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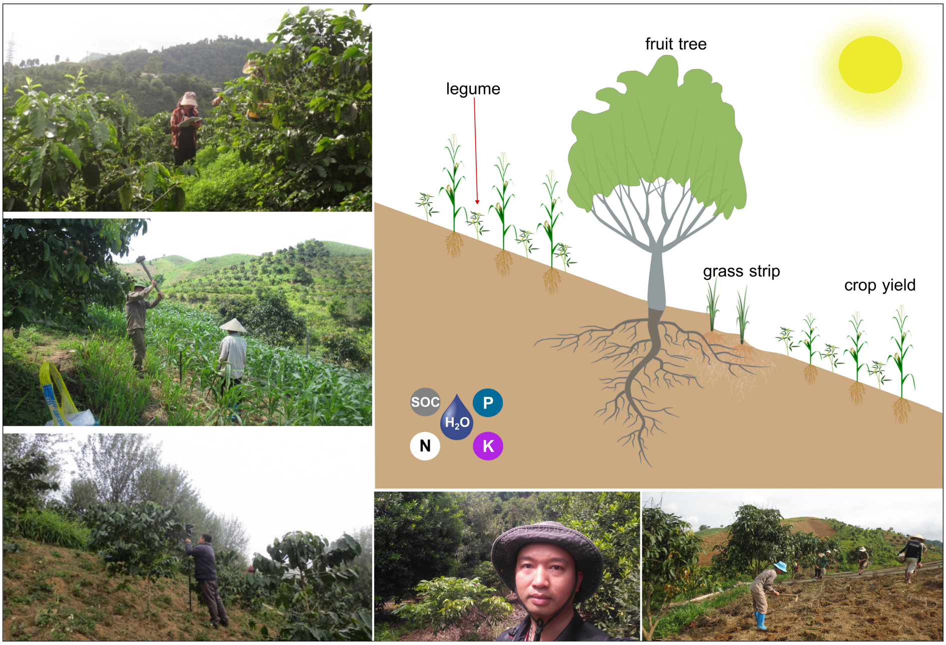
Resource availability and system adjustments for enhanced productivity in fruit tree-based agroforestry on sloping land

HUU THUONG PHAM



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HUU THUONG PHAM
Faculty of Natural Resources and Agricultural Sciences
Department of Crop Production Ecology
Uppsala

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Cover: Illustration of the fruit tree-based agroforestry on sloping land. Photos from northwest Vietnam from upper left: Researcher and farmers recording tree/crop growth, collecting soil samples, measuring light using Hemiview system, myself (Huu Thuong Pham), and farmers sowing maize in the agroforestry experiment.

(Illustration and photos: Huu Thuong Pham)

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Swedish University of Agricultural Sciences, Department of Crop Production Ecology, Uppsala, Sweden

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Resource availability and system adjustments for enhanced productivity in fruit tree-based agroforestry on sloping land

Abstract

Sloping lands are crucial for global food security but are increasingly degraded due to unsustainable farming practices. Agroforestry (AF) can offer a more sustainable solution to this problem. The overall aim of this thesis was to describe the distribution of key resources (light, water, nutrients) affecting crop performance in 3–6-year-old contour cropped and fruit tree-based AF systems on sloping land (15-35°) in Northwest, Vietnam, and to identify possibilities for enhanced complementarity of resource use. These AF systems include fruit trees, maize/coffee, and forage grass. The study also aimed to evaluate and propose system redesigns with incorporated understory legumes to improve resource use and enhance productivity. Slope significantly reduced incident light to crops downslope of the tree rows. Available soil water content (ASWC) increased more upslope than downslope of the grass strips after rainfall events. Differences along the slope were most evident during the dry season, when ASWC was lower in the zones with grass strips compared to other zones. Soil organic carbon (SOC), total nitrogen (N), and available phosphorus (P) and potassium (K) were lower in grass strips and crop zones below grass than in the tree row zone and in zones farther away from grass strips on both up- and downslope sides. The growth and yield of maize and coffee were significantly lower on the downslope than upslope of the tree rows. The effects of trees and grass on crops decreased as the distance between trees and crops increased. Integrating understory legumes into AF systems increased SOC and N in the soil but reduced P and K. Modelling simulations showed the potential of legume relay-cropping for resources optimisation and productivity improvement. This study concluded that practicing AF on sloping land influences resource distribution and crop productivity and discusses the way forward for optimising the use of light and water, and suitable nutrient managements strategies.

Keywords: Coffee yield, Competition, Complementarity, Light distribution, Maize yield, Resource optimization, Sloping land, Soil water, Tree shade

Author's address: Huu Thuong Pham, SLU, Department of Crop Production Ecology, P.O. Box 7403, SE-7050 07 Uppsala, Sweden | World Agroforestry (ICRAF) Vietnam, 13th Floor, HCMCC building, Thuy Khue Street, Tay Ho district, Hanoi, Vietnam

E-mail: huu.thuong.pham@slu.se; p.thuong@cifor-icraf.org

Resurstillgång och systemanpassningar för ökad produktivitet i fruktträdsbaserat agroforestry på sluttande mark

Sammanfattning

Odling på bergssluttningar är avgörande för den globala livsmedelsförsörjningen, men markförstöring på grund av ohållbara jordbruksmetoder är ett allt större problem. Agroforestry (AF) kan bidra till en lösning på detta. Det övergripande syftet med denna avhandling var att beskriva den spatiala fördelningen av viktiga resurser (ljus, vatten, näringsämnen) som påverkar grödan i 3–6-åriga fruktträdsbaserade AF-system på mark med 15-35° lutning i nordvästra Vietnam, och att identifiera möjligheter till ökad komplementaritet i resursutnyttjande. Dessa AF-system inkluderar konturodlade fruktträd, majs/kaffe och remsor av fodergräs. Studien utvärderar och föreslår även inkludering av baljväxter som bottengrödor för att optimera resursanvändningen och förbättra produktiviteten. Markens lutning minskade det infallande ljuset till grödorna nedanför trädraderna. Växttillgängligt markvatteninnehåll (ASWC) ökade mer ovan än nedan gräsremsorna efter regn. Skillnaderna längs sluttningen var tydligast under torrperioden, då ASWC var lägre inom gräsremsorna jämfört med andra systemzoner. Markens halt av organiskt kol (SOC), totalkväve (N) och tillgänglig fosfor (P) och kalium (K) var lägre i gräsremsorna och odlingszonerna direkt nedanför dessa än i trädraderna och längre bort från gräset. Tillväxten och avkastningen hos majs och kaffe var signifikant mindre nedan än ovan trädraderna. Trädens och gräsets effekt på grödorna minskade när avståndet ökade. Integrering av baljväxter som bottengröda ökade SOC och N i jorden men minskade P och K. Modellsimuleringar visade att reläodling av baljväxter har potential att optimera resursutnyttjandet och öka produktiviteten. Slutsatsen är att AF på sluttande mark påverkar resursfördelningen och grödornas produktivitet. I avhandlingen diskuteras också vägen framåt för att optimera utnyttjandet av ljus och vatten, samt lämpliga strategier för näringsförsörjning.

Nyckelord: Fruktträdsjordbruk, Komplementaritet, Konkurrens, Kaffeskörd, Ljusdistribution, Majsskörd, Markvatten, Resursoptimering, Skuggning, Sluttning

Tối ưu tài nguyên và điều chỉnh hệ thống để nâng cao năng suất trong nông lâm kết hợp dựa vào cây ăn quả trên đất dốc

Tóm tắt

Đất dốc đóng vai trò quan trọng đối với an ninh lương thực toàn cầu nhưng ngày càng bị thoái hóa do các hoạt động nông nghiệp không bền vững. Nông lâm kết hợp (NLKH) là một phương thức sử dụng đất có thể giải quyết được thách thức về canh tác bền vững trên đất dốc. Luận án này đánh giá sự phân bố của các nguồn tài nguyên quan trọng (ánh sáng, nước, dinh dưỡng) ảnh hưởng đến năng suất cây trồng trong các hệ thống NLKH canh tác theo đường đồng mức và dựa vào cây ăn quả (3-6 tuổi) trên vùng đất dốc (15-35°) ở Tây Bắc, Việt Nam. Các hệ thống NLKH bao gồm cây ăn quả, ngô/cà phê, và cỏ chăn nuôi. Nghiên cứu cũng đánh giá và đề xuất giải pháp cải thiện hệ thống bằng cách kết hợp với cây họ đậu dưới tán để tối ưu hóa việc sử dụng tài nguyên và tăng năng suất. Kết quả cho thấy đất dốc làm giảm lượng ánh sáng chiếu tới ngô/cà phê phía dưới dốc hàng cây ăn quả. Hàm lượng nước cây trồng có thể sử dụng trong đất ở phía trên băng cỏ cao hơn so với phía dưới băng cỏ sau các trận mưa. Trong mùa khô, lượng nước trong đất ở băng cỏ và bên dưới băng cỏ thấp hơn rõ rệt so với các vị trí khác trên sườn dốc. Hàm lượng các bon hữu cơ trong đất (SOC), nitơ tổng số (N), lân (P) và kali (K) linh động ở các băng cỏ cũng thấp hơn so với trong hàng cây và các vị trí xa băng cỏ ở cả sườn dốc trên và dưới băng cỏ. Ngô và cà phê sát bên dưới băng cỏ có chỉ số sinh trưởng và năng suất kém hơn so với sườn dốc bên trên của hàng cây và băng cỏ. Ảnh hưởng tiêu cực đối với ngô và cà phê giảm khi khoảng cách đến hàng cây và băng cỏ tăng lên. Kết hợp cây họ đậu dưới tán vào NLKH làm tăng SOC và N trong đất nhưng làm giảm P và K sau 3 năm thí nghiệm. Kết quả mô hình hóa cho thấy tiềm năng của trồng xen cây họ đậu để tối ưu tài nguyên và cải thiện năng suất. Nghiên cứu này kết luận ảnh hưởng của đất dốc đối với sự phân bố tài nguyên và năng suất cây trồng trong hệ thống NLKH, đồng thời thảo luận một số giải pháp tiềm năng để tối ưu hóa tài nguyên ánh sáng và nước, cũng như các chiến lược quản lý chất dinh dưỡng phù hợp.

Từ khóa: Cạnh tranh, Đất dốc, Năng suất cà phê, Năng suất ngô, Nước trong đất, Phân bố ánh sáng, Sự che bóng bởi cây, Thúc đẩy, Tối ưu hóa tài nguyên,

Preface

Having been born in an agricultural region, I grew up and spent most of my early career working with farmers in the sloping uplands of northwest Vietnam. I have witnessed the immense challenges and risks they face when cultivating on steep slopes. Despite a few limited inventions in hybrid crop cultivars and machinery, many difficulties persist, and farmers continue to struggle day by day.

I have always believed that by working together, researchers and farmers, we can find solutions to their challenges. The experiences and knowledge shared between farmers and researchers contribute to more sustainable cultivation on slopes. This PhD thesis presents just a small part of the broader projects I have been involved in implementing on sloping uplands.

This work would not have been possible without the collaboration of farmers, SLU, ICRAF Vietnam, local authorities, and other partners. I am also deeply grateful to my family for their unwavering support during difficult times.

Dedication

To my grandparents, my parents and my little family including my sons Pham Tran Huu Thanh and Pham Duy Khang, my daughter Pham Minh Ngoc, and my wife Doan Thu Huong

Gửi tới ông bà, bố mẹ của tôi; và tới gia đình nhỏ thân yêu ở đó có các con tôi Phạm Trần Hữu Thành, Phạm Duy Khang, Phạm Minh Ngọc, và vợ tôi Đoàn Thu Hương

Life is like riding a bicycle. To keep your balance, you must keep moving.

Albert Einstein

The best way to take care of the future is to take care of the present moment.

Thich Nhat Hanh

Contents

List of publications

This thesis is based on the work contained in the following papers:

I. Pham, H.T., La, N., Öborn, I., Bergkvist, G., Mulia, R, Dahlin, S. (2024). Light distribution at the fruit tree-crop interface and consequences for yield in sloping upland agroforestry. *Heliyon*, vol. 10 (2024) e38655, p. 1-17.

II. Pham, H.T., Barron J., Bergkvist, G., Öborn, I., La, N., Mulia, R, Dahlin, A. S. (2025). Tree rows and grass-strips increase water availability in fruit tree-crop agroforestry systems on sloping land. International Journal of Agriculture and Food Research. (Submitted)

III. Pham, H.T., Bergkvist, G., Öborn, I., La, N., Mulia, R, Dahlin, A. S. (2025). Understory legume crops smother weeds and enhance soil fertility in fruit-coffee-grass agroforestry on sloping land. Field Crops Research. (Submitted)

IV. Pham, H.T.[1], Mulia, R.[1], Smethurst, P., Salvan G.A.R., Dahlin, A. S., Bergkvist, G., La, N., Öborn, I. (2025). Resource interactions affect maize productivity in agroforestry scenarios on sloping land: An assessment using APSIM modelling. (Manuscript) ([1] *These authors share first authorship*)

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The contribution of HUU THUONG PHAM to the papers included in this thesis was as follows:

I. Main author. Planned the study together with the supervisors (co-authors). Responsible for management of the field experiments from 2022. Collected data with farmers, local partners, and ICRAF staff. Analysed data with discussion with supervisors. Wrote the draft and revised the manuscript together with co-authors.

II. Main author. Planned the study together with the supervisors (co-authors). Responsible for management of the field experiment from 2022. Collected data with farmers, local partners, and ICRAF staff. Analysed data in discussion with co-authors. Wrote the draft and revised the manuscript together with co-authors.

III. Main author. Designed the agroforestry field experiments and planned the study together with the supervisors (co-authors). Carried out the field experiment and collected data together with local partners and farmers from 2020. Analysed data in discussion with supervisors. Wrote the draft and revised the manuscript together with co-authors.

IV. Sharing first authorship with Rachmat Mulia. Collected data together with farmers, local partners and ICRAF staff. Built, ran, and evaluated model in discussion with co-authors. Contributed writing in Materials and Methods, Results, and Discussions parts. Revised the manuscript together with co-authors.

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Abbreviations

AF	Agroforestry
APSIM	Agricultural Production Systems sIMulator
ASWC	Available soil water content
FAO	Food and Agriculture Organization
IWM	Integrated Weed Management
K	Potassium
LAI	Leaf Area Index
Longan-mango-maize-AF	Longan-mango-maize-grass agroforestry experiment
Longan-AF	Longan-maize-grass agroforestry sub-treatment
Mango-AF	Mango-maize-grass agroforestry sub-treatment
N	Nitrogen
P	Phosphorus
PAR	Photosynthetically Active Radiation
Plum-coffee-legume-AF	Plum-coffee-grass-understory legume agroforestry experiment
SC	Sole coffee
SDG	Sustainable Development Goal
SM	Sole maize
SOC	Soil organic carbon
SOM	Soil organic matter

Sontra-coffee-AF	Sontra-coffee-grass agroforestry experiment
UN	United Nations
VSW	Volumetric soil water

1. Introduction

Society is currently facing monumental challenges to achieve the 17 Sustainable Development Goals (SDGs) set by the United Nations (UN) (UN, 2024). The world population is increasing rapidly and is expected to reach 10 billion by 2050 (UN, 2019), with a decrease in the proportion in working age. Sufficient food to feed every person equates to 14.9 million ton, 1.6 times higher than present world production. This means that humans must produce significantly more food with a smaller number of labours compared to the past (UN, 2019).

According to the FAO statistics (2018), the total global agricultural land in 2018 was more than 4.13 billion hectares, accounting for 33.5% of the total land area. In Asia, the agricultural area accounts for 50% of the total area (FAO, 2020). These extensive areas are crucial sources of livelihood and food production, with more than 70% of the low-income population in the world dependent on them (Farooq et al., 2023).

The shortage of arable flat land has led to the exploitation of vast areas of sloping land (Dudley & Alexander, 2017; Sanders, n.d.), which accounts to about one-fifth of the world's total land area (Y. Li et al., 2019; Nair et al., 2021c). Agriculture in these areas is predominantly characterised by smallholder farming, with traditionally diversified livelihoods (e.g. crop, forestry, livestock) (Dach et al., 2013), and plays a key role in providing food, fighting poverty, and contributing to the SDGs (Panda et al., 2023).

Agriculture on sloping land faces numerous challenges. Shortage of food and income leads farmers excessively cultivating sloping land. Poverty hinders the ability of local farmers to adapt to more sustainable farming practices (Dach et al., 2013). Poor infrastructure (Dach et al., 2013; FAO, 2015) increases transportation and agricultural systems' maintenance costs, resulting high production costs. Steep slopes aggravate soil erosion, an effect that may be accentuated by increased frequence and severity of extreme rainfall events (Feng et al., 2022). Each of these issues must be addressed with reasonable solutions to ensure sustainable development in sloping upland.

Agroforestry (AF) is a land-use approach that allows for a wide range of products from trees, bushes, annual crops, and/or livestock (Gordon et al., 2018). It has been advocated for as a sustainable substitute for sole cropping systems to increase productivity, food, and nutritional security, preserve landscapes, and reduce environmental degradation (Nair et al., 2017, 2021a). Therefore, AF can help to transform agriculture towards sustainability, as well as mitigate and adapt to climate change to achieve the SDGs (Plieninger et al., 2020; van Noordwijk, 2019). Through its greater structural and functional complexity (Jose, 2012), it can be more efficient in capturing and utilising resources, including light, water, and nutrients (Plieninger et al., 2020) than sole crops. Agroforestry is especially well-suited to sloping land (Hoang et al., 2017; Ong et al., 2015) due to its ability to prevent soil erosion (Do et al., 2023), conserve water, mitigate the effects of climate change (Nair & Garrity, 2012), and improve system productivity and production (Do et al., 2020).

Despite the advantages of AF systems, farmers are concerned about the disadvantages, such as higher labour requirements, investments, and competition between system components (Do et al., 2020; Fischer & Vasseur, 2002). Indeed, competition for water (Everson et al., 2009), nutrients (Jose et al., 2000), light (Abbasi Surki et al., 2020), as well as increased pest and disease damage (Schroth et al., 2000) can occur and these are important determinants of the system's performance. Inappropriate system management can lower yield (Sarkar et al., 2024) and reduce farmers' interest in AF cultivation. Thus, understanding the resource distribution and utilisation in the system would benefit AF system design and management towards sustainability and improve farmers' livelihood. Considering the importance of upland regions and the significance of AF practices, it is vital to enrich this knowledge, thereby providing evidence for planning, and upscaling the AF practices on sloping land.

