädjordbruket.

Fruktträdsbaserat trädjordbruk innebar dock högre initiala investeringskostnader än odling av grödor eller träd i renbestånd. Utmaningar som högre investeringskostnader och en instabil marknad för produkterna är hinder för marknadsföring och bredare upptag av odlingssystem med trädjordbruk. Dessutom växte enskilda grödor generellt sett långsammare och gav lägre avkastning vid samodling än i renbestånd, troligen på grund av konkurrens om ljus, vatten och näring.

Fruktträdsbaserade odlingssystem bör anpassa skötselåtgärderna när träden växer för att optimera effekterna av samodling av träd och andra grödor. Åtgärder som att öka planteringsavståndet mellan träd, grödor och gräs, tillföra gödselmedel till träd/grödor i områden med näringsbrist och beskärning av träd skulle kunna maximera produktiviteten och minska konkurrensen mellan komponenterna i samodlingen. Att introducera andra lämpliga värdefulla grödor, eller biologiska kvävefixerande arter, för att minska konkurrensen och stödja tillväxten av träd kan också bidra till att optimera systemet. Ersättningsgrödan beror dock på jordbrukarnas behov och marknadens krav.

För att få både ekonomiska och miljömässiga fördelar av manuell ogräsbekämpning i samodling med fruktträd och för att öka lantbrukarnas acceptans av den metoden för ogräskontroll, måste produkterna från trädjordbruk få ett mervärde på marknaden för att kompensera för de högre kostnaderna. Externt ekonomiskt stöd, fördelaktiga lån och/eller politiskt stöd kan behövas för att täcka de högre investeringskostnaderna och för att förbättra marknadsvärdekedjorna och främja stabilare priser på marknaden. Främjandet av användningen av odlat fodergräs till boskap skulle också göra trädjordbruk som inkluderar fodergräsremsor mer lönsamt.

# Acknowledgements

The work presented in this thesis was conducted as part of the World Agroforestry (ICRAF) project "Developing and Promoting Market-Based Agroforestry and Forest Rehabilitation Options for Northwest Vietnam" (AFLI project), in collaboration with the Swedish University of Agricultural Sciences (SLU) and other partners. The Australian Centre for International Agricultural Research, the CGIAR Research Programme on Forests, Trees, and Agroforestry, and projects funded by the Swedish Research Councils Formas (2019-00376) and VR (2019-03740) provided funding for the work, which is gratefully acknowledged.

I would like to express my heartfelt gratitude to my supervisors, Ingrid Öborn, Göran Bergkvist and Sigrun Dahlin at the Department of Crop Production Ecology, SLU, and Nguyen La and Rachmat Mulia at ICRAF Vietnam, for providing me with the opportunity to pursue this PhD work. Thank you so much for your constant encouragement, valuable advice, patience and support during my PhD studies and for your efforts and time.

I am grateful to Delia Catacutan, the former coordinator of ICRAF Vietnam, for connecting me with SLU so that I had the opportunity for this PhD research. I am also grateful to the ICRAF Vietnam office and current coordinator of ICRAF Vietnam, Nguyen Quang Tan, for giving me the opportunity and flexibility to both study and work. I would like to express my gratitude to my colleagues in the AFLI project, Nguyen Van Thach, Pham Huu Thuong, Vu Thi Hanh, Do Thi Hoa, Do Tien Luc and Nguyen Quoc Huy, for invaluable contributions and assistance in experimental set-up, data collection and companionship during field trips to the study sites. I would also like to thank my colleagues at ICRAF Vietnam, Nguyen Mai Phuong, for assisting me in producing the map of study sites, and Tran Ha My, Pham Duc Thanh and Le Hai Hue, who always helped me when needed.

I am grateful to Chu Van Tien, Tran Quang Khanh and Vu Dinh Chi, who hosted the longan-maize-forage grass trial in Van Chan (Yen Bai Province); to Giang Dung Vu, Mua A Do and Vang A Sua, who hosted the son tra-forage grass trial in Tuan Giao (Dien Bien Province); to Tong Van An, who hosted the longan-mango-maize-forage grass trial in Mai Son (Son La Province); to Giang A Vang, who hosted the son tra-coffee-forage grass trial in Tuan Giao; and to Trang A Su, who hosted the plum-maize-forage grass trial in Tram Tau (Yen Bai Province). I also thank all farmers at the study sites for kind cooperation and assistance throughout my field research.

I gratefully acknowledge the support of researchers from Northern Mountainous Agriculture and Forestry Science Institute, Forest Science Centre of Northwest, and Soils and Fertilizer Research Institute in Vietnam. I thank officials and staff at the Extension Centres in Dien Bien, Son La and Yen Bai provinces for their kind assistance and sharing of experiences during my fieldwork.

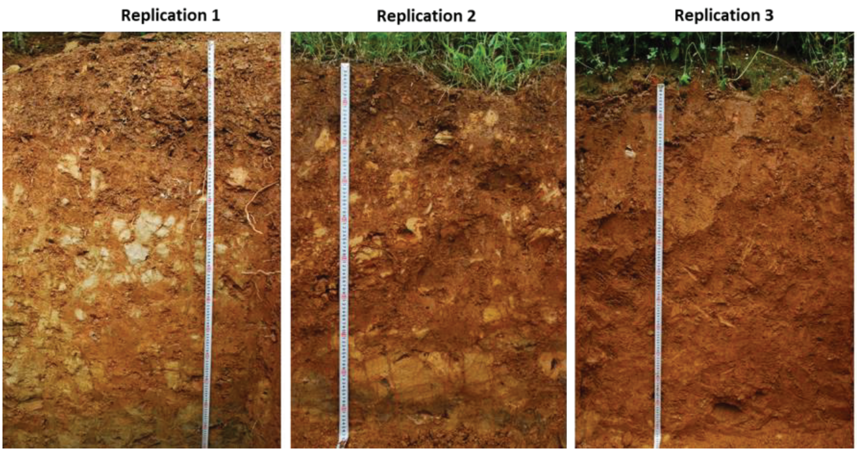
I am grateful to Johannes Forkman, SLU, for statistical assistance and advice, and to Mary McAfee for English language editing.

My thanks to fellow colleagues at the Department of Crop Production Ecology: Elsa Lagerqvist, Rafaelle Reumaux, Libére Nkurunziza, Sandra Makaita Madamombe, James Ajal, Marcos Lana, Robert Glinwood, Mahmoud Suliman and my landlord Klas Rosén. With all of you, I had a fantastic experience living and studying in Sweden.

Finally, I would like to express my gratitude to my parents Do Van Manh and Phan Thi Hoa, who have always believed in me and supported me, and my parents-in-law Nguyen Van Thuat and Nguyen Thi Hien, for taking care of my children. My small family, my wife Nguyen Thi Thuy Ha, my daughter Do Hoang Chi and my son Do Duc Minh, you were a great motivation for me to finish this PhD work.

# Appendix

## Appendix 1. Soil profile at the longan-maize-forage grass trial sites




Soil profile images from the longan-maize-forage grass trial sites.

Soil profile description

| Rep | Hz | Depth (cm) | Description |
|---|---|---|---|
| 1 | A | 0-27 | 7.5 YR 4/3 moist; 7.5 YR 5/6 dry; clay loam; light sticky; mixed stones (20% in soil surface); common roots, from very fine to medium in diameter; few fine to medium pores (earthworm, termite, ant); very few mottles, 7.5 YR 4/1; |
| | B1 | 27-45 | 7.5 YR 4/4 moist; 7.5 YR 5/6 dry; clay loam; light sticky; few roots, very fine to medium in diameter; very few pores, very fine to medium in diameter; very few mottles; |
| | B2 | 45-108 | Sandy accumulation, 7.5 YR 5/6 moist; 5 YR 6/6 dry; clay loam; mixed soft stone, 7.5 YR 6/6, loamy sand; few roots, very fine to fine in diameter; very few pores, fine to medium in diameter (termite); |
| | BC | >108 | 2.5 Y 5/3 moist; 10 YR 7/3 dry; loamy sand; non-sticky; mixed soft stones, 0.1-2mm in diameter; no pores; |
| 2 | A | 0-13 | 7.5 YR 4/2 moist; 7.5 YR 5/4 dry; clay loam; light sticky; common root, very fine to fine in diameter; common medium pores (earthworm, termite and ant); very few mottles, 7.5 YR 4/1; |
| | B1 | 13-70 | 7.5 YR 4/6 moist; 7.5 YR 6/6 dry; clay loam; non-sticky; mixed decay materials, 7.5 YR 5/8; common roots, very fine to fine in diameter (termite); few very fine to fine roots; |
| | BC | >70 | 10 YR 6/6 moist; 10 YR 7/6 dry; loamy sand; non-sticky; |

| | | | |
|---|---|---|---|
| 3 | A | 0-14 | 7.5 YR 5/3 moist; 7.5 YR 6/6 dry; light clay; sticky; common root, very fine to fine in diameter; very few |
| | B1 | 14-64 | 7.5 YR 4/6 moist; 7.5 YR 6/8 dry; clay loam; light sticky; common very fine roots; very few very fine pores; |
| | B2 | 64-122 | 7.5 YR 5/6 moist; 7.5 YR 7/8 dry; clay loam; light sticky; few very fine roots; very few fine pores; |
| | BC | >122 | 7.5 YR 5/4 moist; 7.5 YR 8/4 dry; loamy sand; non-sticky; |

Rep: replications, Hz: soil horizon.

Appendix 2. Soil profile at the son tra-forage grasses (guinea and mulato) trial sites


Soil profile images from the son tra-forage grasses (guinea and mulato) trial sites.

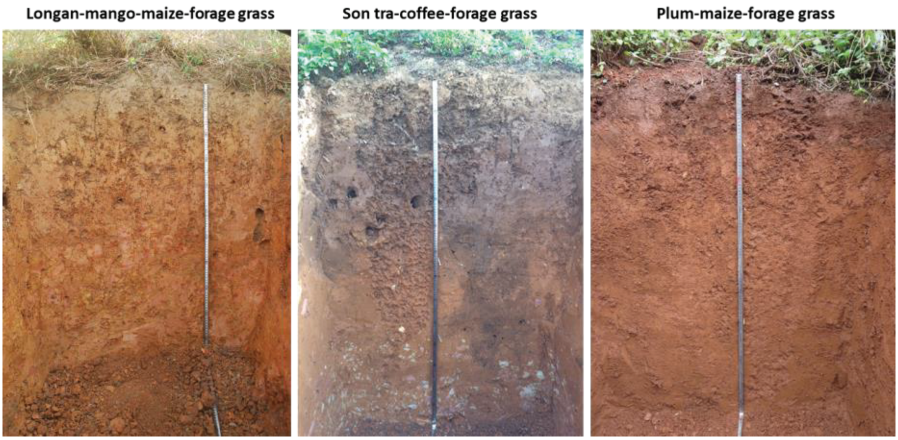
Soil profile description

| Rep | Hz | Depth (cm) | Description |
|---|---|---|---|
| 1 | A | 0-7 | 7.5 YR 4/4 moist; 10 YR 6/4 dry; clay loam; sticky; very few pores, 1mm in diameter; few roots, very fine in diameter; very few nodules, 3mm in diameter, 10 YR 2/2; |
| | B1 | 7-30 | 7.5 YR 5/8 moist; 10 YR 6/8 dry; clay loam; sticky; very few pores, 2mm in diameter; few roots, very fine in diameter; no nodules; |
| | B2 | 30-82 | 7.5 YR 5/8 moist; 10 YR 7/8 dry; clay loam; light sticky; very few pores (termite), 3mm in diameter; very few nodules, 0.3mm in diameter; 10 YR 2/2; very few stones, 5mm in diameter; |
| | BC | >82 | 7.5 YR 7/8 moist; 10 YR 8/6 dry; clay loam; light sticky; no pores; few nodules, 0.3mm in diameter, 10 YR 2/2; few root, very fine in diameter; |
| 2 | A | 0-22 | 7.5 YR 4/3 moist; 7.5 YR 5/4 dry; clay loam; light sticky; few termite channel, 7mm in diameter; few root, very fine in diameter; very few nodules, 2mm in diameter, 10 YR 2/2; |
| | B1 | 22-56 | 7.5 YR 4/6 moist; 7.5 YR 6/6 dry; clay loam; sticky; no pores; very few nodules, 10mm in diameter, 10 YR 2/2; few root, very fine to fine in diameter; few mixed stones, 10mm in diameter; |
| | B2 | 56-86 | 7.5 YR 5/8 moist; 7.5 YR 7/6 dry; clay loam; sticky; very few pores (termite), 5mm in diameter; very few nodules, 10mm in diameter, 10 YR 2/2; few roots, very fine in diameter; no stones; |
| | BC | >86 | 7.5 YR 6/8 moist; 7.5 YR 7/6 dry; clay loam; sticky; very few nodules, 10mm in diameter, 10 YR 2/2; few very fine roots; very few mixed stones, 20mm in diameter; |

| | | | |
|---|---|---|---|
| 3 | A | 0-25 | 7.5 YR 4/2 moist; 10 YR 6/3 dry; clay loam; sticky; very few pores, 2mm in diameter; common root, very fine in diameter; few nodules, 3mm in diameter, 10 YR 2/2; |
| | B1 | 25-55 | 7.5 YR 5/4 moist; 10 YR 6/4 dry; very few pores (termite channels), 30mm in diameter; no nodules; few very fine root; |
| | B2 | 55-80 | 7.5 YR 6/8 moist; 10 YR 8/8 dry; light clay; sticky; very few pores (termite), 10mm in diameter; few very fine root; |
| | BC | >80 | 7.5 YR 6/8 moist; 10 YR 7/8 dry; light clay; sticky; no root; no nodules; no termite channels; |

Rep: replications, Hz: soil horizon.