2. Aims and objectives

The overall aim of this thesis was to determine the effect of slope position on resource availability, crop performance, and the impact of understory legume in fruit tree-base agroforestry (AF) systems on sloping land in Northwest, Vietnam. These systems include fruit trees, maize/coffee, and forage grass. The study also aimed to evaluate the influence of three understory legume crops on system performance and soil fertility, model the AF system's performance on sloping land, and test redesign options to optimise resource use and enhance system productivity.

The specific objectives were to:

(1) Assess light distribution and interception in two fruit tree-based agroforestry systems to identify excessive competition or the potential of additional system components for resource optimisation (Paper I).

(2) Assess the spatial and temporal distribution of soil water in a fruit tree-based agroforestry system, and how it was affected by system components (Paper II).

(3) Assess the effect of understory legume in a fruit tree-based AF system on system performance and soil fertility (Paper III).

(4) Assess the potential of modelling resource distribution and crop productivity in maturing fruit tree-based AF systems on sloping upland using an Agricultural Production System sIMulator (APSIM). Evaluate scenarios with different relay-cropping options for enhancing system performance (Paper IV).

3. Background

3.1 Agroforestry for sustainable slopping land

3.1.1 Definition of agroforestry

Agroforestry integrates woody plants into agricultural systems, thereby enabling a wide range of products from trees, crops and livestock (Gordon et al., 2018; Nair et al., 2021b). It fosters economic and ecological interactions between components throughout at least one year of its life cycle (Leakey, 1996; Nair et al., 2021b, 2021a). The ecological (both structural and functional) and economic benefits of AF systems can be greater than those of sole cropping systems (Atangana et al., 2014). However, these benefits can vary between different systems (Kay et al., 2019) and contexts as well as over time, as AF may initially show a decrease of overall crop yield, since it takes time to produce outputs from the trees (Cole, 2010).

Depending on the priorities and focus of the projects, AF is classified based on different criteria such as structure, function, ecology and socio-economy (Atangana et al., 2014; Nair, 1985). Structural classification of AF refers to spatial and temporal arrangement, and vertical stratification of the different components. This classification is commonly used and simple to understand by individuals with varying levels of knowledge. For example, Figure 1 shows a fruit tree-based AF on sloping land, which integrates fruit trees, maize, and grass strips.

Figure 1. A fruit tree-maize-grass agroforestry (AF) system in Mai Son district, Son La province, Vietnam. Photo was taken in June 2023.

3.1.2 Agroforestry on sloping lands

Several integrated systems have been developed to replace slash-and-burn cultivation and continuous sole-cropping on sloping land. These techniques have evolved from contour strip cropping and alley cropping to more complex multi-strata AF.

The contour strip cropping system grows alternating strips of row crops and forage/grass along the contour lines. This practice can effectively reduce runoff velocity (Chalise et al., 2019), decrease sediment transport capacity and soil erosion (Labrière et al., 2015), enhance water infiltration, and improve soil productivity on sloping land (Thapa et al., 2000). On steeper slopes, this practice needs to be combined with other conservation practices, such as reduced tillage, crop residue mulch (Blanco-Canqui & Lal, 2010), or terraced planting (Durán Zuazo et al., 2020).

Alley cropping involves growing crops between rows of trees or shrubs that are regularly pruned to minimise shading of the short-term crops whilst the pruning residues are returned to the soil as mulch or green manure. This system could potentially reduce runoff and soil erosion (Agus et al., 1999; Do et al., 2023), improve nutrient use efficiency, sequester carbon, increase biodiversity (Elevitch et al., 2018), and optimize crop yields on sloping lands

(Lei et al., 2021) for both short- and long-term production (Kremer & Kussman, 2011). Alley cropping has been widely expanded in many countries (Kinama et al., 2007; Lei et al., 2021; Ng et al., 2008; Osman, 2018), incorporating a diverse range of tree and crop species (Kremer & Kussman, 2011; Molyneux et al., 2012).

Tree-based AF, notably the fruit tree-based system, is widely practiced due to its diversification and the livelihood support it provides farmers with. In Asia and the Pacific, fruit trees, coffee, and rubber are intercropped with grass strips or pineapple in the contour line (Craswell et al., 1997; Duffy et al., 2021). In north-west Vietnam, fruit tree cultivation has expanded rapidly in recent years (General Statistics Office, 2021), and is often integrated with crops such as maize, coffee, and cassava, as well as strips of fodder grass along the contour lines. In China, fruit trees are often intercropped with short-term crops or medicinal plants (Chang et al., 2018). In Pacific Island countries, farmers have adapted fruit tree-based AF by replacing grass strips with e.g. pineapple, kava, or legumes (Wairiu, 2017).

The multi-strata system on sloping land is characterised by a complex, multilevel contour system. It can consist of crops, leguminous or other hedgerows, and trees of varying canopy heights. This AF system has the potential to provide both environmental and economic benefits (Kumar et al., 2018) and has therefore become common across Asia including Southeast Asia (Folving & Christensen, 2007; Tacio, 1993). However, similar to fruit tree-based AF, farmers face trade-offs, including high labour requirements and a decline in short-term income, along with challenges such as knowledge gaps in designing and managing the system (Folving & Christensen, 2007; Kinama et al., 2007). Therefore, the expansion of this AF system requires sufficient knowledge and extension services to adapt recommendations to variations in elevation, climate, and topography (Kumar et al., 2018). To bridge income gaps, farmers must find alternative options (e.g. adding another short-term crop) to enable fast economic returns, particularly in the early stages of these systems (Ly et al., 2012).

3.1.3 Advantages of agroforestry

Many studies examining AF have reported positive effects through both direct and indirect ways (Kuyah et al., 2016, 2019). Direct benefits of AF include improving soil nutrient cycling and increasing SOC (Carsan et al., 2014; Dubiez et al., 2019; Gebre et al., 2021; Koutika & Richardson, 2019;

Zake et al., 2015) through increased inputs of litter, residue, and/or compost (Kinama et al., 2007; Mokgophi et al., 2020). It can also enhance nutrient cycling by reducing soil erosion (Do et al., 2023), minimising nutrients lost through leaching (Zhu et al., 2020), and promoting N accumulation via symbiotic N_2 fixation by legume species (Mokgophi et al., 2020; Ong et al., 2015; Rosenstock et al., 2014). AF systems also contribute to soil water regulation by increasing water infiltration (Anderson et al., 2009), preventing runoff (Zhu et al., 2020), minimising groundwater flow (Oliver et al., 2005), and reducing evaporation (Ilstedt et al., 2016). Moreover, AF can improve the microclimate, create a favourable environment for crops (de Carvalho et al., 2021), and enhance system biodiversity (Torralba et al., 2016) thus strengthening ecological services (Bettles et al., 2021) that can support other benefits.

In terms of indirect benefits, AF can reduce weed growth by increasing shading (Brandt et al., 2016; Song et al., 2020). It also helps to control pests and disease by blocking their movement and harbouring natural enemies (Schroth et al., 2000). As a consequence of these advantages, AF has the ability to enhance climate change resilience (Lasco et al., 2014; van Noordwijk et al., 2021) and contribute to food security (Saqib et al., 2019). Additionally, AF systems provide diverse products (Mokgophi et al., 2020; Rosenstock et al., 2019) and have higher overall productivity than sole-cropping systems (Ong et al., 2015).

3.1.4 Potential disadvantages of agroforestry

When an agroforestry system is not properly designed or managed, it can lead to negative effects. The biggest concern with this is competition between tree and crop components for resources such as light, water, and nutrients. For example, trees can deplete the soil nutrients of crop components (Isaac et al., 2007). Additionally, shading from the trees can reduce crop photosynthesis (Wang et al., 2021) and create favourable environments for certain pests and/or diseases (Roberts & Paul, 2006). Continuous cultivation in the AF systems can also lead to soil compaction depending on the intensification (e.g. cacao AF, Suárez et al., 2021), trampling caused by increased movement during tree/grass management (Yuejin et al., 2022), and mechanisation levels (e.g. timber-cherry AF, Spinelli et al., 2019). Such compaction can reduce infiltration capacity and contribute to soil degradation.

Potential negative impacts can result in lower crop yields in AF systems compared to sole-crop systems, as reported by several researchers (Do et al., 2020; Odhiambo et al., 2001). Further, AF usually requires higher initial investments, especially during establishment, such as a greater need for labour time and resources for purchasing and planting tree seedlings (Do et al., 2020). Consequently, it takes longer to reach the break-even point, posing challenges for smallholder farmers (La et al., 2016). These potential disadvantages of AF can reduce farm income, at least in the short-term perspective, and resultingly discourage the upscale of this land-use (Agus et al., 1999; Sun et al., 2008).

3.2 Resource distribution and utilisation

3.2.1 Sunlight as the indispensable resource for plant life

The average light energy reaching Earth is 1369 W/m^2, with 99% of this energy concentrated within the wavelength range of 250 to 2500 nm. (Campillo et al., 2012; Liang et al., 2012). Only a part of the incident light can be intercepted and used by plants for photosynthesis which is the visible wavelength range of 400 to 700 nm, known as photosynthetically active radiation (PAR), which accounts for approximately 50% of total incident light. Only about 5% of PAR is converted to carbohydrate through photosynthesis for biomass production. The remainder is lost through reflection, transmission, heat dissipation, and other metabolic processes (Campillo et al., 2012). In general, plants' biomass production is strongly correlated with light interception (Sinclair, 1995; Wang et al., 2015). To optimise productivity, farming systems are typically designed to maximise the light interception (Chen et al., 2021).

Light incidence to the crop canopy is modified in agroforestry compared with sole-cropping systems (Meek et al., 1984; Rigueiro-Rodróguez et al., 2009). Tree canopies intercept 10-90% of total incident light (Hassika & Berbigier, 1998), and <10% is reflected, whilst the rest is available for absorption by cultivated crops and weeds (Hassika & Berbigier, 1998). The proportion of light intercepted by tree and crop components depends on their canopy structure (Charbonnier et al., 2017), the location of the shaded area (Meloni & Sinoquet, 1997; Onoda et al., 2014; Sinclair, 1995), the distance between trees (Abbasi Surki et al., 2020), and the ability of crops to fill and utilise gaps. In addition, tree leaf area index (LAI), leaf thickness, leaf inclination (Simioni et al., 2013), and tree height (Bastiaans & Kropff, 2017) are crucial factors determining light interception and transmission to crops beneath the tree canopy.

Light is first intercepted by higher strata trees; therefore, less light reaches the lower crop canopies. Thus, trees and crops interact for this resource through competition or complementarity. The interaction influences the light intensity, which determines the photosynthesis of the canopy, and the light quality, which controls the morphology of the plants such as stem elongation, apical bud dominance, branch reduction, leaf thinning, leaf distribution, etc. (Simioni et al., 2013). The responses to light modification by trees differ between crop species (Charbonnier et al., 2017; Kishore et al., 2021; Soto-Pinto et al., 2000; Zhang et al., 2008). The photosynthetic capability varies considerably among species, between individuals within a sole-cropping plantation, and even among the leaves of the same plant (Craine & Dybzinski, 2013). In shaded conditions, lower plants become elongated to reach the higher canopy where they can receive more light. Crops under shade reduce their LAI, change leaf area distribution, and decrease biomass, resulting in reduced yield (Baumann, 2001; Sinclair, 1995).

Research on light incidence and utilisation in AF has focused on improving system productivity by minimising competition between components and optimising light capture (Kishore et al., 2021; Slattery & Ort, 2021). On flat land, the sun’s position (Tsubo et al., 2001) which is related to latitude, seasonal variation (the declination), and time of the day (Miller, 1981) are the most important factors that control incident light into the system. Tree and tree/crop row arrangement (e.g. row orientation and spacing) also affect light distribution (Aragão et al., 2023; Mattera et al., 2013). Trees and crops are usually arranged in a north-south orientation to optimise light capture and growth (Tsubo et al., 2001). Incident light to crops and crop productivity decline with decreasing distance to tree rows (e.g. Kishore et al., 2021; Qiao et al., 2019, 2020; Sgarbossa et al., 2021), which is an important reason behind why farmers prune tree canopies and select suitable species to minimise light competition (Kang et al., 2014).

On sloping land, the gradient, length, and direction of the slope impact incident light (Sinclair, 1995). A steeper slope gradient and longer slope length increase the tree height for crops on the downslope side of the trees. West- or east-facing slopes have shorter day length than south-facing slopes

(Miller, 1981) and crops on such slopes therefore have less time for photosynthesising. In addition, light optimisation cannot be easily achieved via arranging tree/crop rows in a north-south direction on slopes where contour planting is recommended, primarily to reduce erosion (Juo & Thurow, 1997). The relationship between slope parameters (i.e. gradient, length, aspect, and position), the distribution of light in AF, and the crop's performance on sloping land is not well understood. Improved knowledge of light incidence and interception would be useful to develop AF systems that utilise resources more efficiently, benefiting both farmers and the environment.

3.2.2 Soil water dynamics

Although soil water accounts for a small amount of the total global water (Oki & Kanae, 2006) it plays many essential roles such as solvent for plant nutrients, temperature buffer, and metabolic activator (Filipović, 2020). It also provides water for plants and is often replenished naturally by rain. However, the property of the soil affects its ability to infiltrate and retain water. The flux of infiltration (or infiltrability) is relatively high when water is first applied to dry soil, then diminishes asymptotically toward a constant rate called saturated hydraulic conductivity. When the water supply exceeds infiltrability, it forms runoff on the soil surface, which is affected by several factors (e.g. slope angle, slope length, soil structure, vegetation characteristics, etc.) and causes soil degradation due to erosion. A dense vegetative cover and/or barriers prevent runoff (Sjöman & Gill, 2014), thus increasing the amount of water infiltrated into the soil. The plant cover also affects evaporation from the soil surface and transpiration from vegetation, both of which are key for the water cycle, growth, and development of plants (Kirschbaum & McMillan, 2018). Plants can only capture the available soil water content (ASWC) which is bound between field capacity and the wilting point. Soil water availability is determined by soil texture, structure, organic matter content (Olorunfemi et al., 2016), temperature (Naveed et al., 2019), and salt concentration (Leelamanie & Karube, 2013). To improve ASWC to plants, practices such as retaining crop residues, enhancing mulch, and using compost have been recommended (Wang et al., 2021). In addition, a limited- or no-tillage practice will protect the soil structure and prevent soil from degradation processes (James & Merfield, 2021), leading to improved infiltration and soil water availability.

Agroforestry integrates trees and crops within the same field, and because both these components require water, trees may compete and reduce the amount of water available to crops and vice versa (Craine & Dybzinski, 2013). Plant roots, notably the fine roots (≤ 2 mm), and their distribution are important for water uptake and the water competition between system components (Craine & Dybzinski, 2013; Smithwick et al., 2014) as they limit the ASWC to other species in AF systems (Jose et al., 2018). The disadvantage of water competition between tree/crop components is often observed in the AF system. However, interactions can also be beneficial as certain tree species can enhance ASWC and soil water use efficiency (Muñoz-Villers et al., 2020; Wu et al., 2016; Yang et al., 2020). The differences in water use is an important feature to consider when selecting trees/crop components as trees with deep roots (e.g. mango, Santos et al., 2014) compete to a lesser degree with annual crops than trees with shallow root systems (e.g. longan; Huang et al., 2020). Plants that use less water or accumulate and retain water, such as bananas (Abigaba et al., 2024) or fig tree species (Sarath et al., 2023), are recommended for intercropping in AF systems.

Tree roots can increase soil porosity, infiltration, and water retention, and reduce water stress during dry periods (Ong et al., 2015). Upper-story trees can reduce light reaching the soil and create a cooler micro-climate, thereby, reducing soil evaporation, crop transpiration and water demand (Lin, 2010). Moreover, grass strips on slopes can prevent runoff (Tuan et al., 2014), increasing the amount of water entering soil and thus ASWC.

Through appropriate design and management of AF, the complementarity of components can be optimised and address the trade-off between water resource competition and crop productivity (Oliver et al., 2005). The system design should consider the spatial-temporal distribution of ASWC and other resources (Malézieux et al., 2009). However, there is still insufficient information regarding the effect of combining trees (e.g. fruit tree), crops (e.g. maize), and grass strips in a multi-strata AF system on the spatial-temporal distribution of ASWC in sloping land. Studies on water interaction in AF systems are necessary to understand the mechanisms and improve system sustainability and efficiency (Craine & Dybzinski, 2013).

3.2.3 Plant nutrients in the soil and their use

Plants require about eighteen mineral elements, of which nitrogen (N), phosphorus (P), and potassium (K) are required in the largest quantities. They take up nutrients primarily as ions such as NO_3^-, NH_4^+, HPO_4^{2-}, $H_2PO_4^-$, PO_4^{3-}, and K^+ (Mitra, 2017). Within the soil, nutrients are bound in solid minerals (determined by parental material and their weathering products, Havlin et al., 2006) and soil organic matter (SOM) composed of plant and animal residues and organic compounds synthesised by soil microbes (Brady and Nyle, 2016), exchangeably adsorbed on the surfaces of soil particles, and dissolved in the soil solution. Although generally present in relatively small amounts, SOM plays an important role in nutrient cycling. Nutrients such as N and P are integral components of SOM and can be released into the soil solution through the mineralisation process wherein SOM is decomposed, making them available in forms that plants can absorb (Brady & Nyle, 2016). In addition to the nutrient pools in the soil, certain plants can access N from the atmosphere through symbiotic N_2 fixation, such as leguminous species and associated bacteria (Graham & Vance, 2000).

The nutritional requirements of trees and crops depend on the species, cultivar, amount of production, soil fertility, climate, and crop treatments (De Mello Prado, 2021). Further, nutrients are removed from the soil during crop harvesting on arable land. These removals must be replaced through fertilisation to ensure a sufficient yield for the next season (De Mello Prado, 2021; Mitra, 2017) and to maintain soil fertility.