## Appendix 3. Soil profile at the longan-mango-maize-forage grass, son tra-coffee-forage grass and plum-maize-forage grass trial sites




Soil profile images from the longan-mango-maize-forage grass, son tra-coffee-forage grass and plum-maize-forage grass trial sites.

Soil profile description

| Trial | Hz | Depth (cm) | Description |
|---|---|---|---|
| Longan-mango-maize-forage grass | A | 0-17 | Light yellowish brown (10 YR 6/4), few red (2.5 YR 4/6) and reddish yellow (7.5 YR 7/8) mottles, no rock fragments; light clay; plastic; common very fine roots; clear broken boundary |
| | B1 | 17-36 | Yellowish red (5 YR 4/6), very few red (2.5 YR 4/6) and yellowish (5 YR 5/8) mottles, no rock fragments; heavy clay; very plastic; few very fine roots; clear wavy boundary. |
| | B2 | 36-56 | Yellowish red (5 YR 4/6), very few yellowish red (5 YR 4/6) and yellow (10 YR 7/8) mottles, no rock fragments; heavy clay; very plastic; very few very fine roots; diffuse wavy boundary. |
| | BC | >56 | Yellowish red (5 YR 5/8), abundant mottled with 90% light red (2.5 YR 6/6) and 10% brownish yellow (10 YR 6/8) aggregates, no rock fragments; light clay; plastic; no cracks, no roots; no boundary observed. |
| Son tra-coffee-forage grass | A | 0-23 | Brown (7.5 YR 4/3), very few fine light bluish grey (grey 2-7/5 PB) mottles, no rock fragments; clay loam; slightly plastic; common fine roots; clear wavy boundary. |
| | B1 | 23-44 | Brown (7.5 YR 5/4), no mottles, no rock fragments, light clay; plastic; few very fine roots; clear wavy boundary. |
| | B2 | 44-63 | Yellowish red (5 YR 5/6), very few medium pale yellow (5Y 8/4) mottles, no rock fragments; light clay; plastic, few very fine roots; diffuse wavy boundary. |
| | B3 | 63-69 | Yellowish red (5 YR 5/8), few medium very pale brown (10 YR 7/3) mottles, no rock fragments, light clay; plastic; very few fine roots; diffuse wavy boundary. |
| | BC | >69 | Yellowish red (5 YR 5/8), abundant coarse mottles with 60% light greenish grey (grey 1-8/10Y) and 40% reddish brown (2.5 YR 4/4); no rock fragments; light clay; plastic; very few fine roots; no boundary observed. |

| | | | |
|---|---|---|---|
| Plum-maize-forage grass | A | 0-18 | Brown (7.5 YR 4/4), no rock fragments; light clay; common fine roots; very few pores, 0.5-1 cm in diameter; very few crack, maximum 2 mm in diameter. |
| | B1 | 18-40 | Yellowish red (5 YR 4/6), no rock fragments; light clay; few very fine roots; very few pores, 0.3 cm in diameter; very few cracks, maximum 0.5 mm in diameter. |
| | B2 | 40-80 | Yellowish red (5 YR 5/6), no rock fragments; heavy clay; very few very fine roots; no cracks, no pores. |
| | BC | >80 | Yellowish red (5 YR 5/6), no rock fragments; heavy clay; no cracks, no roots. |

Hz: soil horizon.

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Article

# Fruit Tree-Based Agroforestry Systems for Smallholder Farmers in Northwest Vietnam—A Quantitative and Qualitative Assessment

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Received: 30 October 2020; Accepted: 13 November 2020; Published: 17 November 2020

**Abstract:** Rapid expansion of unsustainable farming practices in upland areas of Southeast Asia threatens food security and the environment. This study assessed alternative agroforestry systems for sustainable land management and livelihood improvement in northwest Vietnam. The performance of fruit tree-based agroforestry was compared with that of sole cropping, and farmers' perspectives on agroforestry were documented. After seven years, longan (*Dimocarpus longan* Lour.)-maize-forage grass and son tra (*Docynia indica* (Wall.) Decne)-forage grass systems had generated 2.4- and 3.5-fold higher average annual income than sole maize and sole son tra, respectively. Sole longan gave no net profit, due to high investment costs. After some years, competition developed between the crop, grass, and tree components, e.g., for nitrogen, and the farmers interviewed reported a need to adapt management practices to optimise spacing and pruning. They also reported that agroforestry enhanced ecosystem services by controlling surface runoff and erosion, increasing soil fertility and improving resilience to extreme weather. Thus, agroforestry practices with fruit trees can be more profitable than sole-crop cultivation within a few years. Integration of seasonal and fast-growing perennial plants (e.g., grass) is essential to ensure quick returns. Wider adoption needs initial incentives or loans, knowledge exchange, and market links.

**Keywords:** fruit tree-based agroforestry; economic benefits; ecosystem services; farmer perspectives; resource competition; systems improvement; uptake and expansion

## 1. Introduction

The United Nations sustainable development goals and Agenda 2030 include poverty eradication, ending hunger, and environmental restoration, among other objectives [1]. Related targets are to implement resilient agricultural practices that increase productivity and production, and to maintain ecosystems that strengthen the capacity for adaptation to climate change and risks and improve land health [2]. Agroforestry, a planned combination of trees and crops with or without livestock on the same land, is increasingly being recognised as a sustainable system to reconcile agricultural production and environmental protection [3,4]. When combined with contour planting on sloping uplands, agroforestry is an effective land-use system to reduce soil erosion and maintain soil fertility [5,6].

In addition, as an integrated and more permanent farming system, agroforestry can generate diverse economic, ecological, and social benefits [3,7] beyond those provided by sole-crop farming systems.

Mountainous areas in the lower Mekong region are experiencing severe forest and land degradation, driven by expansion of unsustainable farming practices [8]. For example, in northwest Vietnam, sole-maize cultivation is widespread over hills and fragile sloping land [9,10]. The northwest region is home to ethnic minorities with a poverty rate of about 14% in 2016, or 8% higher than the average poverty rate at the national level, according to the 2017 statistic book of Vietnam. Around 60% of land in the region has a slope of ≥ 30% [11]. Soil degradation in the region is acute, resulting in low crop productivity [12–16].

Driven by high economic benefits, smallholder fruit-tree cultivation has recently expanded in several provinces in northwest Vietnam [17]. For example, the total area of fruit-tree plantations in Dien Bien, Yen Bai, and Son La provinces reached 58,464 ha in 2018, a 51.4% increase compared with 2015. The main fruit commodities are longan (*Dimocarpus longan* Lour.), mango (*Mangifera indica* L.) and plum (*Prunus domestica* L.). There is also some production of son tra (*Docynia indica* (Wall.) Decne), also called H'Mong apple, which is native to the region and one of 50 special fruits of Vietnam [18]. Son tra is a multipurpose tree, restoring natural forest cover and producing fruit [19].

Despite recent developments, farmers in the northwest region generally lack technical knowledge of agroforestry [9,20], including fruit tree-based agroforestry, in terms of adequate species composition, optimal plant arrangement and spacing, and management practices to optimise delivery of products and ecosystem services over time. Good management could better utilise potential economic, social, and environmental benefits of diversified tree-based farming systems. Farmers in the region usually develop "temporary" agroforestry by combining fruit trees and annual crops such as maize or cassava, and vegetables, in the early years of planting before tree canopy closure, most often in the first to third year after tree planting [21]. Reliable scientific-based information on permanent combinations of fruit trees and annual crops is necessary to promote agroforestry systems that can offer long-term and diverse income sources through product diversification to farmers in the region.

This study assessed the performance of two fruit-tree agroforestry systems in order to obtain knowledge on sustainable farming systems for the region. Quantitative and qualitative approaches were used to assess the agroforestry systems: longan–maize–forage grass and son tra–forage grass. Specific objectives were (i) to evaluate the productivity and profitability of agroforestry systems compared with sole-tree and annual crop systems over the seven years after establishment and (ii) to survey farmers on the performance of fruit tree-based systems to identify possibilities for improvement and wider-scale development.

## 2. Materials and Methods

### 2.1. Site Description

On-farm experiments with two agroforestry systems, longan (*Dimocarpus longan* Lour.)–maize (*Zea mays* L.)–forage grass and son tra (*Docynia indica* (Wall.) Decne.) –forage grass, were carried out on three farms each, using farms as replicates. The farms were situated in Van Chan district (21.56° N, 104.56° E; 374 m a.s.l.) in Yen Bai province and Tuan Giao district (21.56° N, 103.50° E; 1267 m a.s.l.) in Dien Bien province, northwest Vietnam (Figure 1). 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 18.6 °C and 21 °C; and annual rainfall is 1200–1600 mm and 1700–2000 mm in Tuan Giao and Van Chan, respectively. Mean slope of the experimental plots was 27% at both sites.

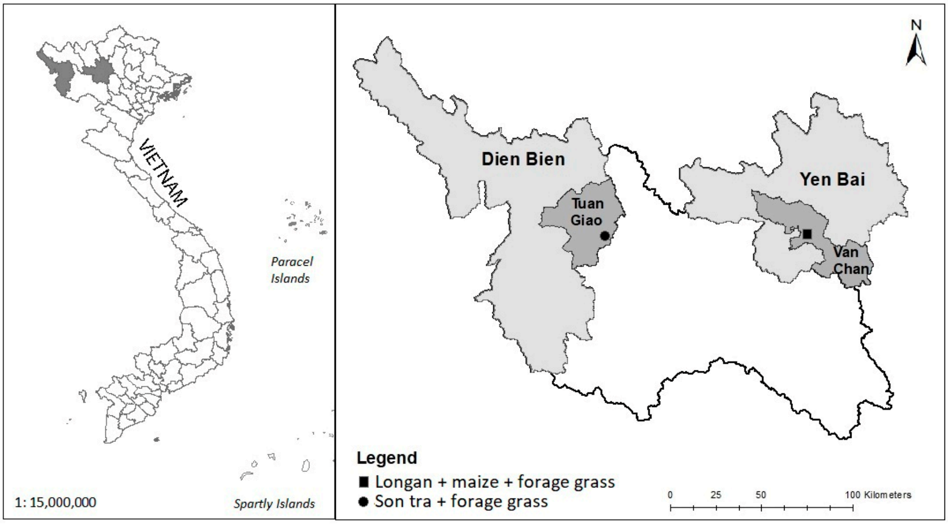


**Figure 1.** Location of the agroforestry experiments with longan-maize-forage grass in Van Chan District, Yen Bai province, and son tra-forage grass in Tuan Giao District, Dien Bien province, north-west Vietnam. Replicate trials were established on three farms in each district.

The soil profile at each site was characterised at the start of the experiments. The soils at Van Chan were silty clay loams, with, on average, pH 4.7, 1.7% soil organic matter (SOM), 0.12% total nitrogen (N), 0.02% total phosphorus (P), and 0.50% total potassium (K). The soil at Tuan Giao was silty clay, with, on average, pH 4.6, 3.8% SOM, and total N, P, and K of 0.24%, 0.02%, and 0.85%, respectively. SOM and total N, and P, and K were determined by the Walkley–Black method [22], Kjeldahl method [23], and digestion with mixed strong acids [24,25], respectively. Available soil P (Bray II) [26] was 5 mg $kg^{-1}$ at Van Chan and 9.2 mg $kg^{-1}$ at Tuan Giao.

## 2.2. Field Experiment Design

Both experiments were designed as randomised complete blocks with three replicates on three different farms. At Van Chan, the experiment lasted seven years (2012–2018). The agroforestry system consisted of longan, maize and guinea grass (*Panicum maximum* Jacq.) (LMG) and was compared with sole-crop maize (SM) and sole-crop longan (SL) (Figure 2a). The sole-crop longan was planted with 5 m row spacing and 5 m spacing between trees within rows (400 trees $ha^{-1}$). In the LMG system, longan was planted at 5 m spacing in double rows along contour lines, with 15 m between two double rows (240 trees $ha^{-1}$). Guinea grass was planted in double rows 0.5 m from the trees, and the distance between two rows was 0.5 m. The seed rate, row spacing, and distance between plants for sole-crop maize was 15 kg $ha^{-1}$, 0.65 m, and 0.3 m, respectively. The seed rate was 10–20% lower in the LMG system, since maize was not sown in the grass strips or within 0.5 m from the canopy of longan, so maize plants were sown with the same row spacing and plant distance in both systems. The longan variety used in the experiment was late maturing. The maize variety used in all cropping systems was the hybrid PAC 999.