In agroforestry, integrating trees and/or grass into crop fields can enhance soil fertility and nutrient cycling (Ong et al. (2015). However, the positive effect of trees on soil nutrients often builds over time and involves reduced losses from erosion and leaching, processes of nutrient uptake by trees (also) from deep soil layers which return to the topsoil in the form of residues, followed by OM decomposition and nutrient mineralisation. Meanwhile, competition can be a major constraint in AF systems in the short-term (e.g. Wei et al., 2024).

The interaction in nutrient demand and uptake between tree and crop components in the AF system depends on their root traits, including distribution, rooting depth, and morphological and physical plasticity (Burgess et al., 2022). To optimise nutrient use and reduce competition, the roots of trees should be positioned in different soil layers than the crops. For instance, the roots of walnut trees grew deeper (>50cm) to access a water source that was unavailable to crop roots when intercropped with durum wheat (Cardinael et al., 2015). In contrast, Dou et al. (2022) reported a reduction in soil nutrients and maize yield near apple trees, where N competition may be the primary constraint (Mead et al., 2010).

Agroforestry is usually recommended for low fertility or degraded soils, particularly on sloping land. Integrating N_2-fixing tree or crop species can enhance soil fertility and benefit crops when the residues or shoot and root litter of the N_2 fixing plants decompose and the N is mineralised. However, to provide considerable N inputs, other nutrients such as P and K must be present in sufficient concentrations to support the vigorous growth of the N_2 fixing plants. Other agronomic techniques, such as pruning, minimum tillage, and weeding, also play important roles in improving soil nutrient management and availability and reducing competition (Ong et al., 2015). Enhancing soil fertility is a fundamental step towards increasing crop productivity, but further research is needed to develop economically viable strategies for minimising nutrient competition in agroforestry.

3.3 Managing resource competition

3.3.1 Agroforestry system design and management

The concept of managing resource competition in AF should be incorporated from the early stage of the system design, planning, and establishment (Ong et al., 2015). Additionally, landscape AF design requires a strong engagement of farmers. Tree and crop arrangements typically follow the types of the aforementioned AF patterns. On sloping land, contour tree rows and grass strips intercropped with annual crops are common AF practices.

The selection of the main tree and crop species and their arrangements in the system depend on the environmental conditions and farmer preference (Ong et al., 2015). Having adequate available information regarding resource partitioning and use efficiency would allow for the optimum spacing arrangement, taking farmers´ specific objectives into account. Further, choosing suitable sowing or planting methods, such as intercropping, relay-cropping, or rotation, can influence resource distribution, utilisation, and competition (Widiyanto & Hani, 2021). The system design also encompasses careful tree species selection to prevent interference with crops. For example, tree and crop components can be intentionally arranged to exploit resources in different soil depths and/or spatial zones, or shade tolerance crops/cultivars can be planted near tree rows (Widiyanto & Hani, 2021). Additionally, integrating local species that are more adaptable to e.g. dry season is encouraged (Lelamo, 2021).

Another key objective of resource management is system maintenance. This involves managing tree and crop densities and manipulating canopy size and shape to maintain biomass productivity whilst minimising competition for light (Kang et al., 2008), water (Jackson et al., 2000), and nutrients (L. Isaac et al., 2003). Root pruning has been suggested to reduce competition towards other components (Hou et al., 2003), although this requires hard labour. However, farmers are often reluctant to adopt a new technique unless its benefits will offset the labour cost associated with pruning. Further research on pruning strategies is needed to enhance the system productivity, quality, and market value. Thinning trees/crops or reducing canopy density also alleviates resource competition (Lelamo, 2021). These techniques enhance nutrients that return to the soil through litter decomposition (Kurniawan et al., 2024). In the AF systems with integrated fodder grass, regular grass harvesting is crucial to avoid competition with the main components, especially during critical growth stages. Management practices should align with the tree/crop phenology and growth cycle (i.e. flowering, maturity) (Whiley et al., 2025).

3.3.2 Weeds

Weeds are undesirable plants for humans due to their negative effects on tree/crop yields (Buhler, 2014; Naylor, 2003). They can reduce agricultural yield by 18-43% (Cobb & Reade, 2010; Latif et al., 2021). The primary mechanism of their negative impact is resource competition, as many weeds share similar traits with crops (Cobb & Reade, 2010), rendering management more challenging. On the other hand, weeds can also benefit biodiversity by providing habitat and food sources for e.g. beneficial insects and birds (Marshall et al., 2003). Therefore, implementing suitable weed management strategies is essential.

In AF systems, trees/crops and weeds share the same resources that are necessary for growth. Many weeds may compete for light by growing taller than the crop canopy, whilst others change leaf angle to maximise light interception, and increase chlorophyll content to enhance photosynthesis

(Deiss et al., 2018; La Notte et al., 2020). Additionally, certain weeds can absorb water more rapidly than crops, making them more efficient in water use and contributing to drought conditions that negatively affect system components. Similarly, certain weeds have higher nutrient demands than trees/crops (Latif et al., 2021) and can take up nutrients more effectively than crops during the early stages, thus reducing nutrient availability for crops (Bastiaans & Kropff, 2017).

Weed management is an indispensable activity and accounts for an important part of the costs in AF (Latif et al., 2021). Effective weed control requires a thorough understanding of weed biology and life cycles of weeds (e.g. germination, spread). Traditional weeding practices include hoeing, harrowing, or burning, whilst the use of herbicides and mechanisation is increasing (Cobb & Reade, 2010), however, the latter may be challenging on sloping land. These methods help remove weed biomass, change seed distribution, and disrupt weed growth (Buhler, 2014). Currently, chemical spraying is the most widely used weeding method due to its high efficiency and low labour costs (Cobb & Reade, 2010). However, chemical weeding harms the ecosystem by destroying beneficial organisms in the field and polluting the external environment which adversely affects human health. Additionally, crops grown in fields using chemical herbicides are not accepted on the market for organic crop products. Moreover, the rise in herbicide-resistant weeds presents another constraint of chemical weed control. The diversity of AF systems, including diverse components and varying land conditions (e.g. sloping land), further complicates weed management by increasing labour requirements and limiting machinery access. Therefore, a combination of different weed control strategies, such as Integrated Weed Management (IWM), is suggested for effective and sustainable weed control (James & Merfield, 2021). Furthermore, appropriate crop variety selection and arrangement in the field can influence weed competition within the system (Deiss et al., 2018).

3.3.3 Understory legume in agroforestry

Understory crops can help control weeds by improving soil cover, competing with weeds for nutrients, water, light, and space, and releasing allelopathic compounds that inhibit weed germination (Nichols et al., 2015), thereby generating unfavourable conditions for weed emergence (Barberi, 2002). Understory crops have been suggested for integration into AF systems as they can provide early income for farmers, diversify yields, improve resource use efficiency, and increase total productivity (Wilkinson & Elevitch, 2000). Additionally, they contribute to carbon sequestration, maintenance of soil structure, and reduction of soil erosion (Campbell et al., 2018; James & Merfield, 2021). Moreover, understory crops enhance system diversity by attracting beneficial insects and other animals whilst suppressing harmful bacteria and fungi (Barberi, 2002; Soto-Pinto et al., 2000. However, understory crops may also compete with the main crops in the AF system, causing yield reduction and/or potentially higher production costs (Nair et al., 2010).

Legumes can support weed management, according to the literature. For example, kudzu (*Neustanthus phaseoloides*) reduced the weed seed bank in the soil by 55% after 3 years when combined with maize and cassava (Ekeleme et al., 2003). Moreover, hairy vetch (*Vicia villosa*) significantly reduced weed biomass and boosted yield in hazelnut (*Corylus avellana*) orchard systems (Işik et al., 2014). In another experiment, hairy vetch could reduce winter weed biomass by up to 90% and completely suppressed summer weed biomass in peach orchards (Samedani & Rahimian, 2006). Similarly, understory *Arachis pintoi* reduced weed biomass in a plantain system by 50-70% (Pumariño et al., 2015). In addition, understory legumes improve soil conditions faster than other crops due to their ability to fix atmospheric N_2, thereby enhancing soil fertility (Tramacere et al., 2024). Understory legumes can increase soil N levels by two to three times compared to non-leguminous understory crops (Binkley, 2005).

3.4 Modelling agroforestry systems

Agroforestry is more complex than sole-crop systems due to the differences in phenology, resource demand, and management (Ong et al., 2015). It requires suitable practices to achieve sustainability, especially in upland areas (Simelton et al., 2017; Stewart et al., 2022). Whilst approaches based on field experiments are expensive and time-consuming (Barbault et al., 2024), agricultural simulation models can complement field studies and support the AF system design and management (Kraft et al., 2021) by virtually testing various hypotheses with relatively limited data requirements (Luedeling et al., 2016).

At least 32 AF models have been developed for different contexts and objectives, including Hi-sAFe, WaNuLCAS, SCUAF, APSIM, SBELTS, WIMISA, and HyPAR (Barbault et al., 2024). These models typically represent key processes such as soil-vegetation-atmospheric transfer (e.g. water balance, energy transfer) and tree-crop-interaction. Data requirements generally include climate, soil properties, management practices, tree/crop growth, and phenology (Figure 2; Barbault et al., 2024). When properly parameterised and calibrated, these tools can provide valuable information to guide recommendations for improving AF system performance.

Nevertheless, plant growth and yield are highly complex and not yet fully understood. Each species interacts with environmental conditions through physiological, phenological, biochemical, and ecological processes, and genetic mechanisms such as photosynthesis, respiration, evapotranspiration and stress tolerance. However, many resource interactions in AF are difficult to quantify, contributing to their scarcity in research (Luedeling et al., 2016). Moreover, in upland areas, slopes influence resource distribution and interactions. None of the existing models adequately represent all ecosystem processes, as noted in a review by Kraft et al. (2021).

Among the mentioned models, WaNuLCAS - water nutrient and light capture in agroforestry systems - was cited in the literature as the most complex for simulating agroforestry. It has been specifically built for and applied to various tropical AF systems (Dupraz et al., 2019; Van Noordwijk & Lusiana, 1998). However, it was designed in two dimensions (2D) and was limited in both the number of species that can be included in the model (Kraft et al., 2021) and the number of zones/positions represented in the system. Agricultural Production SIMulator (APSIM), a 2.5D model, allows for more crop species and a wider range of zones, and was originally developed as a farming systems simulator (Keating et al., 2003). More recently, APSIM has been expanded to address complex farming practices, including AF systems (Smethurst et al., 2017). Indeed, APSIM has been broadly used for designing and evaluating cropping systems, and facilitating on-farm decision-making (Keating et al., 2003) in different regions, including Asia (e.g., Balwinder-Singh et al. 2011, Susanti et al. 2021, Wang et al. 2024).

The APSIM model integrates microclimate simulation better than existing models and has the ability to more precisely model resource distribution and crop response at the plot scale, which is helpful for AF design and management (Kraft et al., 2021). Its framework offers modularity, flexibility, and interoperability, with publicly available source codes for the various modules.

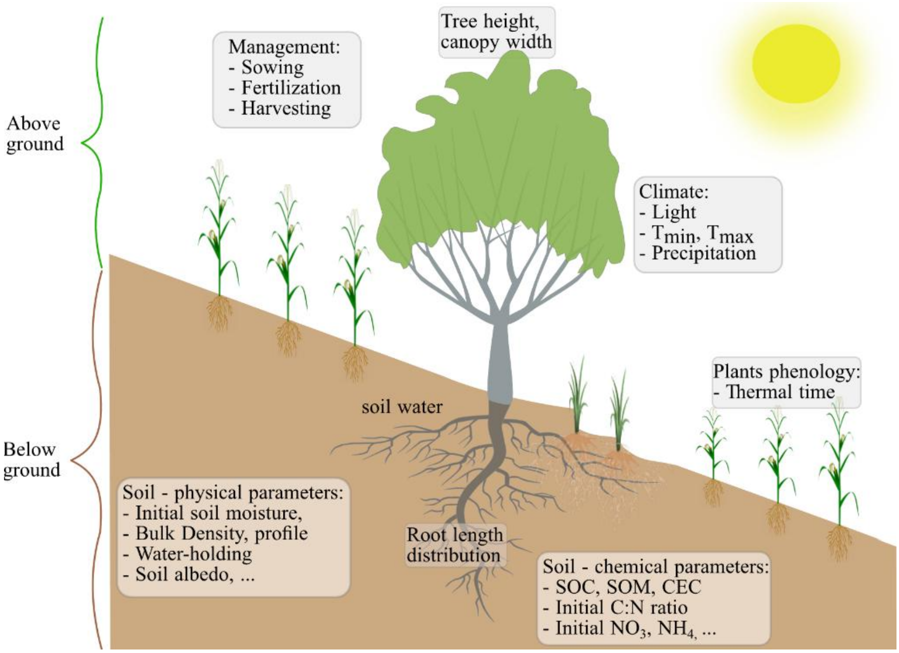

Figure 2. Visualisation of agroforestry system with tree, maize, and grass on sloping land, and the data requirements for modelling.

4. Materials and Methods

4.1 Study sites

The study was conducted in Mai Son district, Son La province, and Tuan Giao district, Dien Bien province (Figure 3-4), in northwest Vietnam (20.8°-22.4°N, 102.3°-104.8°E). Elevation ranges from 300 to 2000 and higher metres above sea level (masl). Over 94% of the land is sloping, of which 87% has a slope gradient >25° (Hoang et al., 2017). The climate in this region is specified as subhumid tropic with mean annual temperatures of 21.5°C and 18.6°C in Mai Son and Tuan Giao, respectively. The average annual rainfall is about 1380 mm in Mai Son and 1680 mm in Tuan Giao, concentrated during the period of May-August.

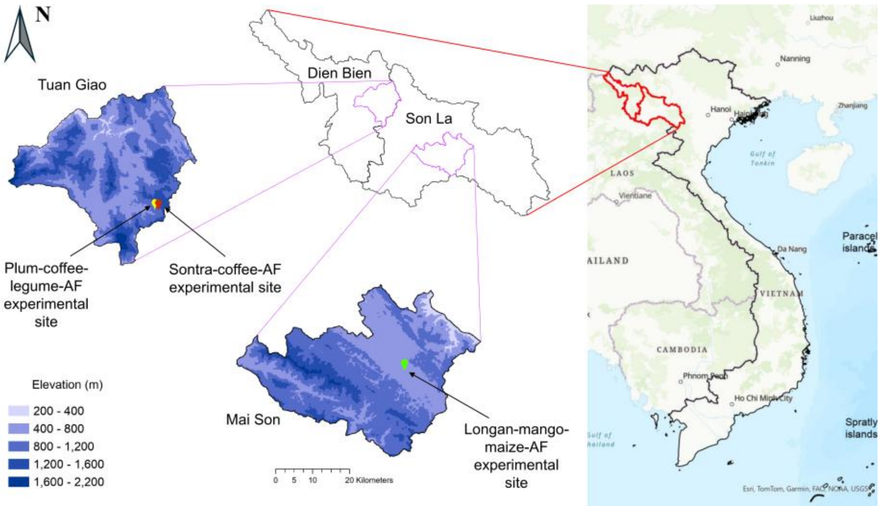

Figure 3. Map showing the locations of the three experimental sites.

Figure 4. Typical landscape in the northwest uplands of Vietnam. Photo was taken in February 2020.

Two semi-mature agroforestry experiments were revisited and maintained from previous studies by Do (2023). A new experiment was also established (Table 1).

Table 1. Details of the field experiments in Mai Son district, Son La province and Tuan Giao district, Dien Bien province

Experiment	**Coordinates**	**Slope (°)**	**Altitude (masl)**	**Location (district-province)**	**Year of establishment**
Longan-mango-maize-AF	21.10°N, 104.06ºE	15°-26°	566	Mai Son, Son La	2017
Sontra-coffee-AF	21.33°N, 103.30ºE	24°-34°	1104	Tuan Giao, Dien Bien	2017
Plum-coffee-legume-AF	21.57°N, 103.50°E	28°-35°	1150	Tuan Giao, Dien Bien	2020

Longan-mango-maize-AF: Longan-mango-maize-grass agroforestry; Sontra-coffee-AF: Sontra-coffee-grass agroforestry; Plum-coffee-legume-AF: Plum-coffee-grass-understory legume agroforestry.

The three experimental sites are characterised by highly degraded soil with shallow soil profiles, low pH, and low concentrations of soil organic carbon (SOC) and soil nutrients (Table 2). Soil profile descriptions in the plum-coffee-legume-AF experiment were carried out in 2023 (WRB, 2022). For longan-mango-maize AF and sontra-coffee AF experimental sites the profile descriptions were carried out by Do et al. (2023). The soil profiles in plum-coffee-legume-AF experiment are described in Appendix 1A-C.

Table 2. Soil properties of the topsoil layers in longan-mango-maize-grass agroforestry (longan-mango-maize-AF), sontra-coffee-grass (sontra-coffee-AF), and three farms of plum-coffee-grass-understory legume (plum-coffee-legume-AF) experiments.

Experiment	**Topsoil** [cm]	**pH** [H_2O]	**SOC** [%]	**BD** [g cm^{-3}]	**N** * [%]	**P** ** [mg $100g^{-1}$]	**K** ***
Longan-mango-maize-AF	0-17	5.5	1.78	1.37	0.15	0.64	7.6
Sontra-coffee-AF	0-23	4.0	2.21	1.15	0.16	0.61	5.6
Plum-coffee-legume-AF	0-16	4.8	2.29	1.23	0.19		
	0-20	5.5	2.25	1.20	0.18		
	0-23	5.9	2.55	1.03	0.19		

*SOC: total soil organic carbon, BD: bulk density, *: total nitrogen (N), **: available phosphorus (P), ***: available potassium (K).*

4.2 Field experiments and experimental design (Papers I-IV)

4.2.1 Field experiments and management

Longan-mango-maize-AF compared longan (*Dimocarpus longan* Lour. 'PHM-99-1-1', Figure 5A)-mango (*Mangifera indica* L. 'GL4', Figure 5B)-maize (*Zea mays* L. 'PAC999Super')-guinea grass (*Panicum maximum* Jacq. 'Mombasa') AF treatment with sole maize (Figure 6). We revisited the experiment site and collected data in 2022 and 2023 (Papers I-II). Data from the previous period (2017-2021) collected by Do (2023), were also used for the modelling in Paper IV.

Figure 5. (A) Longan, (B) mango, (C) sontra, and (D) plum fruits. Photos were taken during the fruits' harvesting season in 2023 by Mr. Su (A), me (B-C), and Ms. Sinh (D).

Figure 6. Longan-mango-maize-grass (longan-mango-maize-AF) agroforestry experiment in Mai Son district, Son La province, Vietnam. Photo was taken in October 2023.

Sontra-coffee-AF compared sontra (*Docynia indica* (Wall.) Decne., Figure 5C)-coffee (*Coffea arabica* L. 'Catimor')-guinea grass (*Panicum maximum* Jacq. 'Mombasa') AF treatment with sole coffee (Figure 7). We visited and collected data in 2022 and 2023 (Paper I).

Figure 7. Sontra-coffee-grass (Fruit tree-coffee AF) agroforestry experiment in Tuan Giao district, Dien Bien province, Vietnam. Photo was taken in July 2022 by ICRAF Vietnam.

Plum-coffee-legume-AF compared plum (*Prunus salicina* 'Hau', Figure 5D)-coffee (*Coffea arabica* L. 'Catimor')-mulato grass (*Brachiaria ruziziensis x B. brizantha x B. decumbens* 'Mulato II')-understory legume with AF without understory legume (Figure 8). Three legume species were introduced: pintoi (*Arachis pintoi*), stylo (*Stylosanthes guianensis*), and peanut (*Arachis hypogaea* L.). Data collection began prior to the experimental establishment and continued until 2023 (Paper III).

Figure 8. One of the plum-coffee-grass-understory legume (Plum-coffee-legume-AF) experimental fields in Tuan Giao district, Dien Bien province, Vietnam. Photo was taken in May 2022.

A randomised complete block design was used for all experiments. There were four replicates in both longan-mango-maize-AF and sontra-coffee-AF. Plum-coffee-legume-AF consisted of three nearby fields with twelve replicates in total. Trees, crops, and grasses were planted along the contour lines in all field experiments.

In longan-mango-maize-AF, longan and mango trees were planted in alternate rows, with a spacing of 10 m between 2 rows (250 trees ha^{-1}). A double-row grass strip was planted 1 m below the tree rows, with a spacing of 0.5 m between rows. Maize was sown with 0.7 and 0.3 m spacing between and within rows, respectively, resulting in a planting density of 71,000 plants ha^{-1} in sole maize. In the AF treatment, the nearest row of maize was planted 1.2 m upslope from the tree trunks and 1.25 m downslope from the grass strip centre, resulting in a 30% reduction of the maize area compared to sole maize.

In sontra-coffee-AF, sontra trees were planted with a spacing of 10 m between rows and 4 m within rows (250 tree ha^{-1}). Grass strips were planted in the same manner as longan-mango-maize-AF. Between two sontra rows, four coffee rows were planted with a spacing of 2 m between rows and 1.4 m within rows (2857 shrubs ha^{-1}). In the AF treatment, the nearest row of coffee was planted 1.5 m upslope from the tree trunks and 1.25 m downslope from the grass strip centre, resulting in a 20% reduction in coffee area compared to sole coffee (3571 shrub ha^{-1}).

In plum-coffee-legume-AF, trees, coffee, and grass were planted following the same design as the sontra-coffee-AF. Understory legumes (pintoi, stylo, and peanut) were planted in single, double, and triple rows between grass and coffee, between coffee and plum, and between two coffee rows, respectively. Legume rows were positioned 0.5 m away from rows of other components, whilst distances between and within their rows were 0.5 m and 0.2 m, respectively.

The information on fertilization for longan-mango-maize-AF is presented in Paper II (Tables S2-S5). The fertilisation regime of sontra-coffee-AF can be found in Paper I (Table S2, S4), whilst fertilisation details for plum-coffee-legume-AF are described in Paper III (Table S2). No fertilisers were applied to grass strips or legumes in any of the experiments.

Weed control in longan-mango-maize-AF was carried out before the maize season, twice during the season, and once after (Paper I, Table S2-S3). In sontra-coffee-AF, weeding was performed three times (Paper I, Table S3). In plum-coffee-legume-AF weeding was conducted five to six times annually (Paper III, section 2.2, Fig. S2).

4.2.2 Experimental design

In longan-mango-maize-AF, the AF plots were divided into two sub-treatments with longan-maize-grass (longan-AF) and mango-maize-grass (mango-AF) sequences. To test the hypotheses, nine zones were identified along the slope of all AF plots in the longan-mango-maize AF (Figure 9A), sontra-coffee-AF (Figure 9B), and plum-coffee-legume-AF (Figure 10) experiments: zones 1 to 4 on the upslope side and zones 6 (grass strip) to 9 on the downslope side of tree row (zone 5).

4.3 Methods used for data collection

4.3.1 Weather data (Papers I-IV)

The temperature (°C), precipitation (mm), and radiation (mol m^{-2}) in longan-mango-maize-AF were collected from a mini weather station installed in June 2021. Additional data from the previous period (2017-2021) was taken from the closest national weather station (~20 km away). This weather data was used in Papers I and II (2022-2023) and Paper IV (2017-2023).

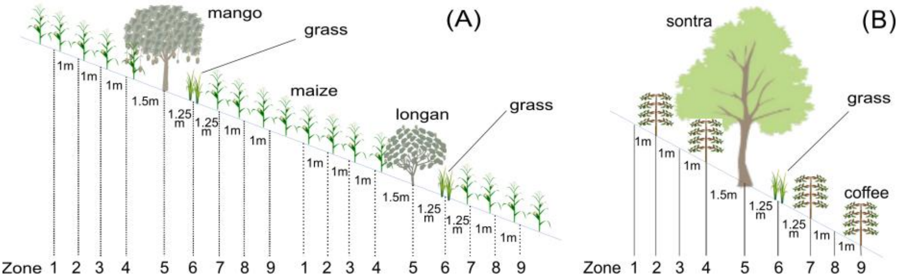

Figure 9. The design of (A) longan-maize-grass (longan-AF) and mango-maize-grass (mango-AF) sub-treatments in longan-mango-maize-grass, and (B) sontra-coffee-grass (sontra-coffee-AF) treatment in sontra-coffee-grass agroforestry experiments. The vertical lines denote the central points of zones.

The precipitation in plum-coffee-legume-AF was recorded using manual rain gauges installed in each of the three fields. Temperature data was collected from a national weather station (ca 5 km away). Due to its proximity, the climatic data in sontra-coffee-AF was assumed to be the same as plum-coffee-legume-AF (Papers I and III)

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

All fruit trees in all experiments were measured non-destructively every three months for growth indicators (height, canopy width, stem-diameter) (Figure 11A). The longan, mango, sontra, and plum fruits were harvested and calculated as yield per tree (Papers I-IV).

Maize height and leaf SPAD were measured in the 7 maize zones in AF and the 3 zones in sole maize treatment plots in longan-mango-maize-AF at 3-4, 6-7, 10-11 fully expanded leaves, and the silking stage. Similarly, at harvest, we took maize samples in a 3.5 m^2 area per zone for grain yield, aboveground biomass, and Harvest Index (HI) indicators (Papers I, II, and IV).

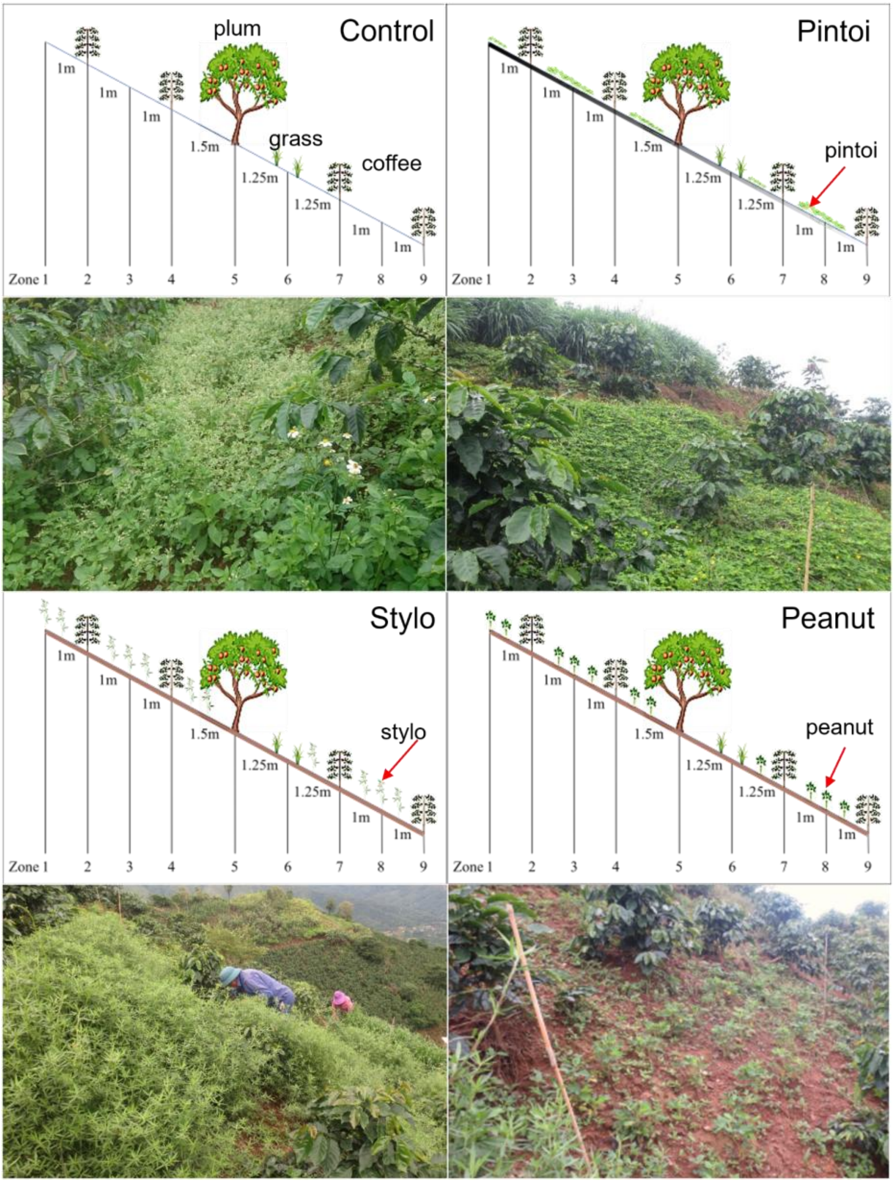

Figure 10. The design of plum-coffee-grass (Control), plum-coffee-grass-pintoi (Pintoi), plum-coffee-grass-stylo (Stylo), and plum-coffee-grass-peanut (Peanut) agroforestry treatments. The vertical lines denote the central points of zones. Photos were taken in June-July 2022.

Coffee shrubs in sontra-coffee-AF and plum-coffee-legume-AF experiments were measured every three months for height, canopy width, leaf SPAD, and stem diameter. Coffee cherries were picked 4 times annually in each of 4 coffee zones in AF and in the three zones in sole coffee treatments. The four harvests were summed up to compute coffee cherry yield (ton ha^{-1}) (Papers I and III).

The data of grass in all experiments was recorded at every cutting occasions. A 4 m grass strip was harvested, subsamples taken (Figure 11B) and then dried to calculate the dry biomass in ton ha^{-1} (Paper I-IV).

In plum-coffee-legume-AF, the prostrate pintoi was not harvested but was cut to control its growth close to trees and shrubs. Its biomass was then left on the surface to dry before mulching around trees and shrubs. Stylo was cut 3-4 times annually when reaching 0.8-1.0 m height, subsamples were taken, dried, and used to calculate the dry biomass (ton ha^{-1}). Stylo biomass was removed from the field to feed the farmers' cattle. Peanut was harvested at maturity, and its yield recorded (ton ha^{-1}) (Paper III). Aside from the pods, peanut biomass was left in the field.

The root distribution and length density of trees, maize, and grass were measured in July 2022 using the soil core break approach (Van Noordwijk et al., 2001). Cores samples (7.3 cm inner diameter) were taken, hand-broken at the middle and the root tips counted. The sub-cores were sunk into water where the roots were gently collected. Tree, grass, and maize roots were classified based on morphology and smell. The root samples (n=62) were then scanned at 300-dpi resolution and the root length was determined from the photos using ImageJ software (http://imagej.nih.gov/ij). A linear calibration between the number of root tips and root length density was made to calculate root length from the entire counted root tip data. Data was used in Paper IV.

Figure 11. Measuring (A) tree/crop growth, (B) harvesting grass, (C) measuring light, and (D) taking soil sample in agroforestry experiments. Photos were taken in 2022-2023.

4.3.3 Light measurement (Paper I)

The Hemiview tool, consisting of a Canon EOS 60D camera and fish-eye lens (Sigma EX DC 4.5 mm) connected to a frame and monopod, was used to take hemispherical images at 1.7 m height (crop level) and to quantify the fraction of light intercepted by the tree canopies (Figure 11C). The SunScan canopy analysis system (SS1-COM, Delta-T), consisting of a SunScan probe (SS1), Sunshine sensor (BF5), and handheld computer (PDA), was used to measure the light intensity at the crop level and soil surface. Based on both measurements, the fraction of light intercepted by the crop canopy (maize in longan-mango-maize-AF, coffee in sontra-coffee-AF) and light reaching the soil surface were calculated (Figure 12). The light distribution data was measured along 5 m row-length in each of the 9 zones of AF treatments and 3 zones in sole maize/coffee in longan-mango-maize-AF and sontra-coffee-AF experiments. The measurements were taken in March, June, September, and December 2022.

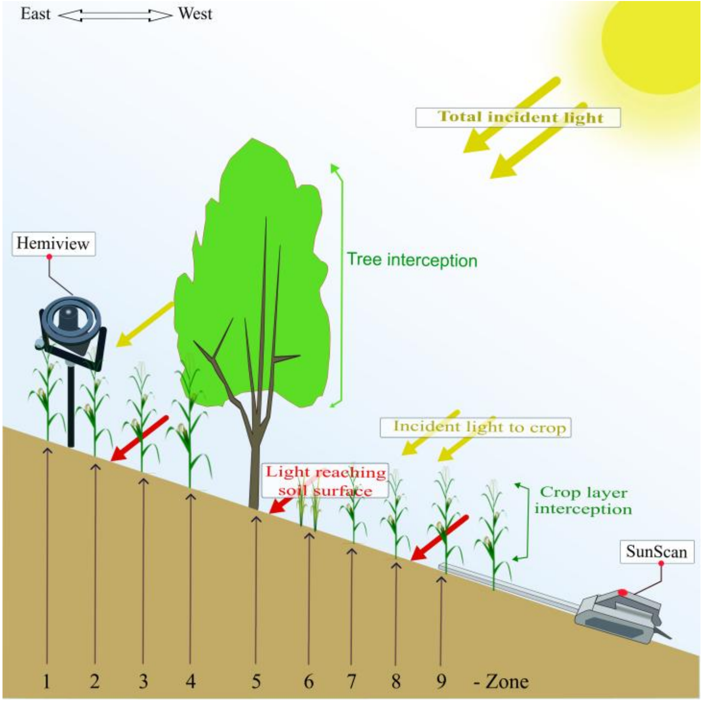

Figure 12. A graphical representation of Hemivew and SunScan method to quantify the light distribution in the fruit tree-based agroforestry treatment.

4.3.4 Soil sampling and measurements (Papers II-IV)

In longan-mango-maize-AF, soil samples were taken to determine gravimetric water content at 0-20, 20-40, and 40-60 cm soil depths (Figure 11D). The samples were taken at 4 maize growth stages (3-4, 6-7, and 10-11 leaf stages and silking) using augers (2.5 cm inner diameter). Five augers were taken at 1 m intervals within each zone and pooled into one sample. The samples were weighed both before (W_{wet}) and after (W_{dry}) oven drying (105ºC), and the volumetric water content (VSW) calculated according to Eq. 1.

$$VSW\ (mm) = BD \times 1000 \times (W_{wet} - W_{dry}) / W_{dry} \qquad (1)$$

The available soil water content (ASWC) was calculated as the difference between the soil water content at sampling and the permanent wilting point (PWP, mm) (Eq. 2), with the PWP estimated using a pedotransfer function by Van den Berg et al. (1997). ASWC data were used in Papers II and IV.

$$ASWC\ (mm) = VSW - PWP \quad (2)$$

Additional soil samples were collected in March 2022 above the fruit tree rows (zone 4), in the fruit tree rows (zone 5) and the grass strips (zone 6), and below the grass (zone 7) in longan-mango-maize-AF. These samples were quickly stored in a portable cold box with dry ice and transported to the laboratory for determination of pH, SOC (Walkley and Black; FAO, 2019), total N (Kjeldahl; FAO, 2021), ammonium-N (mg kg^{-1}), nitrate-N (mg kg^{-1}) (extraction with potassium chloride solution; MOST, 2015), and phosphorus (Bray; FAO, 2021). These data were used in Paper IV.

In plum-coffee-legume-AF (Figure 13), before establishment, soil samples were taken at 0-10 and 10-20 cm soil depths using augers (2.5 cm inner-diameter). We took 24 sub-samples and pooled to one sample per plot. In November 2023, we collected post-experiment soil samples with a similar protocol in five of the zones including zones 1 and 9 (representing middle alleys with least competition), and zones 5, 6 and 7 (representing the most competitive area according to Do et al. (2023) and the results from Paper I). All samples were air-dried and subsequently analysed for SOC, total N, available P (Bray; FAO, 2021), and available potassium (K, extraction with ammonium acetate; MOST, 2011). These soil nutrients data were used in Paper III.

Figure 13. Farmers were collecting data in the plum-coffee-legume-grass agroforestry experiment. Photo was taken in June 2023.

4.3.5 Agricultural Production systems SIMulator (APSIM) agroforestry models (Paper IV)

The APSIM model (APSIM Initiative, 2024; Dean et al., 2018) was used for the modelling. The sole maize, fruit tree-maize-AF models were adjusted from APSIM-Maize and APSIM-Agroforestry respectively. We constructed separate models for upslope and downslope portions of the AF systems (Figure 14). The Forage module was added and presented as grass strip; however, we used paspalum grass (*Paspalum dilatatum*) for this as guinea grass was not available in the APSIM library.