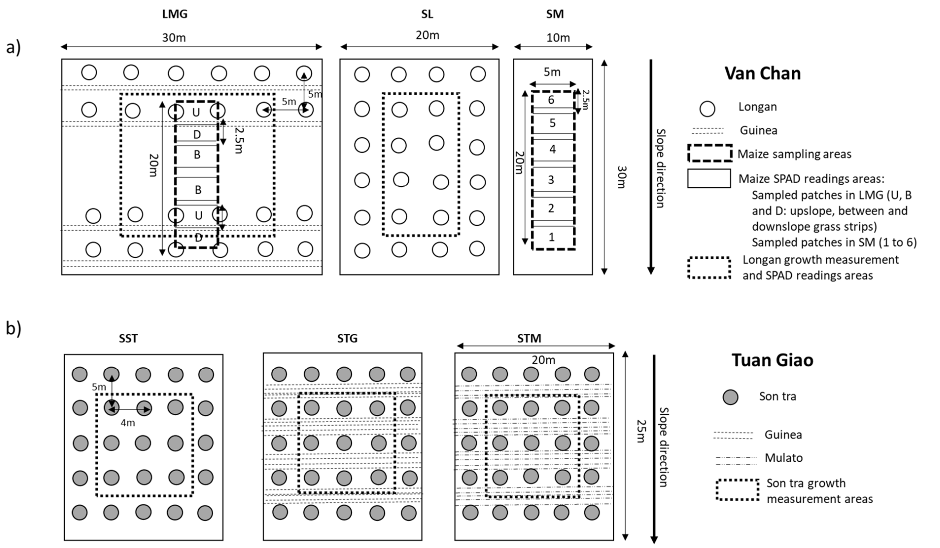


**Figure 2.** Design of field experiments: (**a**) Van Chan: sole-crop maize (SM), sole-crop longan (SL), and longan–maize–forage grass (LMG), U: upslope grass strips, D: downslope grass strips, B: between grass strips. The plot area was 300 $m^2$ for sole-crop maize, 600 $m^2$ for sole-crop longan, and 900 $m^2$ for the LMG agroforestry system; (**b**) Tuan Giao: sole-crop son tra (SST), son tra–guinea grass (STG), and son tra–mulato grass (STM). Plot area was 500 $m^2$.

The experiment at Tuan Giao lasted six years (2013–2018) and comprised three treatments: sole-crop son tra (SST), son tra–guinea grass (STG), and son tra–mulato grass (*Brachiaria* sp.) (STM). In all treatments, son tra was planted with 5 m row spacing and with 4 m spacing between trees within rows (500 trees $ha^{-1}$). Seven rows of guinea grass or mulato grass were planted between two rows of son tra in the STG and STM system, respectively (Figure 2b). The distance between the grass rows was 0.5 m and the strips were 1 m from the son tra rows. Grafted son tra seedlings were used, while guinea grass and mulato grass cuttings were obtained from a nursery.

Mineral NPK fertiliser was applied annually to maize in SM and LMG (NPK 5–10–3) as a basal application, with a topdressing with urea (46% N) and potassium chloride (48.6% K) at maize stage 6–7 fully expanded leaves (50%) and before silking (50%). In the SL and LMG treatments, 15 kg of composted animal manure and 1 kg of mineral fertiliser (NPK 5–10–3) were applied per longan tree in year 1. In years 2–7, 1 kg mineral fertiliser (NPK 5–10–3) was applied per tree, while in years 5–7, 20 kg of animal manure were applied per tree. In SST, STG, and STM, son tra received 15 kg composted animal manure and 1 kg mineral fertiliser (NPK 5–10–3) per tree in year 1 and an annual topdressing of 0.9 kg mineral fertiliser (NPK 5–10–3) per tree in years 2–6. In both experiments, the purpose of planting grass strips was to utilise nutrients in runoff, and therefore no nutrients were applied to the forage grasses. For more information about the experiments in Van Chan and Tuan Giao, see Table S1 in Supplementary Materials (SM).

### *2.3. Data Collection in the Field Trials*

#### 2.3.1. Tree Growth and Tree/Maize/Grass Yield Determination

Eight longan and nine son tra trees in each plot were measured every three months for the whole experimental period to determine base diameter (consistently measured at a height of 10 cm from soil surface because the trees were still small in the early years of experiments), canopy diameter, and plant height. Fresh weight biomass production of forage grasses was measured monthly by harvesting a

5 m forage grass strip per plot and weighing the biomass. Maize grain production was measured by harvesting a 5 × 20 m sub-area within each plot, air-drying the cobs outdoors before shelling and weighing. Fruit yield per plot was determined by collecting and weighing the fruit of all trees at harvest.

#### 2.3.2. Competition for Resources in the Longan–Maize–Forage Grass System

An in-depth study of the variation in plant N concentration, growth, and productivity was carried out in year 7 of the experiment at Van Chan. Maize stover (stems, leaves, cobs, and covers) and grain were harvested at physiological maturity and weighed to determine their fresh weight. Fresh sub-samples of these materials were weighed and dried to constant weight. The ratio between fresh and dry weight was calculated and used to calculate the total harvested dry weight of each material. Within the LMG plots, measurements and sampling were performed in duplicate patches at three positions on the plots; 2.5 m upslope of the grass strips, between grass strips (4 m distance), and 2.5 m downslope of the grass strips (marked U, B, and D, respectively, in Figure 2a). The sampled area of each patch was 2.5 × 5 m. Similar sampling of patches was carried out in SM.

Plant N status was monitored in LMG and SM using a soil plant analysis development (SPAD) 502 Plus chlorophyll meter to determine the amount of chlorophyll present in plant leaves [27], as a proxy for N concentration [28]. The SPAD readings and maize plant height measurements were carried out at four vegetative stages of the maize crop (3–4, 6–7, and 10–11 fully expanded leaves, and silking). In each sampled patch, five maize plants along a diagonal were used for measurements on each occasion. The third, sixth, ninth, and index leaves were used as standard leaves for the stages 3–4, 6–7, and 10–11 fully expanded leaves and silking, respectively. The SPAD readings were taken at two-thirds of the distance from the leaf tip towards the stem [29]. In grass, the SPAD readings were carried out on 10 new fully expanded leaves [30] and height measurements were made on 10 grass plants every month in a 5 m section of each grass strip before cutting during the maize season. For longan, the SPAD readings were taken on eight longan trees within LMG and SL (Figure 2a) at the beginning and end of the maize season. One fully expanded mature leaf on the east, west, south, and north side of each tree was selected. The third leaflet position from the terminal leaf of each fully expanded mature leaf was used as the standard leaf for SPAD readings [31].

#### 2.3.3. Land Equivalent Ratio

A land equivalent ratio (LER) was used to compare yields in the different treatments, with LER greater than 1.0 indicating that the mixed system (intercrop) was more advantageous than the sole crop. LER was calculated as [32]:

$$\text{LER} = \text{Intercrop1/Sole crop1} + \text{Intercrop2/Sole crop2} + \ldots\ldots \quad (1)$$

The fresh yield of sole-crop guinea grass and sole-crop mulato grass was calculated from their average reported dry biomass yield, i.e., 30 ton ha$^{-1}$ year$^{-1}$ [33] and 18.5 ha$^{-1}$ year$^{-1}$ [34], respectively, assuming a dry matter content of 23% [35] and 21% [36], respectively. The LER of the LMG, STG, and STM systems was calculated annually.

#### 2.3.4. Profitability

Cost-benefit analysis was performed for each agroforestry and sole-crop treatment, taking into account details of investment costs, maintenance costs, and revenue from products sold across monitoring years. Net profit was calculated by subtracting all input costs from gross income. Annual inputs included fertiliser, pesticide, labour, planting materials, etc. Total annual income was calculated based on yield and the price obtained for the different products at harvest. Data on the cost of inputs and market prices for products were obtained from the provincial extension departments covering the study sites (see Table S2 in Supplementary Materials). Net profits of each system were calculated as:

$$N = T - I \tag{2}$$

where $N$ is net profit, $T$ is total income, and $I$ is total cost of all inputs, all in USD ha$^{-1}$ year$^{-1}$.

### *2.4. Selection of Participants for Farmer Group Discussions*

Farmers' perceptions and aspirations for the agroforestry systems involving longan–maize–forage grass (in Yen Bai) and son tra–forage grasses (in Dien Bien) were documented in group discussions carried out in January 2020. For each agroforestry system, two villages were selected: one village that hosted an experiment (experiment-hosting village) and a nearby village (non-hosting village) (Table S3 in Supplementary Materials). In each village, farmers who were familiar with or had observed the agroforestry system in the field experiment were selected and divided into three groups based on resources and gender (poor female, poor male, non-poor mixed female and male). Farmers hosting the experiments were interviewed individually, using the same open-ended questions as in the group discussions. In total, there were six different farmer groups at each study site, three in the experiment-hosting village and three in the non-hosting village, plus the three farmers hosting the experiments at each site (experiment-hosting famers). The Vietnamese government's poverty scale [37] was used to capture responses from farmers experiencing different levels of poverty. The questions (see Table S4 in Supplementary Materials) were posed by an interview team, including three researchers from World Agroforestry (ICRAF) in Vietnam who served as facilitators. All interviews were recorded and the responses were transcribed and translated into English by the researchers after each group discussion. The responses from farmers belonging to the different groups were then analysed to identify the consensus or most common responses to each question within each group. Thus, responses from individual farmers are not presented. The main ideas expressed in responses were identified and grouped into themes/categories reflecting farmers' perceptions of the two agroforestry systems tested in terms of tree, maize, and grass performance related to competition for resources, economic and ecological benefits, markets, constraints to adoption, and potential of agroforestry as a future option for the region.

### *2.5. 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 the different treatments on maize, grass, and tree performance; yield; and profitability over the years. Log-transformation was used to normalise the data where necessary. When a significant difference was indicated in F-tests, lsmeans was used to identify significant ($p < 0.05$) differences between means. Repeated measures ANOVA was also applied to compare SPAD values and growth of maize in LMG and SM plots in year 7 of the experiment at Van Chan. ANOVA was used to compare the yield of maize at different positions relative to the grass strips within LMG in the last year, and then Tukey's HSD test was used to identify positions that were significantly different from other positions.

## 3. Results

### *3.1. Tree Growth*

There was a significant effect by cropping systems on growth of longan trees. Base diameter, canopy diameter, and height in the sole-crop (SL) system were significantly greater ($p < 0.05$) than in the LGM system (Figure 3a). By the end of year 7, the base diameter of longan in SL and LMG had increased by 9 and 7 cm, respectively, since planting, and the height of longan trees was about 148 cm in SL and 121 cm in LGM, i.e., a height increase of 36 and 32 cm year$^{-1}$ in SL and LGM, respectively.

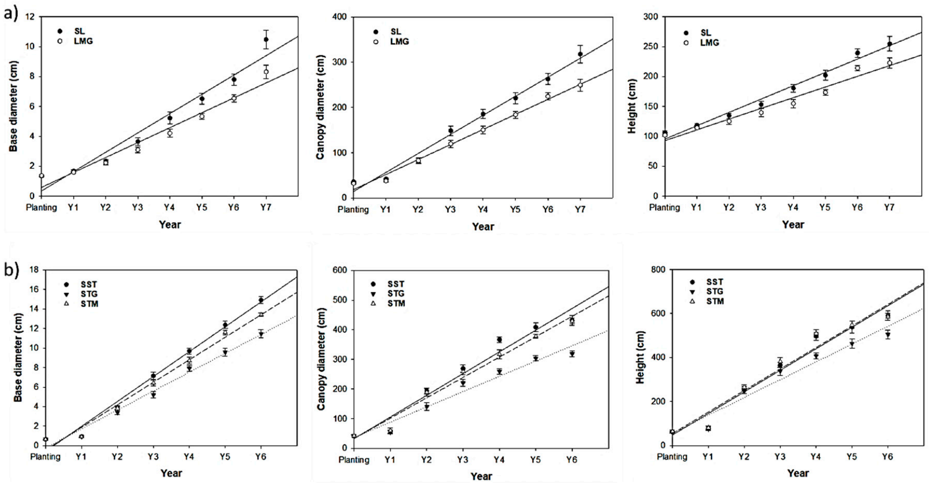


**Figure 3.** Regression lines describing tree growth (mean and standard error): (**a**) Growth of longan in the sole-tree system (SL) and longan–maize–forage grass (LMG) system; (**b**) growth of son tra in the sole-tree system (SST), son tra–guinea grass (STG) system, and son tra–mulato grass (STM) system.

The base diameter of son tra trees was significantly greater ($p < 0.05$) in the sole-tree system than in the systems with forage grass (STM and STG) (Figure 3b). Both tree height and canopy diameter were affected by the cropping system, with an interaction between cropping system and year ($p < 0.05$). Three years after planting, the canopy diameter and height of son tra trees were similar in the agroforestry and sole-tree systems. However, from year 4 to 6, canopy diameter and tree height were significantly higher ($p < 0.05$) in the sole-tree and STM systems than in the STG system (Figure 3b).

### *3.2. Yield and Land Equivalent Ratio*

During the first three years, the products in LMG were primarily maize cobs and forage-grass biomass (Table 1). The grass started yielding from year 2. The products became more diversified from year 4, when longan started to bear fruit, and yield increased during subsequent years. There was no significant effect from the cropping system, or interaction between treatments and year, on maize yield. However, the yield of longan was significantly higher in the sole-tree system than in LMG, and there was a significant interaction between treatment and year ($p < 0.05$). From year 2 to 7, LER of the LMG system ranged from 1.1 to 1.9 (Figure 4a).