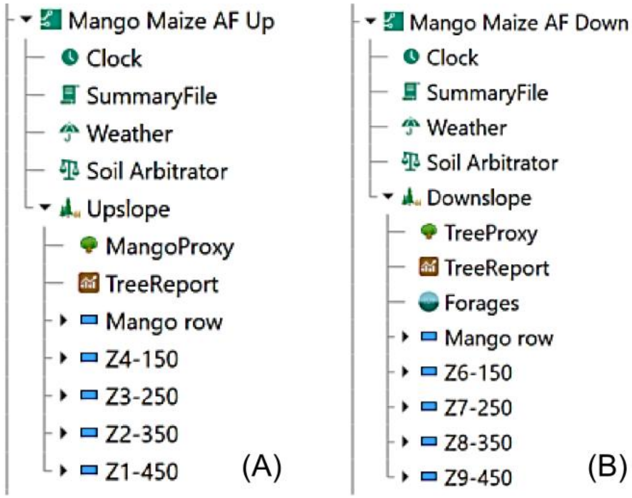

Figure 14. Construction of the upslope (A) and downslope (B) of mango-maize-grass agroforestry (mango-AF) model. A similar approach was used for longan-maize-grass agroforestry (longan-AF) model.

Models were parameterised using soil (Appendix 2), climate, and management data (Appendix 3) collected from the longan-mango-maize-AF experiment by the author (2022-2023) and other researchers (2017-2021) (Do, 2023). The measured soil data consisted of SOC, SOM, NH_4, NO_3, pH, texture, and initial soil water. Soil water at saturation, field capacity, airdry, and wilting point were estimated for all soil depths based on soil texture and SOC using the Soil-Plant-Air-Water (SPAW, 6.02.75) model (Keith, 2025). The slope gradient was measured in the field. Daily climate data includes precipitation, radiation, and the maximum and minimum of temperatures during the period 2017-2023. Maize densities, grain weight, and total grain number per cob were set as observed at harvesting. Sowing date and fertilisation were also included in the Management module. In addition, we parameterised trees in the TreeProxy module using tree height and canopy width from 2017-2023, and root length data obtained in July 2022. Grass harvests were parameterised according to the cutting occasions.

The maize cultivar grown in the experiment was not documented in the APSIM library; thus, we focused on calibrating it in the sole maize model. Sowing depth, leaf appearance, and grain development during the 2023 season were used to calibrate PAC999Super cultivar phenology (i.e. emergency, juvenile, flag leaf, maturity). Measured maize height was used to calibrate plant structures. In the agroforestry models, we predominantly calibrated tree parameters to drive the potential interaction. In the calibration process, we aimed to make maize biomass and grain yield simulation fit the field observation in replicate 4 in both sole maize and AF systems. Detailed variables in calibration are presented in Appendix 4.

The sole maize model was validated using the biomass and grain yield observations from the three remaining replicates (1-3) of the field experiment in 2017-2023. Similarly, the AF models were validated using data in replicates 1-3, but only in 2022 and 2023 as zoning data was unavailable from 2017-2021 and the models require assumptions regarding tree root distribution. Soil water simulated from models was validated using data obtained by 10 water sensors (Atmost 11, Group meter) (inserted in replicate 4) and soil water observed with the gravimetric method in 2022 and 2023 (all replicates).

Relay-cropping scenarios with three legumes consisting of peanut (*Arachis hypogaea*), mung-bean (*Vigna radiata*), and soybean (*Glycine max*) were added to both sole maize and AF models. Legumes were set to be sown 1 month after sowing maize with locally suggested density. No additional fertiliser was set in the models for legumes. The maize performance, system productivity, and resource use were compared between with and without legume relay-cropping.

4.4 Software use and statistical analyses

4.4.1 Software

Data analysis was carried out in R, version 4.1.3-4.2.2 (R Core Team, 2024), and RStudio, version 2022.02-2024.09 (Posit team, 2024). All graphs were made in RStudio, or MS Excel 365 and further visualisation was done in Inkscape (Inkscape's Contributors, 2023). The map of experimental sites was created using ArcGIS Pro (3.3.0, Esri Inc.). Authors used icons retrieved from https://depositphotos.com/vectors/tree.html.

4.4.2 Statistical analyses

To evaluate the effects of treatments, slope positions (zones), and soil layers (only in Papers II and III) on light distribution (Paper I), ASWC (Paper II), soil nutrients (Paper III), tree/crop/grass growth and yield (Papers I-III) linear mixed-effect (LME) models ("lme4" package, Bates et al., 2015) were used. The effects of blocks, plots, and farms (only in Paper III) were modelled as random, whereas the effects of treatments, zones, and soil layers were modelled as fixed. In the repeated measurements analysis (Eq. 3), data measurement dates were modelled as fixed. The analyses were also performed for each data occasion (Eq. 4).

Using R notation, the LME models were specified as

$$y \sim treat + zone + date + treat{:}zone + treat{:}date + zone{:}date + treat{:}zone{:}date + (1|block) + (1|plot) + (1|farm) + (1|block{:}plot) + (1|block{:}farm) + (1|plot{:}farm) + (1|block{:}plot{:}farm) \quad (3)$$

and

$$y \sim treat + zone + treat{:}zone + (1|block) + (1|plot) + (1|block{:}plot) \quad (4)$$

respectively, where y denotes the response variable.

The assumptions of heterogeneity and normal distribution were checked with a simple scatter plot of residuals against fitted values. The Box-cox transformation was applied when necessary to reach the assumptions. The proportion of vegetative cover (Paper III) was transformed using the Logit function. Both transformation methods were built in the "car" package (Fox & Weisberg, 2019).

F-tests were used for testing main effects and interactions in Eq. 3 and 4. When a significant result was shown (at $p<0.05$), Tukey's multiple-comparison method ("emmeans" package, Lenth, 2023) was used to determine the differences between the categories.

In Paper IV, a model evaluation was carried out using the leave one out cross validation (LOOCV) approach. The “caret” package in R was used for this approach (Kuhn, 2008). The root mean square error (RMSE) and mean absolute error (MAE) were computed as goodness-of-fit indicators. Additionally, linear regressions between observed and estimated values were performed for each variable (e.g. incident light, etc) and the coefficients of determination (R^2) were computed. The smaller the RMSE and the MAE, and the larger the R^2, the better models performed.

5. Results

5.1 Rainfall and temperature patterns in study sites

In longan-mango-maize-AF, the annual temperature was 22.0°C and 22.9°C, whilst the total rainfall was 1376 mm and 1200 mm in 2022 and 2023, respectively. The rainy season commenced in May in 2022, whereas it began in June in 2023 (Figure 15A) causing later sowing of maize. In July 2022, there was a dry spell when maize was at the tasselling and silking stage. In July 2023, there was also a short dry period, but this occurred when the maize was at the 7-10 leaf stage (Figure 15B). Total rainfall during the maize season exceeded 800 mm in both years.

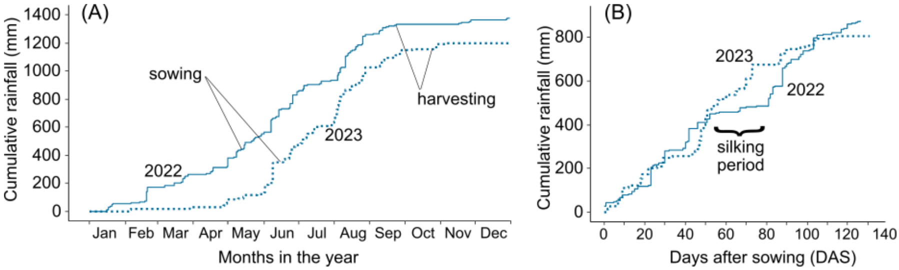

Figure 15. Cumulative rainfall in longan-mango-maize-grass agroforestry experiment (A) throughout 2022 and 2023, and (B) during the two maize seasons. The silking period occurred at a similar number of degree days in both seasons.

In sontra-coffee-AF and plum-coffee-legume-AF, the average annual temperature was 20.2°C during the period of 2020 to 2023, which was lower than in longan-mango-maize-AF. Rainfall was higher in 2022 (1705 mm) than in 2021 (1517 mm) and 2023 (1556 mm), with the majority of it occurring between May and September (Figure 16).

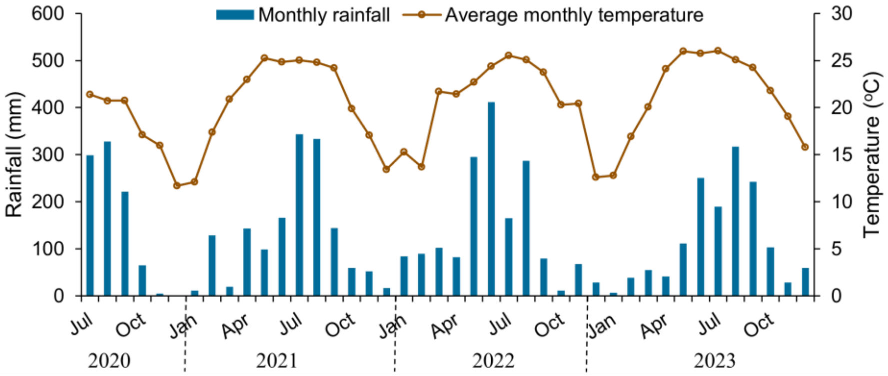

Figure 16. Monthly precipitation and average monthly temperature in sontra-coffee-grass and plum-coffee-legume-grass agroforestry experiments.

5.2 Light distribution in agroforestry on sloping land (Paper I)

In longan-mango-maize-AF, lower incident light to the maize level was found in zones downslope of the tree row compared to upslope. Shading increased with tree size (i.e. longan < mango) and decreased with increasing distance from tree rows (Figure 17). Light reaching the soil surface was on average 0.4-0.6 fraction of the total incident light during the cropping season. There was no significant difference between the light reaching the soil surface in AF treatments and sole maize. On average during maize season, tree intercepted a similar amount of light compared to maize in the AF system. During the off-maize season, the light penetrating below the tree canopies in AF (ca 0.8 of total incident light) was available for weeds.

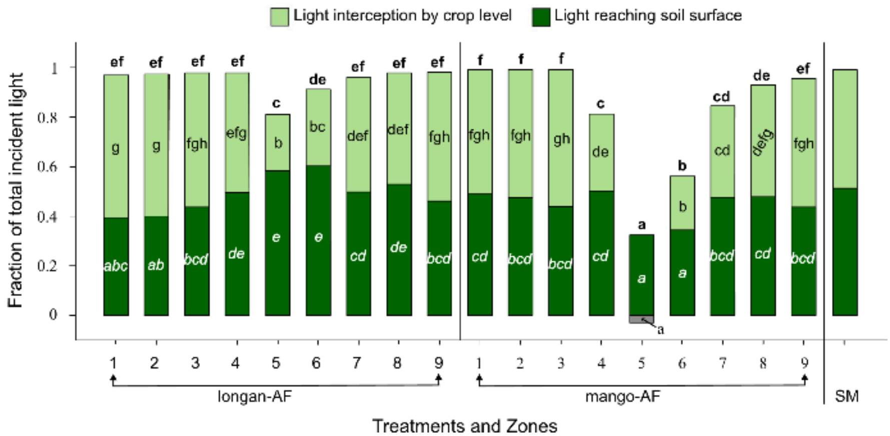

Figure 17. Light distribution and interception in different zones in longan-maize (longan-AF) and mango-maize (mango-AF) sub-treatments and in sole maize (SM), expressed as average over the maize season. Different bold, regular, and italic letters indicate significant differences between zones within agroforestry sub-treatments in terms of incident light to the maize level (1.7 m above soil surface, total height of positive stacked bars), light interception by the maize layer, and light reaching the soil surface, respectively, ($p<0.05$, a<b<…). The grey bar indicates that there was more light reaching the soil surface than the 1.7 m level of the mango canopy.

In sontra-coffee-AF, there was similar tendency of the fruit trees having a stronger impact on incident light to the coffee level and light interception by coffee downslope than upslope. The impact decreased with increasing distance from tree row. The sontra trees, being much larger, had a larger shading effect on both up- and downslope than longan and mango. Light reaching the soil surface varied between 0.2 fraction of total light within coffee rows to 0.4 between coffee rows in the AF treatment (Figure 18).

There was a significantly positive correlation between light interception by the maize layer and maize growth, biomass, and grain yield in longan-mango-maize-AF ($p<0.05$). However, in sontra-coffee-AF, coffee growth and cherry yield did not correlate with incident light to the coffee level nor with light interception by the coffee layer.

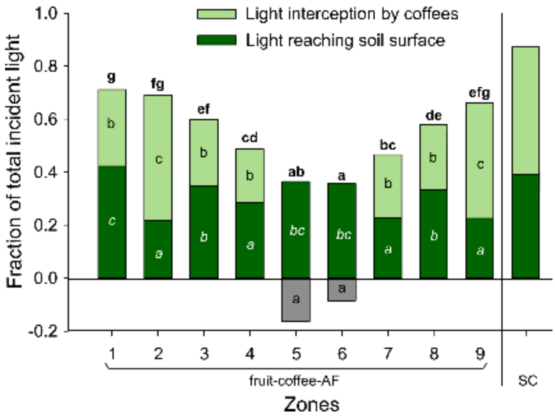

Figure 18. Light distribution and interception in different zones in sontra-coffee (sontra-coffee-AF) and sole coffee (SC) treatments, presented as average in 2022. Different bold, regular, and italic letters indicate significant differences between zones within agroforestry system in terms of incident light to the coffee level (the 1.7 m above soil surface, total height of positive stacked bars), light interception by the coffee layer, and light reaching the soil surface, respectively, ($p<0.05$, a<b<…). Grey bars indicate that there was more light reaching the soil surface than the 1.7 m level in the sontra rows and grass strips.

5.3 Distribution of available water in agroforestry on sloping land (Paper II)

Shortly after rainfall in maize seasons, ASWC was higher in both AF sub-treatments than in sole maize; however, the inverse appeared when measurements were taken more than 4 days after rainfall. During the early dry season (i.e. in December), ASWC was higher in longan-AF than in mango-AF and sole maize. Towards the end of dry season (i.e. March), ASWC was highest in mango-AF, followed by sole maize, and lowest in longan-AF (Figure 19A).

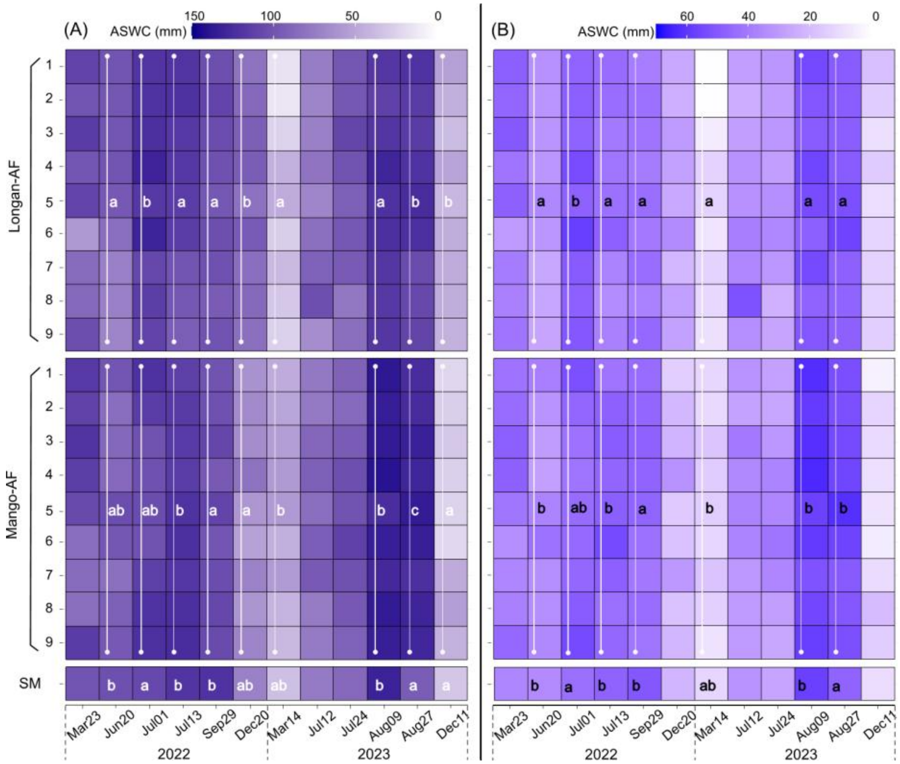

Figure 19. Available soil water content (ASWC, mm) (A) 0 to 60 cm depth and (B) in the 0-20 cm layer in longan-maize-grass (longan-AF), mango-maize-grass (mango-AF) sub-treatments, and sole maize in 2022 and 2023. The letters indicate a significant difference between (sub-)treatments within each measurement occasion ($p<0.05$, a<b).

Close-after rain events, ASWC in 0-60 cm layer generally tended to be lower below the grass strip than in the zone upslope of the tree rows, although the difference was significant on only one occasion ($p<0.001$). During the dry season, ASWC within grass strips tended to be lower than in other zones both up- and downslope (Figure 19A). The ASWC in the 0-20 cm layer fluctuated strongly (Figure 19B), whilst there was less fluctuation in the deeper soil layers (Figure 20A-B). Additionally, ASWC was higher in the topsoil layer than in the subsoil in the mango-AF, whereas there was a reverse trend in longan-AF.

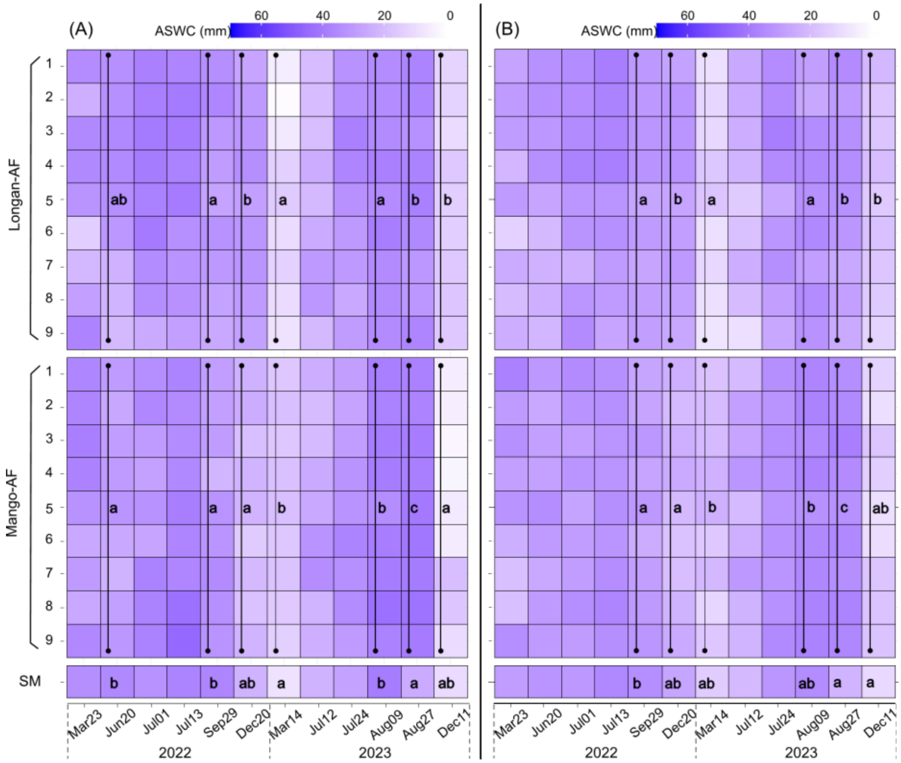

Figure 20. Available soil water content (ASWC, mm) in (A) 20-40 cm layer, and in (B) 40-60 cm layer in longan-maize-grass (longan-AF), mango-maize-grass (mango-AF), and sole maize (SM) (sub-)treatments in 2022 and 2023. The letters indicate significant differences between (sub-)treatments within each measurement ($p<0.05$, a<b).

5.4 Nutrients and effects of integrating understory legumes (Paper III)

The SOC and total N had improved in plum-coffee-legume-AF after the experiments ended in 2023 when compared to the starting values in 2020. The SOC (Figure 21A) and N (Figure 21B) increased more when understory legumes were intercropped compared to the Control. However, there was an opposite observation with the contents of available P (Figure 21C) and K (Figure 21D) which were lower in 2023 than at start of all treatments, and these declines were larger in systems with understory legumes.

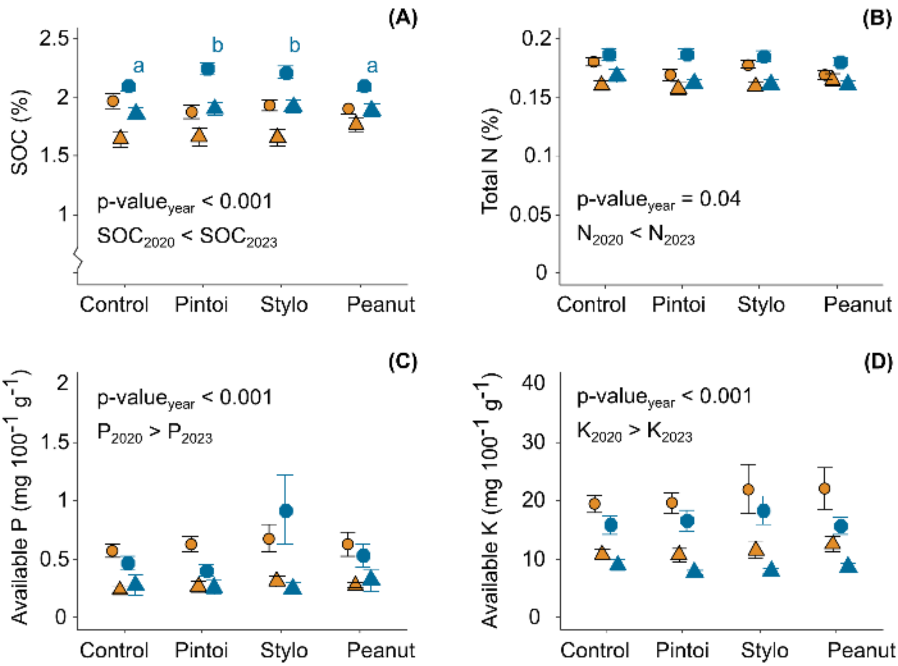

Figure 21. (A) Total soil organic carbon (SOC), (B) total nitrogen (N), (C) available phosphorus (P), and (D) available potassium (K) in plum-coffee-grass (Control), plum-coffee-grass-pintoi (Pintoi), plum-coffee-grass-stylo (Stylo), and plum-coffee-peanut (Peanut) treatments in 2020 (orange markers) and 2023 (blue markers). Circle and triangle shapes denote values in 0-10 cm and 10-20 cm respectively. Data are means ± standard error (bars). The letters indicate significantly different SOC in different treatment in 2023, ($p<0.05$, a<b).

Lower SOC and nutrient concentrations were generally found in the 0-20 cm soil layer within (zone 6) and below the grass strip (zone 7) than in the other zones (Figure 22A-D).

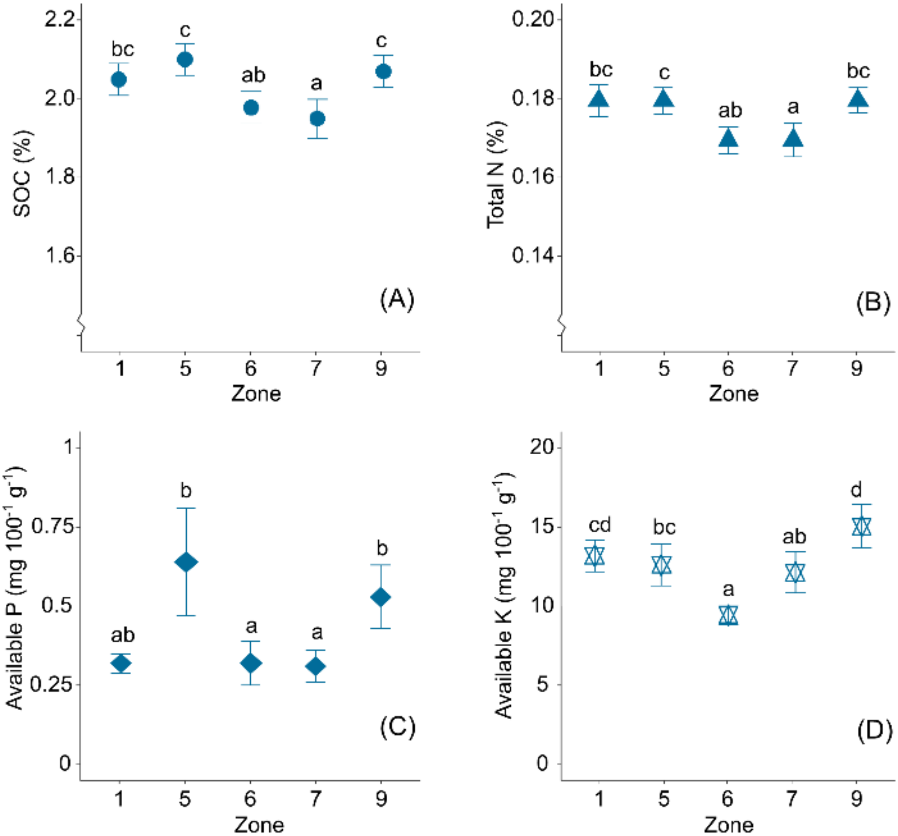

Figure 22. (A) Total soil organic carbon (SOC), (B) total nitrogen (N), (C) available phosphorus (P), and (D) available potassium (K) midway between tree rows (zone 1, 9), in the tree row (zone 5), in the grass strip (zone 6), and below the grass strip (zone 7) across treatments in plum-coffee-legume-grass agroforestry experiment. Data are means ± standard error (bars). Letters denote significant differences between zones, ($p<0.05$, a<b<c<d).

5.5 Performance of crop components

5.5.1 Maize yield in longan-mango-maize agroforestry (Papers I, II, and IV)

Maize height and SPAD values were higher in sole maize than in longan-AF and mango-AF sub-treatments ($p < 0.001$ and $p = 0.03$, respectively). Maize in zone 7 exhibited significantly lower height and SPAD values than other maize zones in both AF sub-treatments ($p < 0.001$).

The maize grain yield and biomass were significantly higher in 2023 than in 2022 ($p<0.001$). Maize yield was similar in both AF sub-treatments but higher in sole maize than in AF in 2023 ($p=0.001$, Figure 23), whilst its biomass was not different between treatments or season (Figure S3 of Paper 2). Zone 7 had lower maize grain yield and biomass than all other maize zones in both AF sub-treatments and seasons (Figure 23, S3 of Paper 2).

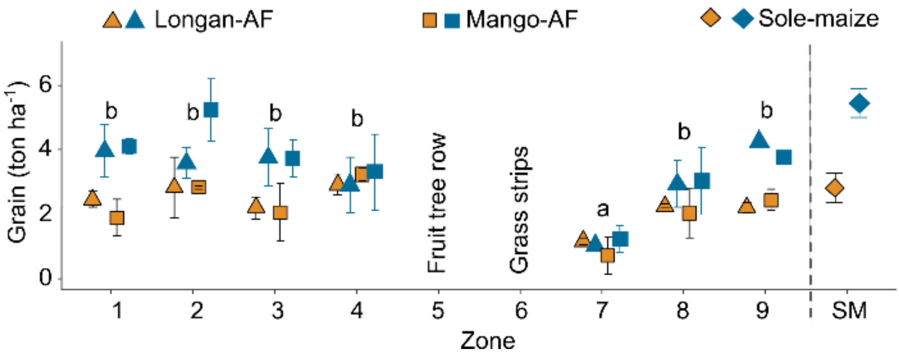

Figure 23. Grain yield of maize in different zones of longan-maize-grass (longan-AF, triangles) and mango-maize-grass (mango-AF, squares), and in sole maize (SM) (sub-)systems in 2022 (orange symbols) and 2023 (blue symbols). Data are means ± standard error (bars). Letters indicate significant differences between zones in the agroforestry sub-treatments ($p<0.05$, a<b).

Similar to grain yield, the maize Harvest Index (HI) was higher in 2023 than in 2022 ($p<0.001$). It was not different between longan-AF, mango-AF, and sole maize systems/treatments, or between zones within the two AF sub-treatment (Figure 24).

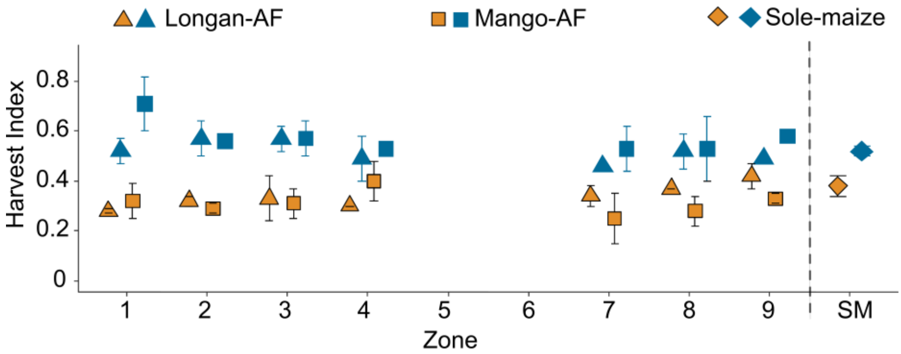

Figure 24. Harvest Index (HI) of maize in different zones of longan-maize-grass (longan-AF, triangles) and mango-maize-grass (mango-AF, squares), and in sole maize (SM) (sub-)systems in 2022 (orange symbols) and 2023 (blue symbols). Data are means ± standard error (bars).

5.5.2 Coffee performance in fruit-coffee agroforestry systems (Papers I and III)

Six years after establishing sontra-coffee-AF (Paper I), average coffee height, canopy width, stem diameter, and leaf SPAD did not significantly differ between AF and sole coffee across measurements ($p>0.05$). However, the yield of coffee cherries was significantly higher in sole coffee ($p<0.05$). There was a clear tendency for coffee below the grass (zone 7) in the AF treatment to have lower values on growth indicators and yield than in the other coffee zones, although significant differences were not always found at every measurement (p-value ranged, Figure 25A).

In plum-coffee-legume-AF (Paper III), coffee shrubs below the grass (zone 7) tended to have lower height, smaller canopy width, and lower leaf SPAD than other zones, but a significant difference ($p<0.05$) was only found immediately above tree row (zone 4) (height and canopy width) and farther way (zone 9) (leaf SPAD). Coffee below the grass also tended to show a lower coffee yield ($p=0.12$). When legume was added to plum-coffee-AF, coffee demonstrated significantly lower performance after 3 years of establishment (Figure 25B).

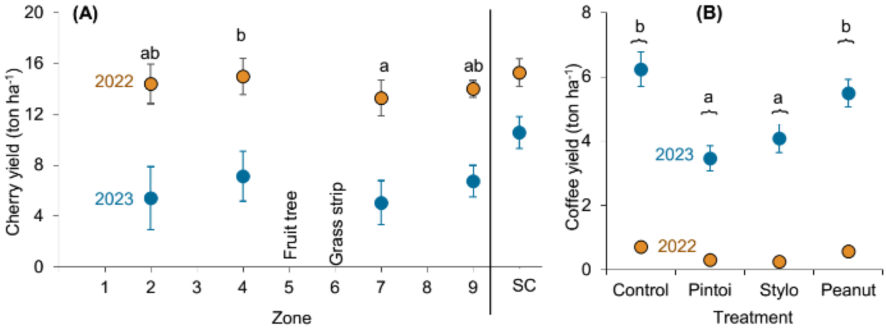

Figure 25. Coffee fresh cherry yield in (A) sontra-coffee-grass treatment zones and sole coffee (SC) in 2022-2023, and (B) plum-coffee-grass-legume treatments in 2022-2023. Data are means ± standard error (bars). Letters (a<b) indicate the significant differences between coffee zones in A, and between treatments in B, (p<0.05, a<b).

5.5.3 Grass biomass (Paper I-IV)

The grass biomass varied between the experiments and treatments (Table 3). It was low in sontra-coffee-AF, reflecting the impact of the large sontra trees. Grass biomass tended to be higher in longan-AF than in mango-AF but there was no significant difference (p>0.1). In plum-coffee-legume-AF, introducing Stylo significantly boosted the grass biomass compared to the system with Peanut (p<0.05), whilst the grass in the Control (no understory crop) and Pintoi were intermediate.

Table 3. Biomass of grasses in different fruit tree-crop agroforestry treatments in longan-mango-maize-grass, sontra-coffee-grass, and plum-coffee-grass-legume experiments in 2022 and 2023. Data are means ± standard error.

AF treatment	**Dry grass biomass (ton ha^{-1})**	
	2022	2023
Longan-maize-grass	2.3 ± 0.1	1.8 ± 0.2
Mango-maize-grass	2.0 ± 0.1	1.6 ± 0.1
Sontra-coffee-grass	1.0 ± 0.1	1.7 ± 0.1
Plum-coffee-grass	3.1 ± 0.5	2.9 ± 0.6
Plum-coffee-grass-pintoi	2.9 ± 0.5	2.9 ± 0.4
Plum-coffee-grass-stylo	3.5 ± 0.7	3.2 ± 0.4
Plum-coffee-grass-peanut	3.0 ± 0.7	2.6 ± 0.6

5.5.4 Legume biomass (Paper III)

Throughout the study period, we did not remove pintoi biomass from the treatment plots. Stylo produced large amounts of biomass which was harvested and carried out of the experiment in 2022 and 2023 (Table 4). For peanut, only pods were exported equalling to approx. 0.1 ton ha^{-1} each year.

Table 4. Average legume biomass carried out of the treatments in plum-coffee-grass-legume agroforestry (AF) experiment. Data are means ± standard error.

AF treatment	**Legume** species	**Dry biomass (ton ha^{-1})** 2022	2023	Estimation**
Plum-coffee-grass	-	-	-	-
Plum-coffee-grass- pintoi	Pintoi	0	0	1.9
Plum-coffee-grass-stylo	Stylo	6.4 ± 0.1	5.3 ± 0.1	-
Plum-coffee-grass-peanut	Peanut	0.1*	0.1*	0.3

(*) denotes peanut pod yield. (**) Biomass accumulation in 2022 was estimated by Fan (2023).

5.6 Modelling fruit tree-maize-agroforestry on sloping land and testing relay-legume option

5.6.1 Model performance

The model validation showed a better fit for grain yield in sole maize (Figure 26A) than longan-AF (Figure 26B) and mango-AF (Figure 26C). All model validations showed outliers with the observed data from replicate 1 in both seasons (2022, 2023). The calculated values of root mean squared error (RMSE) and mean absolute error (MAE) were lower for maize grain yield than biomass (Table 5).

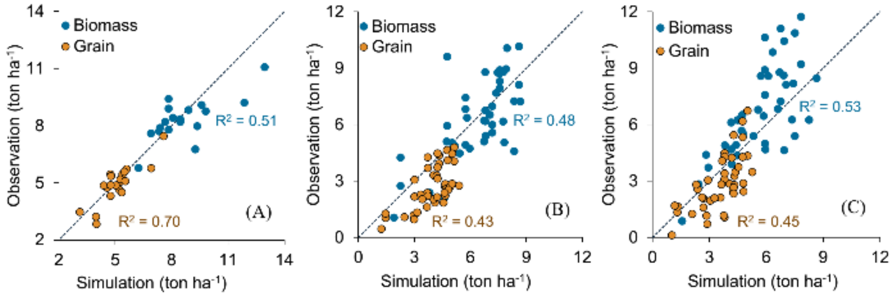

Figure 26. Linear relationships between observed and estimated maize grain and biomass when validating (A) sole maize, (B) longan-maize-grass, (C) and mango-maize-grass agroforestry models using data in replicates 1, 2, and 3 of longan-mango-maize-grass experiment.