In the STG and STM agroforestry systems, the guinea grass and mulato grass were harvested from year 2 (2014), with high yield (Table 1). The agroforestry practices had more products from year 3, when son tra started to bear fruit. However, there was a significant effect from the cropping system on the productivity of son tra ($p < 0.05$), with fruit yield being significantly lower in agroforestry than in the sole-crop system. LER of the agroforestry practices from year 2 to 6 ranged from 0.5 to 1.1 for STG and 0.6 to 1.8 for STM (Figure 4b).

**Table 1.** Yield of maize (dry grain), longan, and son tra (fresh fruit) in sole-crop/tree systems (SM, SL, SST) and of these crops and forage grasses (fresh matter) in agroforestry systems (LMG, STG, STM) in the seven years of the field experiments.

| | | Yield (Ton ha$^{-1}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Crop/Trees** | **Cropping System** | **2012** | **2013** | **2014** | **2015** | **2016** | **2017** | **2018** | **Mean** |
| Maize | SM | 5.9 (±0.1) | 4.7 (±0.4) | 4.1 (±0.3) | 4.2 (±0.3) | 4.3 (±0.1) | 4.2 (±0.2) | 4.6 (±0.5) | 4.6 (±0.2) |
| | LMG | 5.5 (±0.3) | 5.3 (±0.1) | 3.9 (±0.2) | 4.1 (±0.2) | 4.1 (±0.1) | 4.0 (±0.2) | 4.2 (±0.4) | 4.5 (±0.3) |
| **By cropping system** | | | | | $p$-value = 0.33 | | | | |
| **Cropping system x year** | | | | | $p$-value = 0.35 | | | | |
| Longan | SL | | | | 0.35 (±0.2) | 0.32 (±0.3) | 0.47 (±0.1) | 3.04 (±1.1)a | 1.04 (±0.7)a |
| | LMG | | | | 0.06 (±0.03) | 0.18 (±0.2) | 0.38 (±0.2) | 0.90 (±0.3)b | 0.30 (±0.1)b |
| **By cropping system** | | | | | $p$-value = 0.02 | | | | |
| **Cropping system x year** | | | | | $p$-value = 0.03 | | | | |
| Guinea grass | LMG | | 4.4 (±4.4) | 19.5 (±2.3) | 15.9 (±1.2) | 18.2 (±1.1) | 18 (±1.5) | 14.6 (±4.1) | 15 (±2.3) |
| **Son tra** | SST | na | | | 0.6 (±0.4) | 5.6 (±4.1) | 2.1 (±1.6) | 8.7 (±7.6) | 4.2 (±1.8)a |
| | STG | na | | | 0.2 (±0.1) | 1.8 (±0.8) | 0.2 (±0.2) | 1.8 (±1.3) | 1.0 (±0.5)b |
| | STM | na | | | 0.2 (±0.1) | 0.9 (±0.4) | 0.5 (±0.4) | 4.7 (±3.4) | 1.6 (±1)ab |
| **By cropping system** | | | | | $p$-value = 0.03 | | | | |
| **Cropping system x year** | | | | | $p$-value = 0.75 | | | | |
| Guinea grass | STG | na | | 67 (±26.3) | 61 (±11) | 55 (±6.3) | 56 (±2.9) | 67 (±5.9) | 61 (±2.6) |
| Mulato grass | STM | na | | 58 (±29) | 65 (±4) | 74 (±7.6) | 64 (±4.7) | 66 (±4) | 65 (±2.5) |
| **By cropping system** | | | | | $p$-value = 0.62 | | | | |
| **Cropping system x year** | | | | | $p$-value = 0.85 | | | | |

SM: sole-crop maize, SL: sole-crop longan, LMG: longan–maize–forage grass, SST: sole-crop son tra, STG: son tra–guinea grass, STM: son tra–mulato grass; na: not applicable since the experiment was established in 2013. Values are mean ± standard error; different letters indicate significant differences ($p < 0.05$).

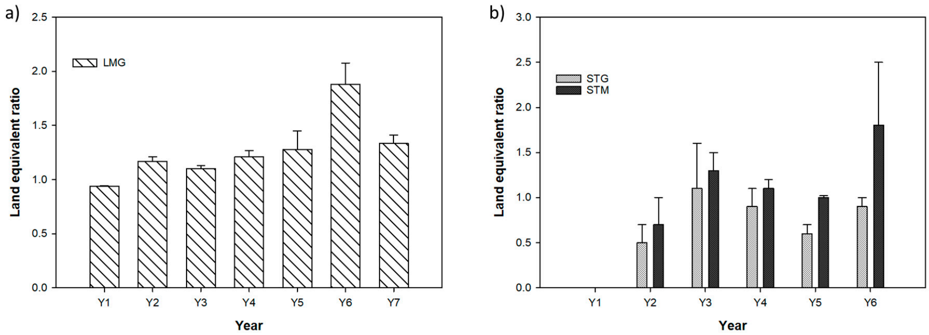


**Figure 4.** Land equivalent ratio (LER) of the agroforestry practices in each year of the experiment, expressed as mean and standard error (bars): (**a**) Longan–maize–forage grass (LGM); (**b**) son tra–guinea grass (STG) and son tra–mulato grass (STM).

### 3.3. Leaf Nitrogen Content and Competition in LMG

The SPAD value was significantly higher in sole-crop maize than in the LMG system ($p < 0.05$) from maize development stages 6–7 to silking, while maize plant height was significantly higher from 10–11 fully expanded leaves to silking (Table 2). However, the biomass of maize, including grain and stover, was not significantly different between the sole-crop and agroforestry systems.

**Table 2.** Dry yield, height, and SPAD readings of maize in the longan–maize–forage grass system (LMG) and the sole-crop system (SM) in year 7 of the experiment.

| | Maize Growth Stage | | | | | At Maturity | | |
|---|---|---|---|---|---|---|---|---|
| | **Cropping System** | **3–4 Leaves** | **6–7 Leaves** | **10–11 Leaves** | **Silking** | | **Cropping System** | **Dry Yield (Ton Ha$^{-1}$)** |
| SPAD | SM | 38.0 | 44.6a | 52.1a | 57.7a | Grain | SM | 4.6 |
| | LMG | 38.5 | 41.3b | 47.8b | 54.3b | | LMG | 4.2 |
| *p*-value | | | <0.001 | | | *p*-value | | 0.25 |
| Height (cm) | SM | 28.4 | 65.2 | 112.1a | 230.4a | Stover | SM | 5.6 |
| | LMG | 26.9 | 61.4 | 96.3b | 218b | | LMG | 4.9 |
| *p*-value | | | <0.001 | | | *p*-value | | 0.09 |

Different letters indicate significant differences ($p < 0.05$).

The height of maize upslope, downslope, and between grass strips in LMG during year 7 was not significantly different from the height of maize in SM at the stages of 3–4 and 6–7 fully expanded leaves (Figure 5a). However, in later development stages, maize growth was significantly higher ($p < 0.05$) between two grass strips than immediately upslope or downslope of the grass. In stages 6–7 and 10–11 fully expanded leaves and silking, the SPAD readings of maize between grass strips were also significantly ($p < 0.05$) higher than those upslope and downslope of grass strips. The average SPAD readings for longan trees were not significantly different between LMG and SL (Figure 5a). Meanwhile, the average SPAD readings of guinea grass recorded 43.4 within LMG. This indicates that competition for N took place at positions where trees, crops, and grass were close to each other within the LMG system.

In LMG, the yield of maize grain between grass strips was 24% higher ($p < 0.05$) than in SM and about 62% higher than in upslope and downslope maize in LMG (Figure 5b). Yield of stover was also significantly higher (53–59%) between grass strips than for maize upslope and downslope of grass strips. Overall, the results clearly showed competition between grass, longan, and maize upslope and downslope of the grass strips within the LMG system in year 7.

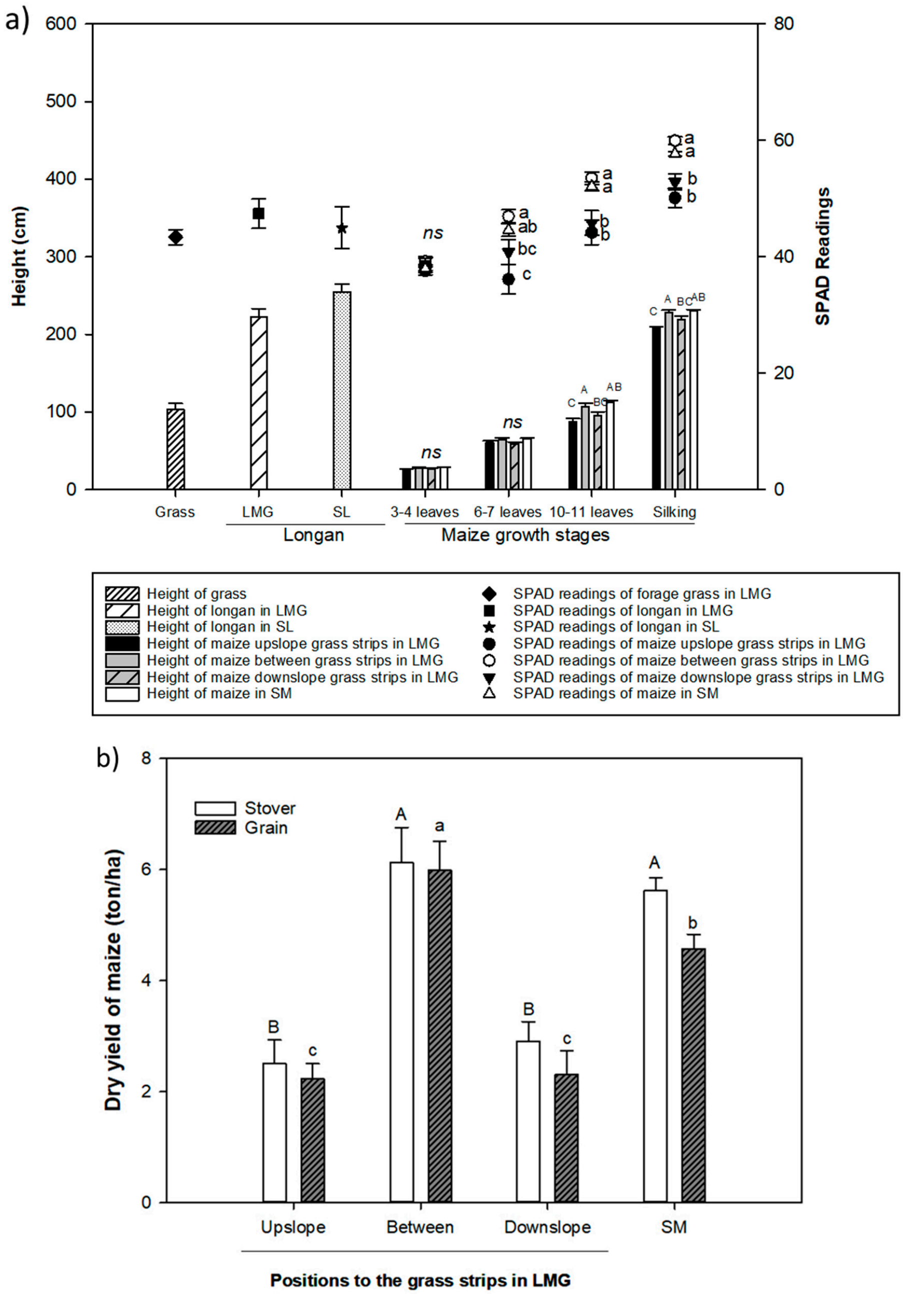


**Figure 5.** (**a**) Height of the tree and crop components and SPAD (soil plant analysis development) readings in the longan–maize–forage grass (LMG), sole-longan (SL) and sole-maize (SM); (**b**) dry yield of maize growing in different positions (upslope, between, downslope) relative to the grass strips within LMG in year 7. Values are means and standard errors. Bars with different upper case (stover) and lower-case (grain) letters indicate significant differences ($p < 0.05$).

### *3.4. Profitability*

Sole maize had a mean annual investment cost of 670 USD ha$^{-1}$, while that of the sole-longan and the LMG system was 3.7-fold and 3.2-fold higher, respectively. The average maintenance cost of SL and LMG was 300 and 863 USD ha$^{-1}$ year$^{-1}$, respectively (Figure 6a). The net profit was related to the cropping system, with an interaction between cropping system and year ($p < 0.05$). The mean net profit of LMG (1018 USD ha$^{-1}$) was 2.4-fold higher than for SM, while the SL system only achieved a positive profit from year 6 (Table 3). The trend of decreasing net profit of SM across year was partially due to the decreasing selling price of maize over time (presented in the Supplementary Materials Table S2) and lower maize yield in the subsequent compared to the initial years of experiment. From year 2, the net profit from LGM was equal to that from SM, while from year 4 the net profit from LGM was significantly ($p < 0.05$) higher than for SM and SL. In addition, the cumulative profit from LMG was positive from year 2 and higher than that from SM from year 4 (Figure 6a). In contrast, the cumulative profit from SL was still negative in year 7.

**Table 3.** Net profit from the agroforestry systems and the corresponding sole crop/tree.

| | **Net Profit (USD ha$^{-1}$)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Cropping System** | **2012** | **2013** | **2014** | **2015** | **2016** | **2017** | **2018** | **Mean (±SE)** |
| SM | 1118a | 611a | 388a | 246b | 233b | 196b | 190b | 425.9 (±118.9)b |
| SL | −2463c | −355b | −229b | 40b | −41b | 112b | 947ab | −284.4 (±336.8)c |
| LMG | −391b | 839a | 1550a | 1179a | 1380a | 1404a | 1168a | 1018.2 (±231.6)a |
| By cropping system | | | | | $p$-value < 0.001 | | | |
| Cropping system x year | | | | | $p$-value < 0.001 | | | |
| SST | na | −1422 | −290 | 42 | 2120 | 538 | 3238 | 704.5 (±632.4)b |
| STG | na | −1772 | 3297 | 2853 | 3069 | 2381 | 3570 | 2232.9 (±746.6)a |
| STM | na | −1772 | 2661 | 3018 | 4067 | 3147 | 4773 | 2648.7 (±857.1)a |
| By cropping system | | | | | $p$-value = 0.005 | | | |
| Cropping system x year | | | | | $p$-value = 0.72 | | | |

SM: sole-crop maize, SL: sole-crop longan, LMG: longan–maize–forage grass, SST: sole-crop son tra, STG: son tra–guinea grass, STM: son tra–mulato grass; na: not applicable since the experiment was established in 2013. Values are means; different letters indicate significant differences ($p < 0.05$).

In the year of establishment, the total input costs were approximately 1772 USD ha$^{-1}$ for both STG and STM, but lower (1422 USD ha$^{-1}$) for SST. In the following years, STG and STM required higher investment than the sole-tree system, mainly deriving from labour costs for forage-grass harvesting (Figure 6b). There was a significant effect ($p < 0.05$) of cropping system on net profit, with the mean net profit in STG (2233 USD ha$^{-1}$) and STM (2649 USD ha$^{-1}$) being around 3.2- and 3.7-fold higher, respectively, than in SST (Table 3). The SST system gave a positive net profit from year 3, but the cumulative profit from STG and STM was positive and higher than from SST from year 2 (Figure 6b).

### *3.5. Farmers' Perceptions and Aspirations for Fruit Tree-Based Agroforestry*

#### 3.5.1. Tree and Crop Performance in Agroforestry

Most farmers were fully aware of possible effects of competition for resources (light, water, nutrients) on the performance of tree and crop components within the agroforestry systems (Figure 7). All interviewees in Van Chan noted that growth and productivity of maize in the longan–maize–forage grass system were lower than in sole-maize cultivation. They attributed this to close distance between trees, crops, and grass leading to competition in the agroforestry system. However, non-hosting village groups claimed that longan trees performed better in agroforestry than in sole cultivation since they believed that longan trees utilised the nutrients applied to the maize. However, the experiment-hosting village, the experiment-hosting farmers in Van Chan, and all interviewees in Tuan Giao reported that growth and productivity of trees in both agroforestry systems were lower than when trees were grown separately.

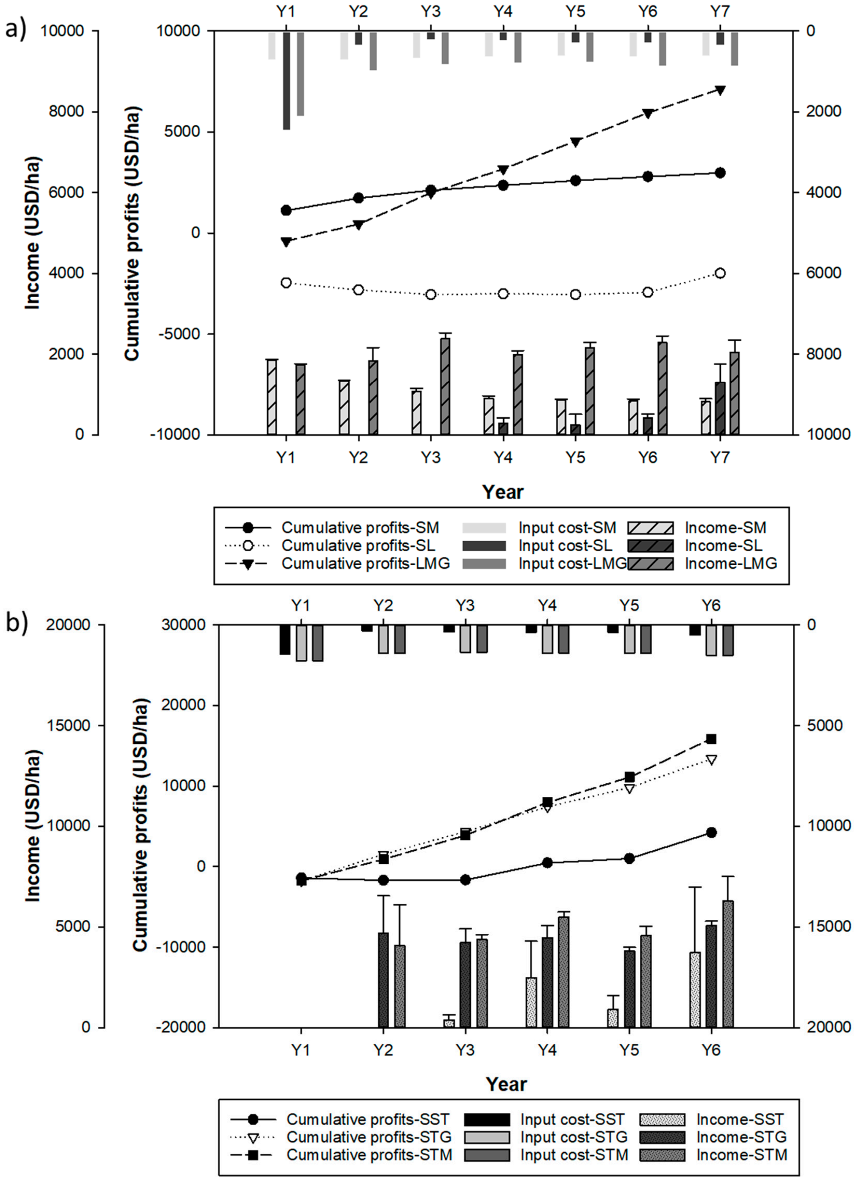


**Figure 6.** Input costs, income, and cumulative profit from: (**a**) the longan–maize–forage grass (LGM) compared with sole maize (SM) and sole longan (SL); (**b**) the son tra–guinea grass (STG) and son tra–mulato grass (STM) compared with sole son tra (SST).

The interviewees also suggested that the agroforestry systems could be optimised through better management of trees and crops (Figure 7). The groups proposed different solutions to improve the efficiency, such as adding more fertilisers to plants suffering from nutrient deficiency in areas where trees, crops, and grass affected each other's nutrient availability, reducing tree density and pruning to reduce shading. In addition, modifying the planting distance between trees and grass was suggested by groups from both sites. The farmers interviewed also suggested less-competitive crops for the agroforestry systems, e.g., legume species with biological N-fixation such as soybean and groundnut in LMG in Van Chan (3 of 7 groups), and upland rice or cucumber in STG and STM in Tuan Giao (2 of 7 groups).

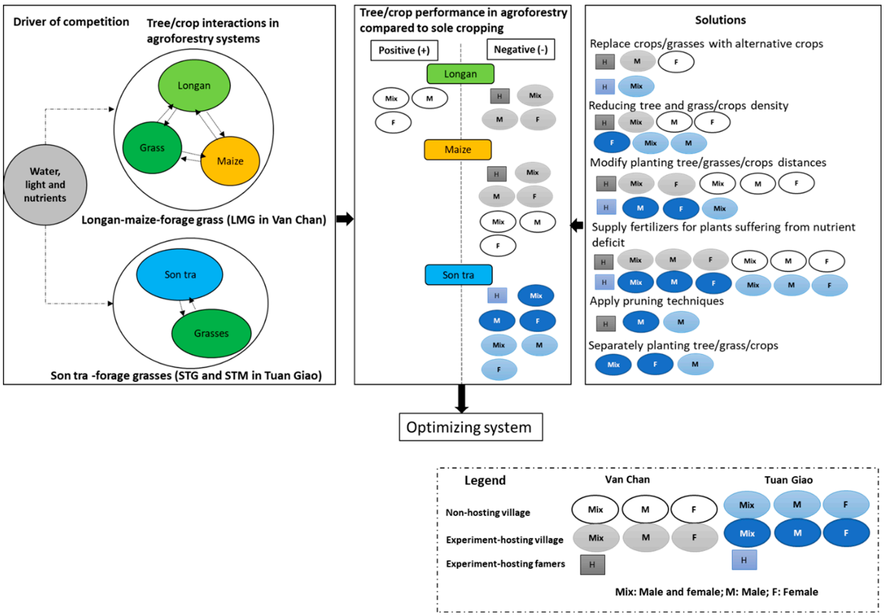


**Figure 7.** Farmers' perception of the performance of trees and crops in the agroforestry experiments in Van Chan and Tuan Giao compared with that of sole crops/trees. Open-ended questions were used in group interviews with non-hosting and experiment-hosting villages; experiment-hosting farmers were interviewed individually.

### 3.5.2. Benefits of the Agroforestry Systems

All famer groups in Van Chan and Tuan Giao shared the opinion that the experimental agroforestry systems produced earlier and more diverse products and gave higher economic benefit than the sole crop/tree (Figure 8a). Most interviewees reported that after 3–4 years, when the trees began to bear fruit, the income from agroforestry was much higher than from sole-crop cultivation. They also reported ecological benefits of the agroforestry systems in terms of reduced erosion, weed control, enhanced soil moisture and fertility, and greater resilience to extreme weather conditions (drought, snow, and frost) compared with sole-crop cultivation (Figure 8a). However, no group mentioned any benefits regarding pests and diseases, while only one group (the host farmers in Van Chan) mentioned terrace formation as an advantage (Figure 8a,b). Female and mixed groups in Tuan Giao claimed that the soil was less fertile and soil moisture lower in agroforestry than sole-tree cultivation, because the very dense forage grass used much water and nutrients within the agroforestry system (Figure 8b). Only the groups in Van Chan and the host farmer group in Tuan Giao expressed appreciation of the reduced labour requirement for harvesting forage from the grass strips in the agroforestry system (Figure 8b). These groups mentioned the possibility of using the forage to feed livestock, produce green manure, and provide earlier income when sold on the local market.

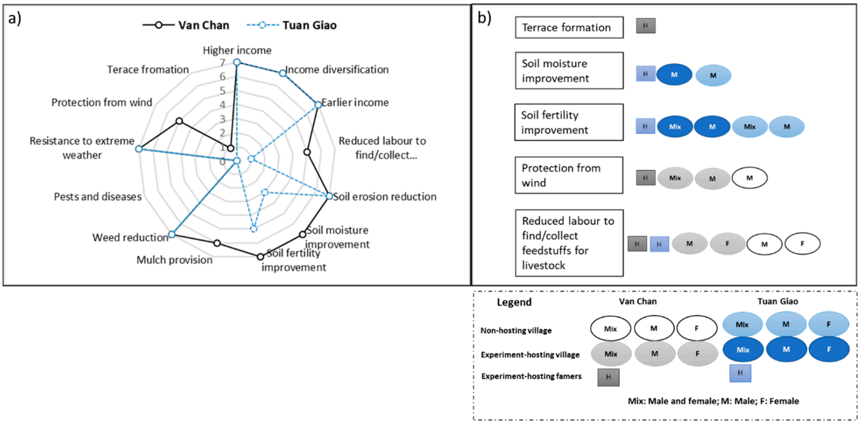


**Figure 8.** (**a**) Farmers' perceptions about benefits of agroforestry systems and number of farmer groups mentioning each of the identified benefits; (**b**) perceived benefits and the farmer groups in Van Chan and Tuan Giao that mentioned each. Open-ended questions were used in group interviews with non-hosting and experiment-hosting villages; experiment-hosting farmers were interviewed individually.

### 3.5.3. Constraints to Uptake of Agroforestry

Most of the farmer groups recognised and listed constraints to the uptake of agroforestry and proposed possible solutions to improve uptake in the local region (Figure 9). At both Tuan Giao and Van Chan, all groups indicated that the investment costs were higher than for sole-crop cultivation, making it difficult for poor households to adopt agroforestry. Management of pests and diseases in agroforestry was also more complicated, with more tree and crop components. An unstable market and low prices for products were other constraints to the uptake of agroforestry in the region.

All groups in Van Chan indicated that harsh weather events such as drought and lack of awareness among farmers of the benefits of agroforestry (4 of 7 groups) were the main drawbacks to the uptake of agroforestry. In Tuan Giao, all farmer groups considered that it would be difficult to combine traditional free grazing of livestock on crop residues with agroforestry. The forage grass was not considered valuable, since in this area with only free-grazing livestock farmers are not accustomed to collecting fodder. Extreme weather such as snow and frost and lack of techniques for implementing agroforestry were reported as other constraints to the adoption of agroforestry.

The farmers interviewed proposed solutions to address these issues (Figure 9). At Van Chan and Tuan Giao, all farmer groups mentioned training in agroforestry techniques, support in obtaining seedlings and fertilisers, and financial support or access to low-interest loans/credits as important incentives for implementing agroforestry. Development of market links for agroforestry products and a stable market were also considered key factors for agroforestry adoption by all farmer groups, but the suggested schemes differed. In Van Chan, the interviewees envisaged creating a stable market by building a farmers' cooperative to improve product quality to meet market demand and a processing factory to produce secondary products from longan fruit. The interviewees wanted maize replaced with other, higher-value annual crops. In Tuan Giao, the interviewees wanted a market link to a processing factory that would buy and add value to son tra and create a stable market.