Table 5. Root mean square error (RMSE) and mean absolute error (MAE) of maize grain yield and biomass in sole maize, longan-maize-grass agroforestry (longan-AF) and mango-maize-grass (mango-AF) models

Model	**Grain yield (ton ha^{-1})**		**Biomass (ton ha^{-1})**	
	RMSE	MAE	RMSE	MAE
Sole maize	0.66	0.42	1.32	0.88
Longan-AF	0.59	1.30	1.05	1.24
Mango-AF	0.71	1.06	1.20	1.70

In the agroforestry models, light distribution was calibrated by adjusting the tree sizes (height and biomass). With the current version of the AF models, we could simulate soil water availability during the rainy season in a satisfactory manner. However, it strongly underestimated close to the tree rows and grass strips in zones 4 (Figure 27A) and 7 (Figure 27B) during the dry season. The under-estimation was found in both the longan-AF and mango-AF models.

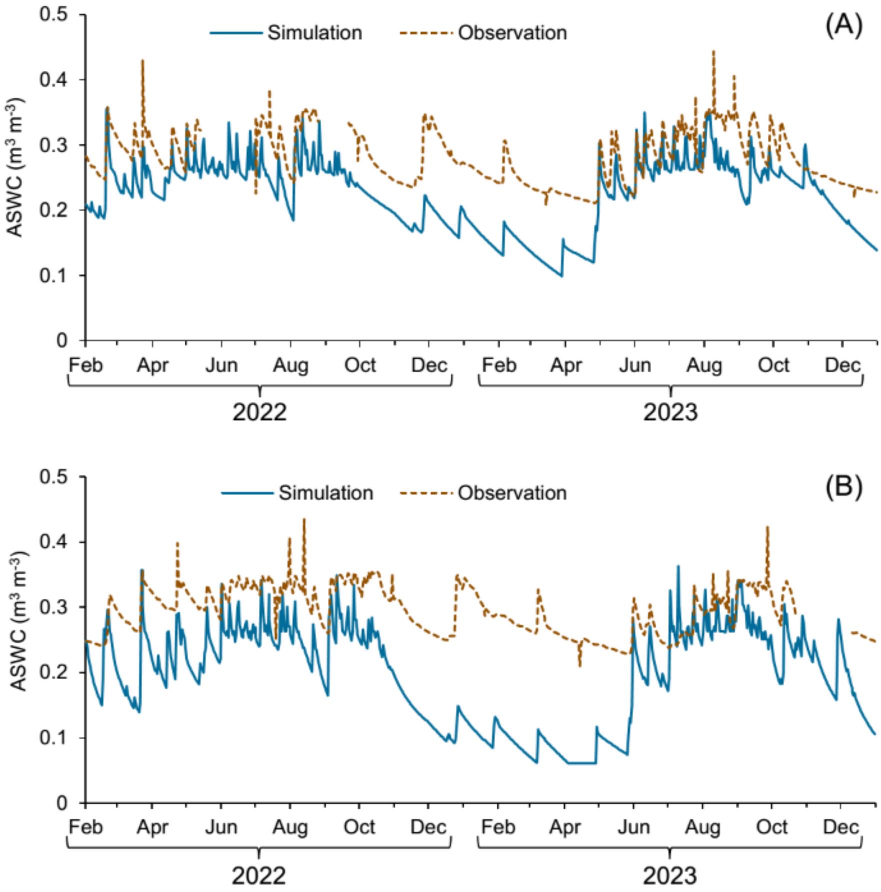

Figure 27. Simulated and observed available soil water content (ASWC) in 0-20 cm soil layer, (A) above fruit tree row (zone 4) and (B) below grass strip (zone 7), in mango-maize-grass agroforestry sub-treatment of longan-mango-maize-grass experiment.

Nitrogen (N) uptake by plants is closely related to the soil mineral N concentration (Kaye & Hart, 1997), indicating that the status of N in the system is reflected by total plant N. Our leaf SPAD data (Figure 28A) showed lower plant N concentration below grass strips in both longan-AF and mango-AF sub-treatments ($p < 0.001$) whilst the biomass was also smaller, reflecting a considerably lower N uptake. These results were in line with the simulated total N in plant biomass data (Figure 28B) in different maize zones.

(A)

	Zone	2022 Jun-3	2022 Jun-18	2022 Jun-30	2022 Jul-15	2023 Jul-7	2023 Jul-22	2023 Aug-12	2023 Aug-31
longan-AF	1	37.5	42.3	54.1	58.3	34.2	50.5	52.8	57.0
	2	37.3	47.3	56.0	57.6	37.0	47.8	52.2	51.1
	3	37.3	41.1	51.9	51.8	39.2	46.1	51.5	51.8
	4	33.4	45.5	51.5	56.0	36.9	46.0	50.2	55.8
	7	35.3	29.5	44.1	46.7	34.7	41.0	42.4	41.9
	8	32.5	39.9	48.8	51.5	31.2	49.6	43.8	48.6
	9	34.3	39.1	53.0	56.7	34.8	38.6	44.6	53.8
mango-AF	1	39.4	38.8	49.8	48.7	37.5	48.3	47.8	50.3
	2	46.3	42.8	51.4	52.6	40.5	46.4	52.6	49.5
	3	40.3	39.3	51.5	52.0	42.0	49.7	47.0	57.1
	4	34.8	37.5	51.5	55.7	43.2	55.5	46.2	53.0
	7	23.5	24.6	44.3	44.5	36.1	40.3	49.9	47.5
	8	38.8	39.6	50.3	49.4	37.4	42.4	51.2	51.0
	9	36.7	42.8	52.7	51.5	35.7	48.0	45.8	52.7

(B)

	Zone	2022 3Jun22	2022 18Jun22	2022 30Jun22	2022 15Jul22	2023 7Jul23	2023 22Jul23	2023 12Aug23	2023 31Aug23
longan-AF	1	0.05	0.43	1.92	3.50	0.04	0.68	2.38	4.40
	2	0.04	0.35	1.59	2.92	0.03	0.53	1.90	3.55
	3	0.03	0.27	1.25	2.35	0.05	0.76	2.63	4.88
	4	0.03	0.26	1.21	2.28	0.04	0.70	2.46	4.32
	7	0.02	0.15	0.71	1.46	0.03	0.40	1.61	3.21
	8	0.02	0.16	0.74	1.49	0.04	0.51	1.97	3.88
	9	0.03	0.20	0.97	1.87	0.04	0.52	1.97	3.91
mango-AF	1	0.04	0.30	1.40	2.59	0.05	0.75	2.60	4.80
	2	0.04	0.32	1.50	2.76	0.04	0.61	2.14	3.98
	3	0.03	0.26	1.21	2.27	0.04	0.64	2.27	4.32
	4	0.02	0.17	0.83	1.66	0.04	0.55	2.11	4.04
	7	0.02	0.11	0.54	1.12	0.03	0.35	1.29	1.98
	8	0.03	0.22	1.05	2.06	0.06	0.80	2.68	4.00
	9	0.03	0.23	1.10	2.11	0.04	0.64	2.29	4.40

Figure 28. (A) Observed maize leaf SPAD values and (B) simulated total N in aboveground maize biomass, in longan-maize-grass (longan-AF) and mango-maize-grass (mango-AF) sub-treatments. The different colours indicate levels of values given in the boxes within each data occasion. A high value is greener, whereas a low value is more yellow.

5.6.2 Legume relay-cropping as a potential option

The simulations showed that the three legume species would have almost similar effects on maize growth and yield. Adding legume relay-cropping into the sole maize and longan-AF models caused a slight reduction in both maize biomass and grain yield (Figure 29A, C). However, an opposite effect was found in the mango-AF model where maize biomass and grain yield were higher than without legume integration (Figure 29B).

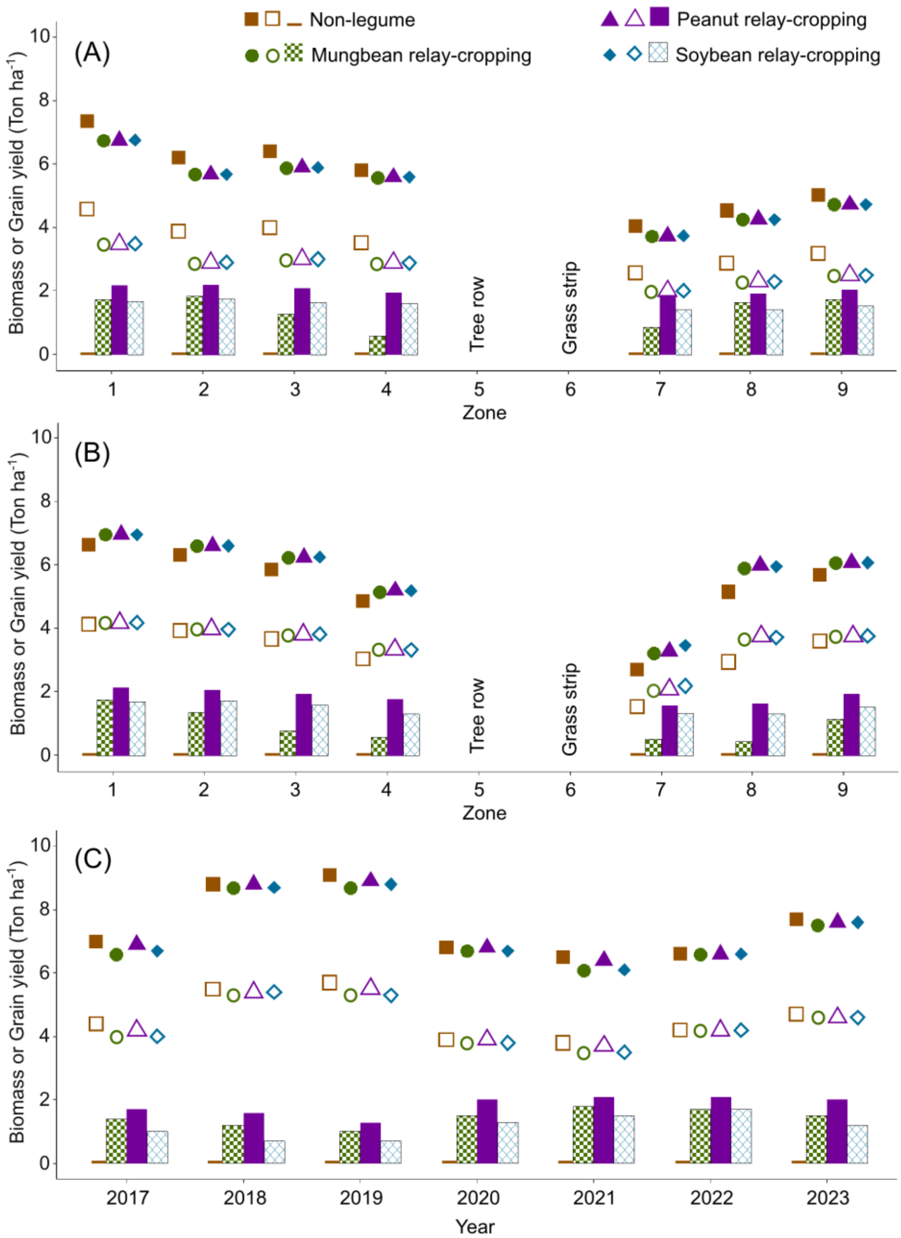

Figure 29. The simulations of (A) longan-AF, (B) mango-AF agroforestry and (C) sole maize models. Performances of maize biomass (filled symbol), maize grain (open symbol), and legume grain (bar) in non-legume and legume relay-cropping scenarios.

Among the three legumes, the simulations predicted that peanut yield would be the highest, followed by mungbean and soybean. The yield of the three legumes was reduced in mango-AF compared to longan-AF, with mungbean relay-cropping showing the largest yield reduction (Figure 29A-C). Adding peanut prolonged the cropping season the most with an 11 week extension in 2022 (Figure 30A, C) and about 9 weeks in 2023 (Figure 30B, D). Mungbean and soybean seasons ended 1 and 3 weeks earlier than peanut, respectively.

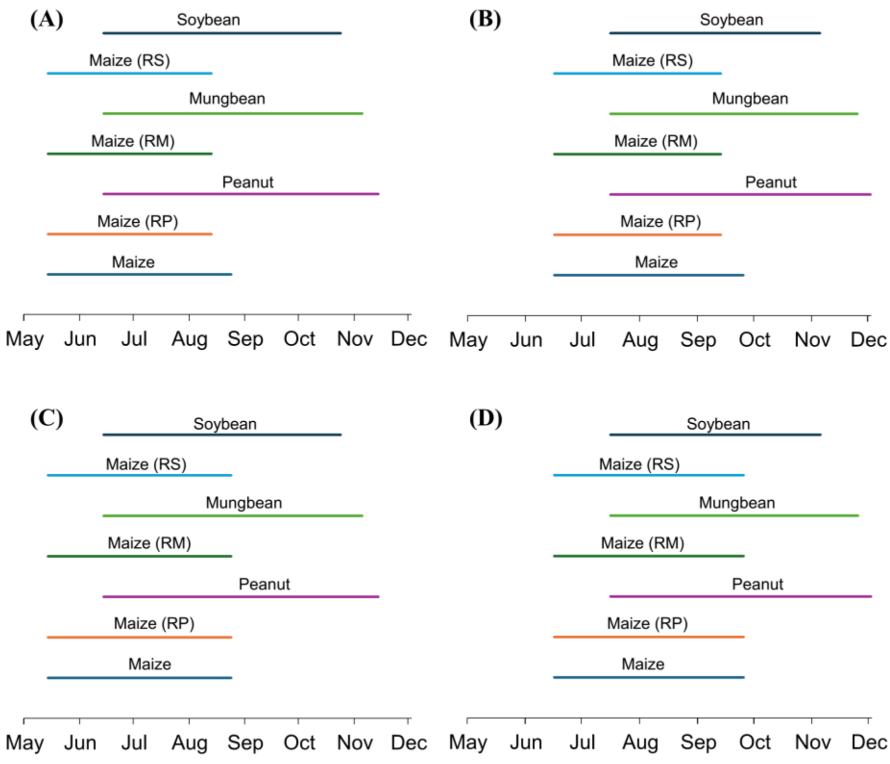

Figure 30. Seasonal timelines modelled with relay-peanut (RP), relay-mungbean (RM), relay-soybean (RS) and without relay-cropping in the fruit tree-maize-agroforestry for (A) 2022 and (B) 2023, and in the maize systems for (C) 2022 and (D) 2023.

The simulation showed higher total nitrogen (N) in the soil when integrating legumes into both fruit tree-maize-AF (data not shown) and maize systems (Figure 31). However, the simulations also showed a trend of reducing total N in maize, longan-AF, and mango-AF systems over time in scenarios with- and without adding relay-legumes.

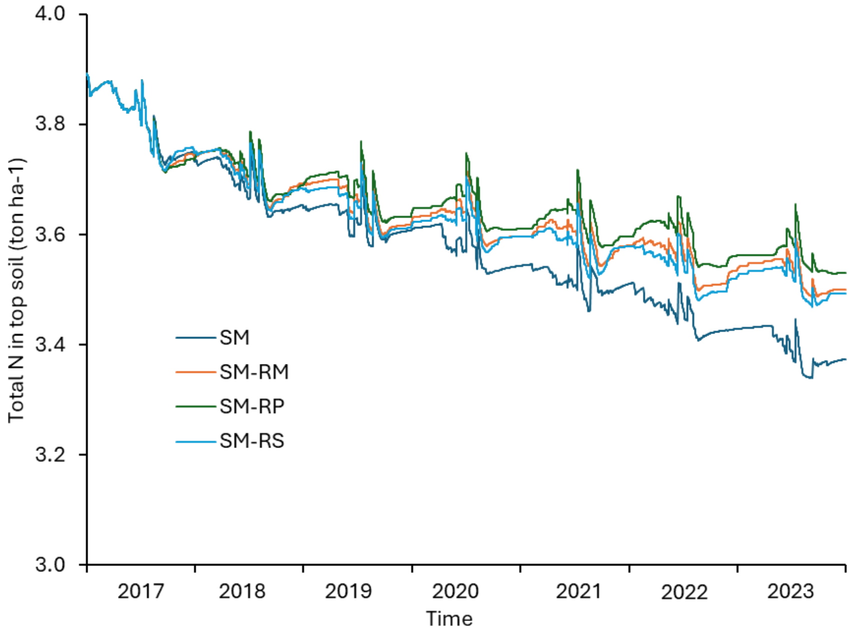

Figure 31. Estimated values of total nitrogen (N) in topsoil layer (0-20 cm) in sole maize (SM) and its relay-cropping with mungbean (SM-RM), peanut (SM-RP), and soybean (SM-RS) by modelling.

6. Discussion

6.1 Slope affects resource distribution in fruit tree-based agroforestry on sloping land

6.1.1 Light distribution and interception

Light reaching the experimental areas was less than total incident light in both sites. The experiments faced west-southwest and were affected by the hillslope delaying the sunrise and shortening the day length (Miller, 1981). Tall trees surrounding the experiments probably also shaded the experiment to a certain extent and reduced the amount of light reaching the crop level in the experiments (Aguilar et al., 2010; Malézieux et al., 2009). In the agroforestry systems, the amount of incident light to the crops was lower close to the tree rows compared to farther way (Paper I), in agreement with findings by Nicodemo et al. (2016) and Abbasi Surki et al. (2020).

The incident light to the crop level is known to be significantly influenced by tree size, including height, canopy width, and canopy structure (Ong et al., 2015). However, with the management practices used in the current experiments, shading was not a significant factor in determining yield (Paper I). Considering both economic and environmental targets, the experiments in this study were designed with a 10 m spacing between tree rows (Paper I-III). This is in line with current recommendations that aim for an appropriate balance between erosion protection and productivity (Friday et al., 1999). On flat land, farmers can use a wider spacing between tree rows due to the lower risk of soil erosion (Hou et al., 2003), which results in a lower shading impact on the crop compared to narrower row spacing.

In this study, downslope crops received a smaller fraction of light than upslope crops (Paper I), which appears to be a novel finding. On the upslope side of the trees, slope decreased the tree canopy's altitude relative to the crop level whilst it increased it on the downslope side. This difference was more apparent in longan-mango-maize-AF, because of regular pruning, than in sontra-coffee-AF where tree height and canopy width were subjected to limited control, causing much shading both up- and downslope of the tree rows.