All farmer groups in Van Chan and Tuan Giao saw a need for plant protection interventions to control pests and weeds as a way to reduce the labour costs of implementing agroforestry. According to farmers in Tuan Giao, shifting from free grazing to captive grazing and promoting livestock production to utilise the forage grass would increase the feasibility of agroforestry in the region. Although drought is a major concern in Van Chan, only the experiment-hosting farmers and the female farmer groups mentioned construction of water storage facilities as a solution. They saw a need for an electric pump and water tanks on the top of hills to supply water for tree/crops during drought periods.

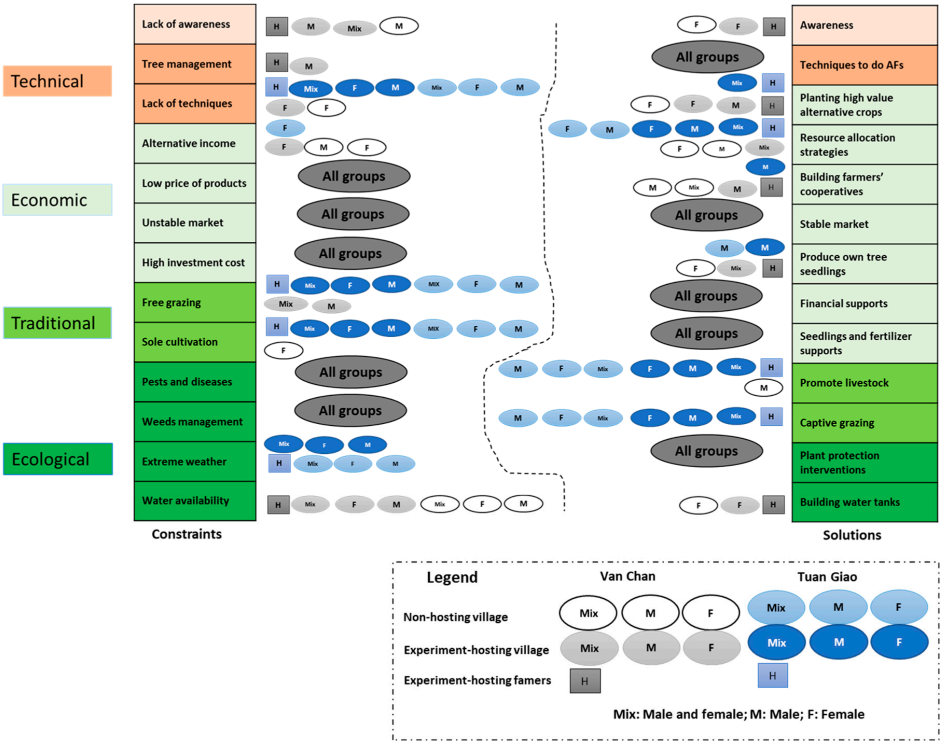


**Figure 9.** Farmers' perceptions of constraints (left) and solutions (right) to the uptake of agroforestry (AF) in Van Chan and Tuan Giao, and (centre) the farmer groups that mentioned the respective constraint/solution. Open-ended questions were used in group interviews with non-hosting and experiment-hosting villages; experiment-hosting farmers were interviewed individually.

All farmer groups interviewed mentioned a need to reduce the investment costs of agroforestry (Figure 9), e.g., by producing their own fruit-tree seedlings (3 of 7 groups in Van Chan and male groups in Tuan Giao). Some groups suggested offsetting the investment costs by planting higher-value crops to replace maize in Van Chan (4 of 7 groups) and forage grasses in Tuan Giao (2 of 7 groups). In addition, all farmers in Tuan Giao and 3 of 7 groups in Van Chan (Figure 9) indicated that resource allocation strategies could help reduce the maintenance cost of implementing agroforestry. They believed that during the first three years of the experiments, when the trees had not yet produced fruit, the farmers prioritised the annual crops and grasses to generate annual income. Later, when the trees were maturing and bearing fruit, farmers prioritised the trees.

#### 3.5.4. Factors Enabling Expansion

The farmers at both Van Chan and Tuan Giao indicated that large-scale annual crop production on sloping land is an unstable system (land degradation, low yield). However, the ownership of land by local farmers is suited to implementing agroforestry. In addition, agroforestry has potential in both areas because it can bring economic and ecological benefits for local farmers. The local climate conditions are suitable for longan trees in Van Chan and for son tra trees in Tuan Giao, so both species can produce high yield. Recently, many farmers in Van Chan have shifted from sole-maize production to fruit trees and intercropping of fruit trees with annual crops, while farmers in Tuan Giao expressed interest in grafted son tra seedlings because they start to produce fruit rapidly. Local farmers saw potential for intercropping high-value trees (e.g., longan, mango, plum) and high-value crops (e.g., medicinal plants, soybean, green bean) in Van Chan, or amomum (*Amomun xanthioides* Wall.) in Tuan Giao (Figure 10).

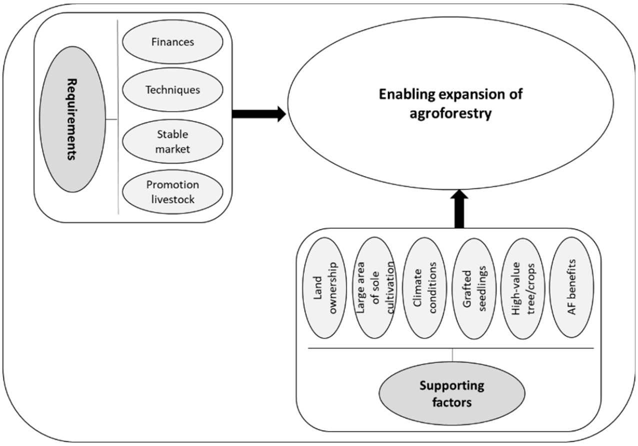


**Figure 10.** Farmers' perspectives about factors enabling expansion of agroforestry in Van Chan and Tuan Giao.

However, based on the interview responses, techniques to implement agroforestry, a stable market for products, and financial support for farmers in the establishment year(s), in combination with expansion of livestock production, would be required to expand agroforestry in northern upland areas of Vietnam (Figure 10).

## 4. Discussion

### *4.1. Effects of Competition for Resources on Tree and Crop Performance in Agroforestry and Ways to Improve the Systems*

Total income was higher in the agroforestry systems than in the sole-cropping systems studied, but individual crop components generally grew more slowly in agroforestry systems than in sole-crop/tree systems, most likely due to competition for light, water, and nutrients [38]. The tree species in maize agroforestry systems may contribute differently to tree–crop interactions, e.g., leguminous tree species have been shown to compete less with maize for N than non-leguminous species [39–41]. The presence of tree roots, especially in the maize-cropping zone, also affects the competition with maize, and is determined by e.g., inherent rooting patterns, management, and soil conditions [41,42]. Conversely, maize restricts root development of trees in the cropping zone of agroforestry systems. A study on maize-based agroforestry systems in the sub-humid highlands of western Kenya indicated that the length of fine roots of intercropped trees (*Grevillea robusta* and *Senna spectabilis*) decreased in the maize root zone because of competition and damage to tree roots during weed hoeing [43]. In addition, maize uses the C4 photosynthetic pathway and is sensitive to shading [44] and may therefore be more negatively affected by tree shading in agroforestry systems than C3 species. Such competition was evident in the LMG system in our study, with slower growth and lower yield of longan and maize in areas where trees and crops were close to each other. This was particularly evident in year 7, when SPAD measurements showed competition for N between trees, crops, and grass growing close to each other (Table 2 and Figure 5).

In our experiments, the grass component of the agroforestry systems was competitive and negatively affected N uptake and growth of trees and maize. A previous study of maize intercropped with guinea grass in northwest Vietnam [45] found that aboveground biomass of maize at positions downslope and upslope of grass strips was around 60% and 40% lower, respectively, than that of maize 3 m from grass strips and sole maize, as we found for the LMG system (year 7). The farmer groups interviewed confirmed that maize downslope and upslope of grass strips showed lower growth and yield compared with maize farther from grass strips and sole maize, and that longan also had lower growth and yield as an intercrop than as a sole crop.

In our experiment, the yield from sole-longan planting was 2–4-ton ha$^{-1}$ at the seventh year after tree planting. However, higher yield can be expected with e.g., improved irrigation. For example, in Hung Yen province of the Red River Delta region of Vietnam, the longan yield could reach 20 ton per ha$^{-1}$ in the eighth year after tree planting [46]. Thanks to better market access including for export, partially due to the proximity to Hanoi as the country's capital and urban centre, the farmers in the province could derive high income from selling longan, and they partially allocate the income to improving irrigation systems [46]. The farmers in the province have been cultivating longan for decades.

However, the degree of competition may differ between grass species. A study in Costa Rica showed that when guinea grass and mulato grass were planted 0.9 m from *Eucalyptus deglupta* they produced similar grass biomass, but root length density (RLD) at 0–0.4 m depth was up to three-fold higher under guinea grass than under mulato grass [47]. At 0–0.4 m depth but 0.45 m from *E. deglupta* trees, RLD of guinea grass was up to four-fold higher than that of mulato grass. Thus *E. deglupta* growth was significantly reduced by the presence of guinea grass, and to a lesser extent by mulato grass, compared with sole-crop *E. deglupta* [47]. The STG and STM systems in our study confirmed the competition from guinea grass and mulato grass strips with the trees. In these systems, the forage grasses were planted 1 m from son tra rows, resulting in lower growth and yield of son tra trees with guinea grass than with mulato grass or sole-tree cultivation, while the two grasses produced similar grass biomasses.

It is possible to reduce competition between trees and crops by pruning the trees [41], as proposed by farmer groups in our study. Another option may be to intercrop C3 crops instead of C4 crops, as previous studies have indicated that yields of C3 crops are less reduced in agroforestry systems [48,49]. In our study, farmer groups suggested improving the efficiency of the agroforestry systems by planting legume species such as soybean and groundnut instead of maize in LMG, and by planting upland rice or cucumber to replace forage grasses in STG and STM. Greater planting distance between trees, crops, and grass strips would reduce competition. Supplying more fertiliser to plants suffering from nutrient deficiency in competition zones was also suggested in the group interviews.

### *4.2. Productivity Benefits and Ecosystem Services of Agroforestry Systems*

Evaluation of the agroforestry systems tested in this study indicated that they provided earlier products than sole-tree systems and more diverse products than sole-maize systems. They also gave higher total productivity for farmers than the sole-crop systems from the second year onwards. During the first three years, total productivity was mainly from forage grasses and maize, with the LMG, STG, and STM systems giving forage-grass biomass for farmers from the second year. The products became more diverse from year 4, when the trees started to bear fruit, with yield increasing in subsequent years.

We found that the LMG agroforestry system was more productive than sole maize and longan from year 2 onwards, as indicated by LER ranging from 1.1 to 1.9 (Figure 4a). In a previous study on agroforestry systems based on apple (*Malus domestica*), e.g., apple/maize, apple/peanut, and apple/millet, LER was found to be 1.2–1.3 after the apple trees started bearing fruit from year 6 [50]. In our study, LER of the STM system was >1.0 from year 3, when the son tra started bearing fruit. However, in the STG system LER was <1.0, which can probably be explained by competition, as previously shown [47]. Other studies on forage grasses have reported that guinea grass [33] produces more biomass than mulato grass [34] in sole-grass cultivation. It may therefore affect the LER of the STG agroforestry system. Management of tree and crop components of a fruit tree-based agroforestry system thus needs to change from the year of establishment to when trees are maturing and high-producing, so that farmers can overcome competition effects and optimise the efficiency of land use [50]. In this study, the farmer groups interviewed suggested that a resource allocation strategy could improve the productivity of different components of the agroforestry systems. In the first three years, when the trees had not yet produced fruit, their main priority was the annual crop and grasses, whereas they paid more attention to the trees when they started bearing fruit. The farmers needed the short-term income from annual crops to support the long-term benefits from the fruit trees.

Growing forage grasses can be an incentive to improve smallholder livestock production by improved the daily weight gain of cattle and reducing labour in finding feedstuffs [51]. In this study, farmer groups confirmed that growing forage grasses reduces the labour requirement for finding/collecting feedstuffs for livestock in areas where captive grazing is common practice. This may be particularly beneficial for rural women in the study region, as 60% of the workload in farming is carried out by women [11]. In areas where free grazing is common practice like in Tuan Giao district, farmers will be less motivated/perceive less benefit from growing forage grass. This can be a "temporary" constraint for agroforestry adoption in the areas because along with population growth and higher demand for agricultural lands, the area of free-gazing lands will become more limited in the future. Therefore, we strongly considered fodder grass as one of main components of the tested agroforestry systems. Moreover, agroforestry systems with grass have been identified as the most suitable practice for northwest Vietnam to reconcile livelihood and erosion control [9].

Sole-maize cultivation on steep slopes in the northwest region of Vietnam produced annual soil loss that reached up to 174 ton ha$^{-1}$ [15]. However, growing forage grass along the contour lines can play a significant role in reducing soil loss, especially on the steep slopes of the study region [15]. All experiments in our study were conducted in lands with about 27% slope, and measurement of soil erosion was not part of our study. However, a study in the northwest region that measured and compared soil erosion rate in agroforestry and sole-crop plantations clearly showed that soil erosion was substantially reduced in agroforestry [52]. The study found that the erosion rate in longan–mango–maize–forage grass agroforestry was 43% lower than that measured in sole-maize cultivations, and the rate in son tra–coffee–forage grass was 34% lower than that measured in sole-coffee plantations. All agroforestry systems and sole-coffee plantations observed in the study were three years old. A higher reduction in the soil erosion rate can be expected in more mature agroforestry such as in our experiments that have larger tree-canopy cover.

Ecological benefits or ecosystem services noted by farmers in this study were the effect of grass strips in reducing soil erosion and maintaining soil moisture and fertility, but also in forming terraces on the steep slopes [52]. In steeply sloping areas, the terraces formed could significantly increase agricultural productivity and enhance water-use efficiency when combined with other agricultural techniques [53].

### 4.3. Economic Benefits of Agroforestry Systems and Possibilities for Improvement

The agroforestry systems evaluated here showed higher profitability than the sole-crop systems from year 2 onwards. However, the initial investment cost for agroforestry was high: 2122 USD ha$^{-1}$ for LMG and 1772 USD ha$^{-1}$ for STG and STM. Farmers in the region lack the financial resources to shift to new practices [10]. New practices thus need to be shown to be safe and ensure food security before smallholders risk changing from their current system. The main incentive for farmers to adopt agroforestry is increasing yield and stable prices for their products. When comparing production and profitability, a cycle of some years must be considered, because it takes longer to establish perennial trees than annual crops and the financial input is higher in agroforestry systems. Therefore, initial investment funding (possibly organised by farmers themselves), subsidies, or loans will be necessary to compensate for the high investment and maintenance costs in the first few years of agroforestry [16].

The farmer groups interviewed proposed some ways to make implementation of agroforestry more profitable. First, the establishment of agroforestry will require financial support or access to low-interest loans/credits. In addition, implementing agroforestry with fodder-grass strips would become more beneficial for local people if changing from free to captive grazing were promoted. To achieve both in the study region, local farmers can seek support from the Vietnamese government through e.g., the National Target Programme (NTP) on New Rural Development [54] or the NTP-Sustainable Poverty Reduction and 135 Programme [55]. In addition, they can seek loans (low interest rate) from formal actors such as the Vietnam Bank for Agriculture and Rural Development, the Vietnam Bank for Social Policy, and People's Credit Funds [56].

Second, the farmers interviewed suggested producing their own low-cost tree seedlings to reduce the investment cost. These could be grown in community nurseries, where all members share costs and provide inputs [57]. The project Agroforestry for Livelihoods of Smallholder Farmers in Northwest Vietnam (2012–2016), together with relevant stakeholders, has provided training for farmers on the establishment and management of smallholder and group nurseries, producing tree seedlings by seedling propagation, grafting, and marcotting techniques. The project has published various technical extension materials on producing different tree-species seedlings suitable for local conditions. These technical sources could be useful for local farmers producing their own tree seedlings [58].

Third, the interviewees believed that they could achieve stable production by forming growers' cooperatives and could improve product quality to meet market demand. The cooperatives could provide production services, including inputs for farm households, fertilisers, feed ingredients, plant protection chemicals, and vaccines for livestock. They could also mediate between entrepreneurs and farmers, representing and protecting the rights of farmer members in contracting to supply raw materials to processing enterprises and export agricultural products [11]. In rural development work, agricultural service cooperatives can make a significant contribution [11]. Recently, the Vietnamese government introduced a programme to develop 15,000 cooperatives and effective agricultural cooperative unions in rural areas, with the government providing institutions, mechanisms, and policies to support the programme [59]. This offers an opportunity for farmers in the region to develop cooperatives to ensure stable production of agricultural products.

## 5. Conclusions

Agroforestry systems based on fruit trees, grass, and crops had higher productivity, higher profitability, and earlier returns on investment than sole-crop fruit systems, but also higher initial investment costs. The agroforestry systems produced a diversity of products and provided ecosystem services such as erosion control and soil fertility improvement. However, challenges such as higher investment cost and an unstable market for agroforestry products make it uncertain whether agroforestry can be easily promoted in the area.

During development of the agroforestry systems, there were negative effects on growth and productivity of the different components, most likely due to competition. There was evidence of competition for nitrogen between tree, grass, and crop components at positions upslope and downslope of the grass strips. These competition effects need to be considered when designing agroforestry systems and formulating management regimes.

Future fruit tree-based agroforestry systems should apply adaptive management while the agroforestry system is maturing and consider measures such as widening the planting distance between trees, crops, and grass; supplying fertiliser to plant components suffering from nutrient deficiency; and pruning trees in competition zones. Introducing high-value crops or biological N-fixing species to reduce competition and support the growth of trees can also be considered in order to optimise the systems.

To enable uptake and expansion of agroforestry in northwest Vietnam, financial support to meet the higher investment costs for agroforestry and for better value chains with market stability are prerequisites for farmers. Local farmers can produce their own tree seedlings to reduce the investment cost for agroforestry in the region.

**Supplementary Materials:** The following are available online at http://www.mdpi.com/2073-445X/9/11/451/s1, Table S1: Fertilisation regime applied in the sole-crop and agroforestry systems in Van Chan and Tuan Giao; Table S2: Cost of cropping inputs and prices paid for products at the study sites, 2012–2018 (data provided by the provincial extension department); Table S3: Groups selected for farmer group discussions (FGD); Table S4: List of questions used in farmer group discussions.

**Author Contributions:** Conceptualization, V.H.D., I.Ö., and N.L.; methodology, V.H.D., I.Ö., and N.L.; formal analysis, V.H.D.; investigation, V.H.D., H.T.P., and V.T.N; writing—original draft preparation, V.H.D.; writing—review and editing, I.Ö., G.B., A.S.D., R.M., N.L., H.T.P., and V.T.N. All authors have read and agreed to the published version of the manuscript.

**Funding:** This study was part of the project "Developing and promoting market-based agroforestry and forest rehabilitation options for northwest Viet Nam" (short name AFLI) led by World Agroforestry (ICRAF) and funded by the Australian Centre for International Agricultural Research and the CGIAR Research Programme on Forests, Trees and Agroforestry, in cooperation with the Swedish University of Agricultural Sciences (SLU) within the Swedish Research Council Formas funded project 2019-00376.

**Acknowledgments:** We highly appreciate the support of researchers and technical staff from the AFLI project at World Agroforestry (ICRAF) and national partners in Vietnam. Our thanks to researchers at the Northern Mountainous Agriculture and Forestry Science Institute and Forest Science Centre of Northwest Vietnam for their assistance. We are grateful to Chu Van Tien, Tran Quang Khanh, and Vu Dinh Chi, who hosted experiments in Van Chan, to Giang Dung Vu, Mua A Do, and Vang A Sua, who hosted experiments in Tuan Giao, and to the local authorities and farmers in the study sites for their support during field research.

**Conflicts of Interest:** The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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# II

Agriculture, Ecosystems and Environment 345 (2023) 108323

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

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

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A R T I C L E  I N F O

*Keywords:*
Contour planting
Green infrastructure
Soil and nutrient losses
Steep slopes
Sustainable farming

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

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https://doi.org/10.1016/j.agee.2022.108323
Received 30 September 2022; Received in revised form 11 December 2022; Accepted 15 December 2022
Available online 22 December 2022
0167-8809/

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

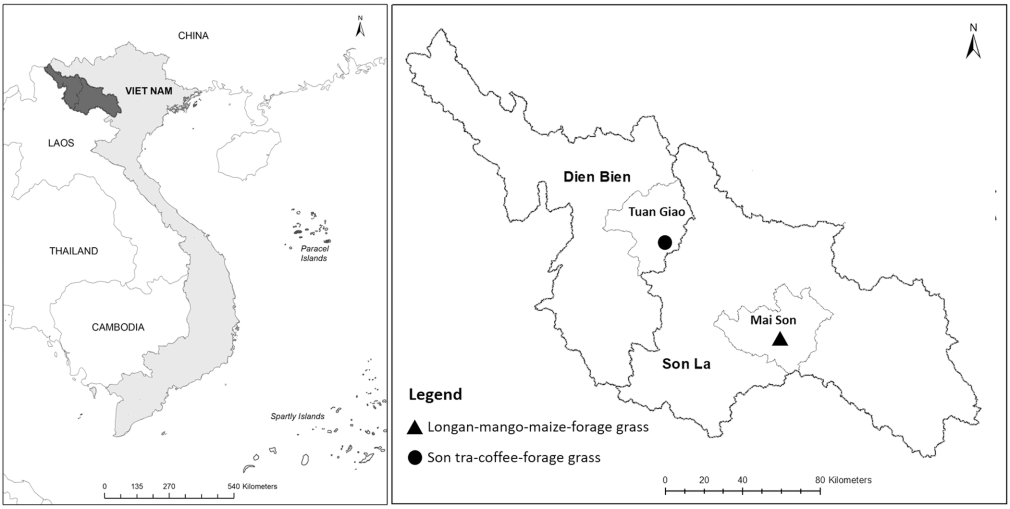


**Fig. 1.** Location of the agroforestry experiments with longan-mango-maize-forage grass in Mai Son District, Son La Province, and son tra-coffee-forage grass in Tuan Giao District, Dien Bien Province, north-west Vietnam.

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 | 33 | 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:

$$V1 = (h1 \times w)/2 \quad (1)$$

$$V2 = (h2 \times w)/2 \quad (2)$$

$$Vt = V1 - V2 \quad (3)$$

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***.

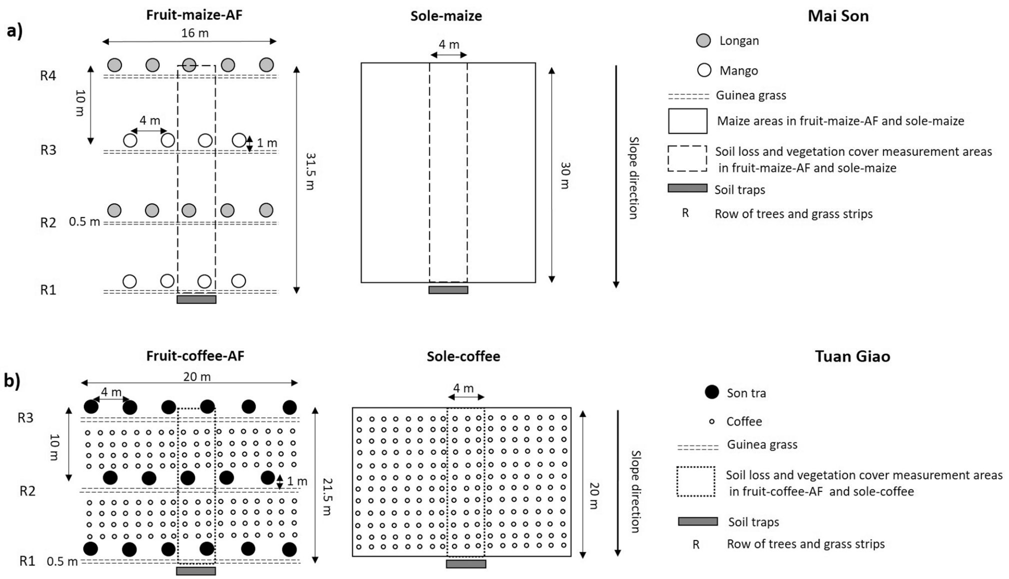


**Fig. 2.** Design of field experiments at (a) Mai Son: longan-mango-maize-forage grass (fruit-maize-AF) and sole-crop maize (sole-maize), with plot area 504 and 480 $m^2$, respectively, and (b) Tuan Giao: son tra-coffee-forage grass (fruit-coffee-AF) and sole-crop coffee (sole-coffee), with plot area 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.

| Site | Chemical fertiliser and amendment dose ($kg^{-1}$ $ha^{-1}$) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 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

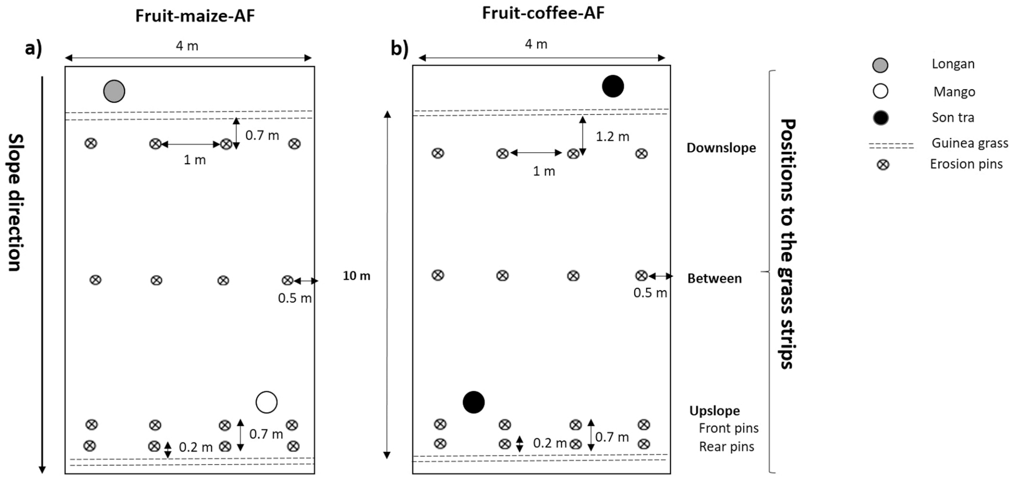


**Fig. 3.** Positions of erosion pins in one section of each agroforestry plot to evaluate sediment movement down the slope. (a) Longan-mango-maize-forage grass (fruit-maize-AF) at the Mai Son site and (b) son tra-coffee-forage grass (fruit-coffee-AF) at the Tuan Giao site.

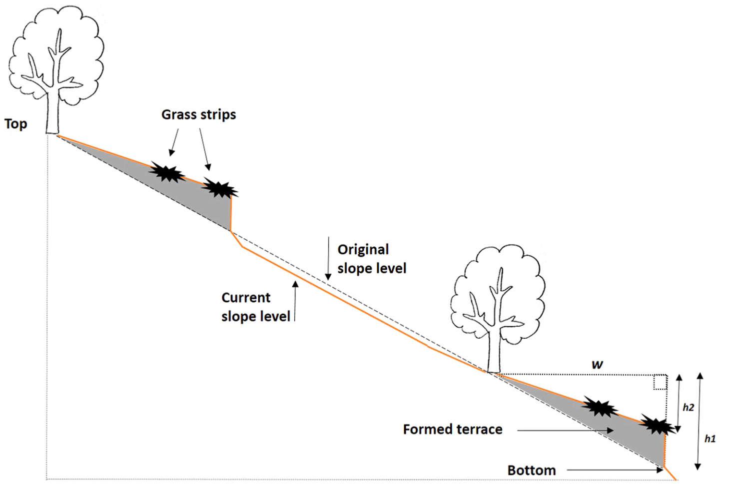


**Fig. 4.** Method used for estimation of volume of terrace formed in the five growing seasons after establishment of trees and grass strips in longan-mango-maize-forage grass (fruit-maize-AF) at the Mai Son site and son tra-coffee-forage grass (fruit-coffee-AF) at the Tuan Giao site.

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

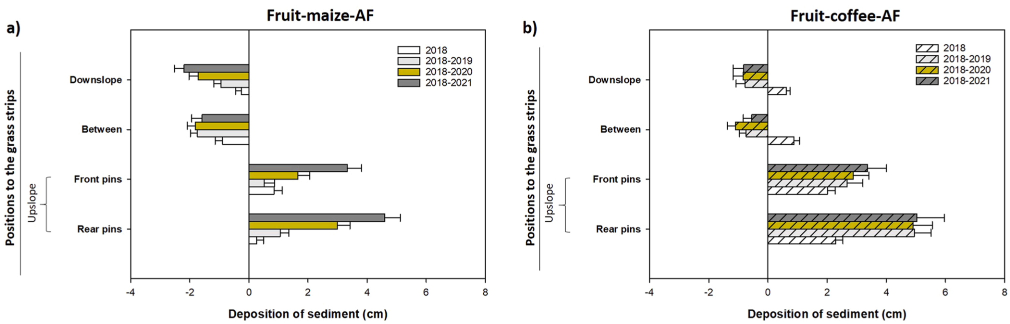


**Fig. 5.** Sediment movement downslope within the two agroforestry systems based on changes measured at erosion pins. The X-axis shows soil loss (negative values) or accumulation (positive values) over time, and the error bars indicate standard error. (a) Longan-mango-maize-forage grass (fruit-maize-AF)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

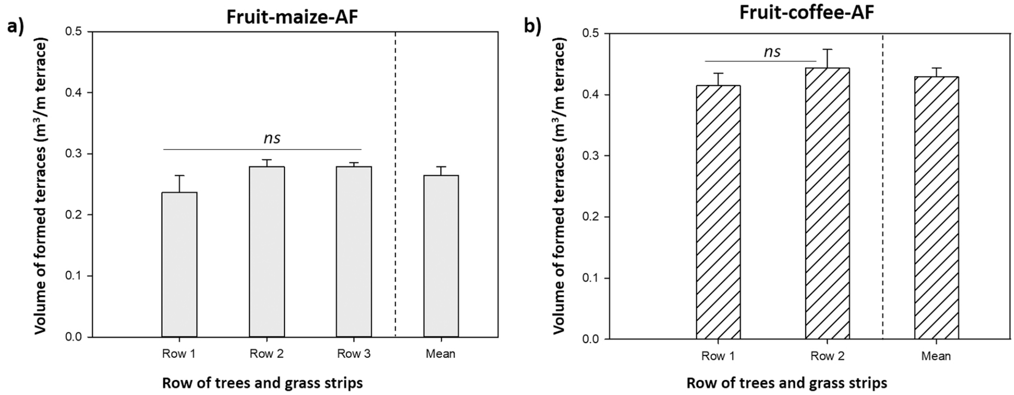


**Fig. 6.** Mean volume of terrace formed by tree and grass strips in the two agroforestry systems after five growing seasons. Error bars indicate standard error. (a) Longan-mango-maize-forage grass (fruit-maize-AF) system at the Mai Son site and (b) Son tra-coffee-forage grass (fruit-coffee-AF) system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

| 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.

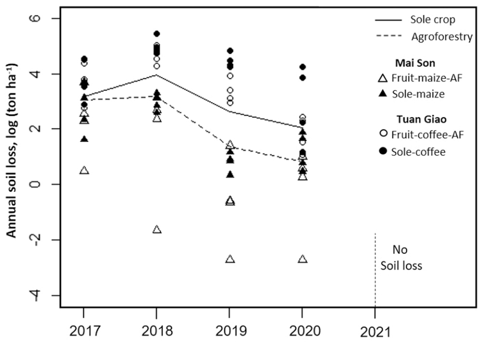


**Fig. 7.** Interaction plot for annual soil loss in the agroforestry systems fruit-maize-AF (longan-mango-maize-forage grass) and fruit-coffee-AF (son tra-coffee-forage grass) compared with sole-crop maize (sole-maize) and sole-crop coffee (sole-coffee), respectively, at the Mai Son and Tuan Giao sites.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

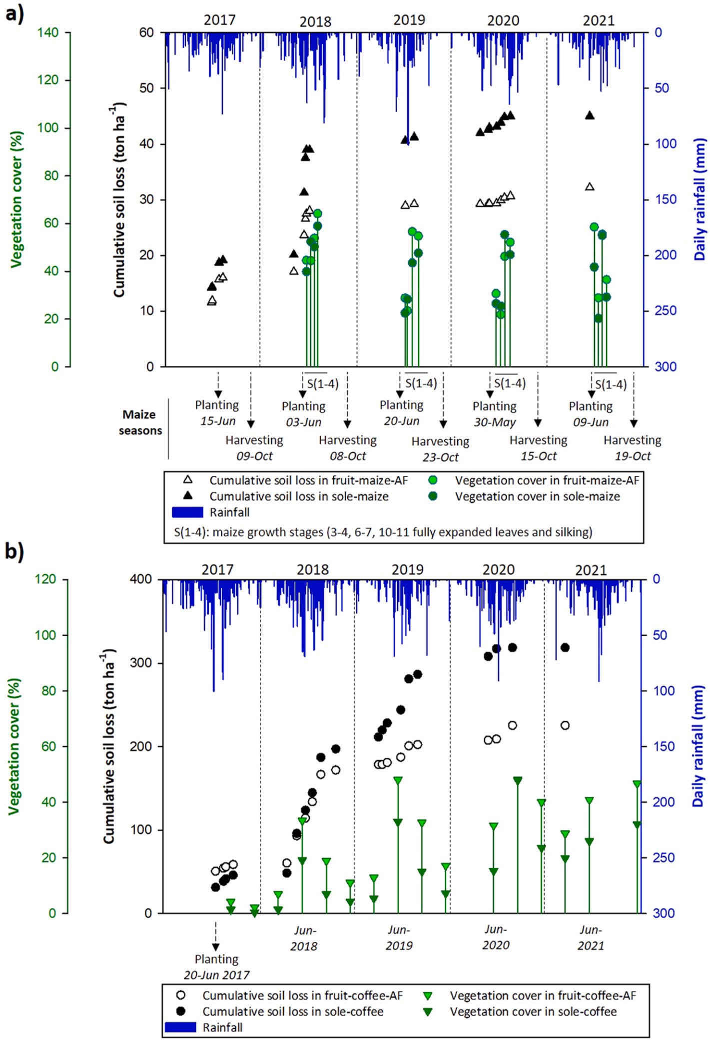


**Fig. 8.** Cumulative soil loss over the five-year study period, daily rainfall and percentage vegetation cover over time in the agroforestry systems and sole-crop systems. (a) Longan-mango-maize-forage grass (fruit-maize-AF) and sole-crop maize (sole-maize) and (b) Son tra-coffee-forage grass (fruit-coffee-AF)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

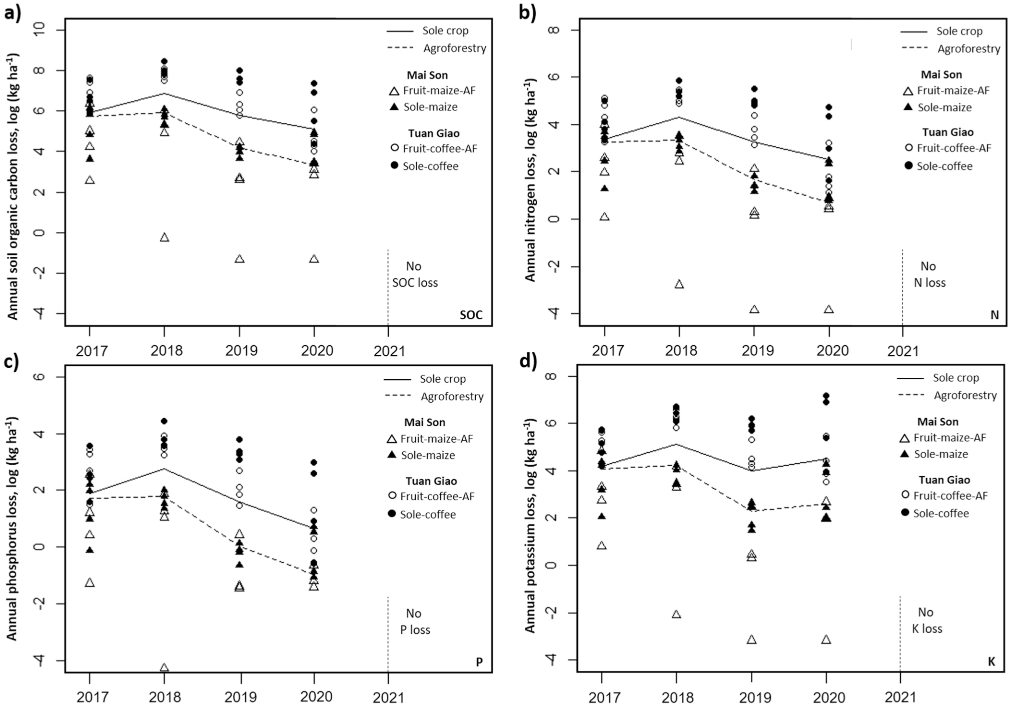


**Fig. 9.** Interaction plot for annual losses of (a) soil organic carbon (SOC), (b) nitrogen (N), (c) phosphorus (P) and (d) potassium (K) through soil erosion in fruit-maize-AF (longan-mango-maize-forage grass) and fruit-coffee-AF (son tra-coffee-forage grass) compared with sole-maize (sole-crop maize) 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.

## Acknowledgements

This research was conducted as part of the project "Developing and Promoting Market-Based Agroforestry and Forest Rehabilitation Options for Northwest Vietnam" (AFLI project) led by World Agroforestry (ICRAF) in collaboration with the Swedish University of Agricultural Sciences (SLU) and other partners. Funding for this study was obtained from the Australian Centre for International Agricultural Research, the CGIAR Research Programme on Forests, Trees and Agroforestry, and projects funded by the Swedish Research Councils Formas (2019–00376) and VR (2019–03740), which are gratefully acknowledged.

We highly appreciate the support of researchers and technical staff from the AFLI project at World Agroforestry (ICRAF) and national partners in Vietnam. Our thanks to Johannes Forkman, SLU, for statistics support and advice, and to Mary McAfee for English language editing. We are grateful to Tong Van An, who hosted experiments at Mai Son, to Lau A Vang, who hosted experiments at Tuan Giao, and to the local authorities and farmers at the study sites for their support during the field research.

## 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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Doctoral Thesis No. 2023:63

This thesis examined whether fruit tree-based agroforestry on smallholder farms on sloping uplands can have a positive impact on sustainability. The results showed that agroforestry with fruit trees, grass strips and crops could be a viable option for sustainable agricultural production on sloping uplands, through improving profitability and soil conservation compared with sole trees or crops. To optimise tree/crop yield in such agroforestry systems, adaptive management is needed to reduce competition and improve spatial resource availability. Wider adoption will require initial incentives or loans, knowledge exchange and market links.

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ISSN 1652-6880
ISBN (print version) 978-91-8046-178-8
ISBN (electronic version) 978-91-8046-179-5