The maize season lasted less than 4 months in longan-mango-maize-AF (Tollenaar & Dwyer, 1999), whilst longan and mango intercepted between 0.1 and 0.2 fraction of the incident light depending on the species and season (Paper I). Therefore, large amounts of light reached the soil surface and were available for weeds, notably after the maize season. This can be expected to particularly favour growth of weed species that have a high light demand (Dhyani et al., 2009) and increase their consumption of resources, of which water especially is in short supply during the dry winter season (Paper II). In sontra-coffee-AF, coffee maintained a more stable soil cover throughout the year, but light reaching the soil surface especially between coffee rows or within the tree rows, was still abundant.

6.1.2 Soil water distribution

The available soil water content (ASWC) in short periods after precipitation was typically higher in maize zones upslope than downslope of the tree row and grass strips (Paper II). The difference between up- and downslope in this study could be attributed to the grass strips, which acted as 'living fences' (Bosi et al., 2020) and prevented soil erosion (Song et al., 2020), formed terraces (Do et al., 2023) that reduced the slope gradient, and trapped runoff (Tuan et al., 2014), thereby allowing more time for water infiltration and increasing water storage above the grass strips (Melville & Morgan, 2001). The effect of the trees´ root systems (Bosi et al., 2020) and the soil cover from trees/grass (Agus et al., 1997; Hernández et al., 2015) may have improved soil structure (e.g. aggregate formation) and decreased bulk density (Meetei et al., 2020; Zhai et al., 2022), and also possibly enhanced water infiltration and ASWC along the tree rows and grass strips (Huang et al., 2014).

The zone immediately upslope of the tree rows showed the same tendency as the rainy season of having higher average ASWC than other zones, especially the grass strip zone (Paper II). Longan and mango are evergreen fruit tree species (Carr, 2014; Hong, 2021) and maintained a stable shade over seasons, thus reducing heat flux to the soil surface (Paper I) and soil water evaporation (Ilstedt et al., 2016). There are also theories claiming that tree root systems can lift water from deeper soil layers in a so-called “hydraulic lift” and contribute to soil moisture in shallower layers (Kitajima et al., 2013), but such mechanisms have been rejected by other researchers (e.g. Nie et al., 2012). Furthermore, the larger distance to the grass strips most likely decreased the effect of grass water consumption in the zone upslope of the tree rows, contributing to higher ASWC compared to the zone downslope.

6.1.3 Soil organic carbon and nutrient distribution

The overall increase in SOC and soil total N observed in plum-coffee-legume-AF after three experimental years compared to the fields before the experiment was established confirms the beneficial effects of the AF systems (Paper III). This study’s result was in line with a previous study partially conducted on the same sites used in Paper I and II in the current thesis, by Do et al. (2023). The authors reported a reduction of SOC and nutrient losses in AF (without legumes) compared with sole maize due to the terrace formation. Adding understory legumes helped to increase SOC and N (Paper III). The positive effect of AF on SOC and total N corroborates findings by a number of researchers (Dollinger & Jose, 2018; i.e. Kremer & Kussman, 2011; Ong et al., 2015; Zake et al., 2015).

The overall concentrations of available P and K decreased in all plum-coffee-legume-AF treatments, especially with understory legume integration (Paper III). This result was in line with Arévalo-Gardini (2015) and Ilany et al. (2010) and was likely caused by larger total biomass growth and nutrient demand in the treatments with understory legumes (Dou et al., 2022; Wei et al., 2024; Gitari et al., 2018). In our study, we fertilised the fruit trees to fulfil their expected needs, but grass and legumes were mainly there to increase resource use efficiencies, and they were therefore not fertilised. Hence, the need of the crops was higher than those supplemented by fertilisation during the experimental period.

The increase in SOC in the AF system with understory legume integration (Paper III) would potentially improve soil fertility in the long term, which has been shown in biological function, aggregate stability, and soil organic

N content (Diacono & Montemurro, 2011). Plants take up nutrients from the soil and bind in their tissues, therefore certain nutrients will accumulate in the organic matter, particularly if the produced plant biomass is not harvested and becomes temporarily unavailable. The nutrients will eventually be released through decomposition and mineralisation processes (Havlin et al., 2006), but the accumulation can cause deficits in the meanwhile. The rate of decomposition and mineralisation depends on various factors such as characteristics of the plant residues (Ntonta et al., 2022), soil fauna and microbial communities (Frouz, 2018), other biophysical factors (i.e. weather, soil condition; Turmel et al., 2015), and management of the residues (Loomis et al., 2020). In addition, SOC enrichment enhances humus formation, which leads to higher cation and water holding capacity in the soil (Havlin et al., 2006), thus higher nutrient availability can be expected to increase in the long-term.

In the centre of the grass strip and immediately below, SOC, total N, available P and K were lower than in the fruit tree row and midway between two tree rows (Paper III). This result is partially supported by a previous study also conducted in the longan-mango-maize-AF experiment used for Papers I and II of the current thesis (Do et al. 2025). In that study, the higher SOC and nutrient concentrations upslope of the tree rows and grass strips were explained by the terrace formation and nutrient accumulation caused by the grass serving as a barrier, whilst erosion occurred below the grass strips (Do et al., 2023). The lower SOC within the grass strips was unexpected given the dense root system of the grass and the expected high C inputs to the soil (Paper IV). Grass roots may have retained their physical structure until the sampling occasion due to the slow decomposition rate caused by their high lignin concentration (Sumiyoshi et al., 2017). Resultingly, much of the grass roots may have been removed during sample sieving at 2 mm before analysis (MOST, 2011b).

The reduction of soil nutrients within and below the grass strips was most likely due to efficient nutrient uptake by the unfertilised grass (Paper III) and the export of nutrients through harvested grass (about 3 tons of dry grass biomass ha^{-1}). This result also agreed with Pou et al. (2011), who reported lower soil nutrient concentrations when integrating perennial grass strips. The plant available nutrients, particularly N, was likely insufficient for vigorous grass growth in the experiments. Grass requires 120 kg N fertiliser ha^{-1} to produce about 8 tons of dry biomass under tropical conditions

(Castagnara et al., 2011). Indeed, Strotz (2023) observed that farmers in the study region actively fertilised grass to increase the grass production. To improve the grass production, fertiliser application may be needed for the grass strip, and the rates increased just below the strips to maintain soil nutrient balance and manage competition between system components.

6.1.4 Modelling crop yield and resource distribution

The APSIM model demonstrated satisfactory simulation of maize grain yield in the sole maize system (Paper IV). This has also been achieved in a number of previous studies that modelled maize performance using APSIM (Archontoulis et al., 2014; Dilla et al., 2018; Sun et al., 2016; Zhou et al., 2022) or other models, such as WaNuLCAS (Khongdee et al., 2022) and DSSAT (Worou et al., 2018). However, the biomass simulation was less accurate compared to the grain yield simulation in the sole maize model, similar to findings by Morel et al. (2020), who found that maize growth in the latter part of the season was not satisfactorily simulated. In this study, maize structure, including height and leaf number were calibrated with data collected in replicate 4 in 2023. The underestimation of biomass could be attributed to the accumulation constant rate of maize biomass from photosynthesis in APSIM (Brown et al., 2021), being lower than the actual value of PAC999Super, which was the maize cultivar used in the current study.

The longan-AF and mango-AF models showed potential to simulate maize grain and biomass (Paper IV). When validating models with data from replicates 1-3, the higher observed values in replicate 1 were mainly responsible for the lower accuracy of longan-AF and mango-AF models than in the sole maize model. This discrepancy could be caused by site-specific factors, such as smaller trees in replicate 1 compared to those in the other replicates, whilst tree parameters from replicate 4 were used to calibrate light distribution in the APSIM models. Additionally, replicate 1 was located near the top of the hill, where it was possibly less affected by shade (Paper I). Consequently, maize performed better there than in other replicates and the simulation.

Agroforestry models have been previously reported, such as APSIM Gliricidia-maize model (Smethurst et al., 2017) and WaNuLCAS model (Hussain et al., 2016; Khasanah et al., 2015). However, crop growth and yield were affected differently on the up- and downslope sides of the tree rows and grass strips (Paper I-III). Dilla et al. (2020) assessed the effect of shade on maize in different zones relative to tree rows horizontally (only in a 2D model) and did not examine the effect of different slope sides. Similarly, the AF windbreak model in the APSIM library could simulate the crop yield at various distances from the tree row, but only in one direction (Huth et al., 2002). This study´s attempt to simulate the difference between up- and downslope is thus novel and presents a valuable addition to the agroforestry model library.

The APSIM agroforestry models performed well in simulating soil water during the rainy season. However, during the dry season, the simulation strongly underestimated soil water and predicted extreme competition for soil water around the tree rows and grass strips (Paper IV). In contrast, higher ASWC was observed in these zones compared to the simulation (Paper II). This suggests that certain factors may not be considered in the AF models. For example, the effect of the fruit trees and grass strips on terrace formation (Do et al., 2023), water trapping (Melville & Morgan, 2001), and/or microclimate improvement (Lasco et al., 2014) may not be adequately simulated in the current AF models. This argument is similar to a report by Kraft et al. (2021) who expressed that APSIM was limited in capturing surface friction and preferential flow path infiltration.

The APSIM models demonstrated a potential to simulate the nutrient distribution within the system, e.g. by showing the lowest soil N estimates below the grass strips. It also predicted that the effect of nutrient depletion declined in zones farther away from the grass strips (Paper IV). The stronger competition for soil nutrients below the grass strips was configured and calibrated through root length distribution in the Tree proxy module. This model prediction was in line with observed maize grain yield and was supported by previous APSIM work by Dilla et al. (2020).

In summary, the AF models used in this study had the potential to simulate maize grain yield, biomass, and resource distribution at plot-scale on sloping land. However, several limitations were identified, including the inaccuracies of water simulation in the dry season, the dynamics of light and nutrient distribution, and the effectiveness of microclimate. We also could not properly calibrate the grass strips in these models, and the grass strips played a significant role in resource use and biomass production in the AF system. Proper calibration of grass is necessary to improve model accuracy.

6.2 Potential resource limitation in the fruit tree-based agroforestry on sloping land

Agroforestry maintained vegetation cover better than sole crops, due to the canopies of both evergreen (longan, and mango) and deciduous (sontra and plum) trees, and the perennial grass strips (guinea and mulato). Thus, AF systems can capture more light compared to sole crop systems (maize and coffee). In addition, the conservation role of trees and grass resulted in higher ASWC in AF than in sole maize measured shortly after the rain events. However, resource utilisation by trees and grass caused competition issues. The difference in ASWC between AF and sole maize during the maize season was relatively small due to high precipitation during the maize growing season (Paper I-II). The lower ASWC in AF during the flowering stage of the fruit trees, which occurs during the dry season, indicates that water availability can be an issue for the trees. The increase in SOC and N with AF (Paper III) reflected the superiority of AF in accumulating SOC (Do et al., 2023) and preventing N loss (i.e. via soil erosion, runoff) (Tuan et al., 2014). On the other hand, the overall decrease in available P and K in AF (Paper III) emphasised the importance of adjusting fertiliser rates as demand increases with additional system components.

Crops performed poorly and yielded less than average immediately below the tree rows and grass strips but performed better in the zones further downslope (Papers I-III). Maize is an C4 plant (Usuda et al., 1985) and is sensitive to light limitation (Bellasio & Griffiths, 2014; Drost, 2020; Macatanong et al., 2022). Reduced light decreases photosynthetic rates and crop yield in maize AF (Peng et al., 2009; Suryanto et al., 2014) and could explain part of the yield loss in the zone immediately below the grass strips (Papers II and IV). Coffee below the grass strips in sontra-coffee-AF received approximately 0.6 fraction of total incident light (Paper I) but this is within the optimum range for yield of coffee (Soto-Pinto et al., 2000) and therefore unlikely limited the coffee performance. The difference between ASWC in different zones was small in the maize season (Paper II). A maize cultivar with similar yield requires about 500 mm (Chen et al., 2010), whereas seasonal rainfall surpassed 800 mm in the experiments (Papers II and III) and exceeded the combined demand of tree, crop, and grass. However, drought periods can still impact yields. The dry spell during tasselling and silking in 2022 likely caused the low maize grain yield and Harvest Index (HI) (Paper II). Maize sensitivity to stress during these development stages (Tollenaar & Dwyer, 1999) probably reduced pollination effectiveness (Vennam et al., 2023), grain numbers and weights (Safdar et al., 2016). The similar HI in all zones and treatments (Paper II) indicated that that the differences in maize performance between zones occurred during the juvenile stages of maize and affected both vegetative and reproductive organs (Cerrudo et al., 2012). Lower leaf SPAD values and biomass immediately below grass strips than farther away indicated less available N in this zone (Papers I and III). Since no fertiliser was applied to the grass strips, they apparently exploited nutrients and competed with crops for those nutrients. About 1.4-3.0 ton of grass dry biomass per hectare was annually harvested and removed from the field (Papers II and III). The two grass species in this study are highly nutritional with an N concentration in the biomass of approximately 2 % (Argel, 1993; Silva et al., 2016; Sokupa et al., 2024; Strotz, 2023), therefore, harvesting grass may have removed 28-60 kg N per hectare and other soil nutrients.

On the upslope side of tree rows and grass strips, there was no difference in crop yield and ASWC between the different zones (Papers I-III). Immediately above tree row (zone 4), both maize and coffee produced higher yield and biomass despite receiving and intercepting a similar fraction of incident light compared to downslope (zone 7). The tree rows showed higher nutrient concentrations than the grass strips and immediately below but were not different from zones farther away (Paper III). Upslope crops growing close to the tree rows may have utilised the fertilisers applied to the trees and experienced reduced stresses (i.e. drought, extreme temperature) due to the favourable microclimate created by trees (Nair & Garrity, 2012). These benefits could offset any potential negative effect of competition on upslope crop near the tree row.

6.3 Options to improve agroforestry on sloping land

6.3.1 Species selection

The growth habits of fruit trees, crops, and grass affect the light distribution and utilisation in the AF systems. To improve resource use and reduce competition, combining diverse species of trees and crops which exploit complementary resource pools has been recommended (Ong et al., 1991). For example, deep-rooted tree species potentially optimises the use of drainage water from the top- and upper subsoil (Kitajima et al., 2013). Longan and mango are evergreen species (Hernández Delgado et al., 2011; Pham et al., 2015) and maintain stable light to lower levels, whilst sontra and plum are deciduous species (Duo et al., 2003; Tiep et al., 2018; Ziska et al., 1989) and subsequently intercept considerably less light after leaf-fall. These tree species further exhibited different phenology traits, such as the timing of flowering, which is a stage when resource utilisation peaks. For example, longan, mango, and sontra/plum in our experiments flowered during February-April, December-February, January-March, respectively. Longan and plum have more shallow root systems than mango and sontra (Huang et al., 2020), and may thus consume proportionally more water from the shallow soil layers than mango and sontra that can take up water from deeper soil layers. On sloping land, trees with deep root systems can reduce the risk of land slides (Hairiah et al., 2020). The nutrient demand of different fruit species also varies (Litz, 2009; Ma et al., 2022; Menzel & Waite, 2005) and should be considered when selecting species, arranging them in the field, and planning management.

Selecting appropriate companion crops can help minimise the negative effect of competition and optimise the resource use. Shade-tolerant species or cultivars should be considered for the downslope side of fruit trees and grass strips, where incident light is lower than upslope (Paper I), to reduce the negative effect of shading. The species selection also must consider other microclimate conditions in AF compared to sole crops (Cleugh, 1998), as demonstrated by the scenarios testing where understory legumes performed differently, with peanut yielding the highest, followed by soybean and mungbean (Paper IV). If annual crops should be grown during the dry season, it is important to select cultivars that can produce yield with lower available water compared to the rainy season, as was in the case of for hill rice (Kamoshita et al., 2008), maize (Edmeades et al., 1997), bean (López-Salinas et al., 2011), and cassava (El-Sharkawy, 1993). There is also the option of choosing native species, since they generally survive during the dry season, such as *Streptocaulon juventas* (Lour.) Merr. and/or *Gymnopetalum cohinchinensis* (Lour.) Kurz, both of which were observed in the experimental areas. We additionally observed that farmers changed crops over the years when noticing yield reductions (Figure 32). This crop rotation practice can improve the nutrient status of the crops because crops differ in their nutrient requirements (Ouda et al., 2018). Moreover, rotation can also help control pests, diseases (Zohry & Ouda, 2018) and weeds (Paper III).

Figure 32. Farmers replaced maize with cassava in the longan-mango-maize-grass agroforestry system in the 2024 season. Photo was taken in June 2024.

In our experiments, within and below grass strips showed the lowest resource availability, especially regarding light and nutrients (Papers I and III). Selecting a different grass species than guinea and mulato grass, which were used in the current experiments, could be an option to reduce grass competition. Grass species with lower height can be used to reduce potential light competition with main crops (e.g. Figure 33). For example, mulato grass in plum-coffee-legume-AF had lower height than guinea grass in the other experiments and likely competed less for light. Grasses with deeper root systems such as e.g. vetiver (Hamidifar et al., 2018; Raman et al., 2018) can be considered to reduce water and nutrient competition in areas that have a high risk of erosion. In addition, current grass species in the experiments can be alternated with leguminous strips (Tuan et al., 2014) which could positively impact the soil nitrogen pool via atmospheric N_2 fixation, even though the shallow root system of certain legumes (Gómez-Carabalí et al., 2010) could cause competition with trees and crops.

Figure 33. Tree and grass shaded the below maize in longan-mango-maize-grass experiment where two farmers supported soil sampling. Photo was taken in July 2023.

6.3.2 Tree and crop arrangement

Light reaching the soil surface, especially after the maize season, (Paper I), became available for weed growth. One way to optimise the use of this resource and enhance overall system productivity is by increasing the spatial and temporal vegetation cover through system components, whilst minimising competition among them. Increasing tree and crop density could enhance soil cover (Dahmardeh, 2011), however, farmers should be aware of the trade-off, particularly the increased competition for water and nutrients. Integrating understory legumes into the fruit tree-coffee-AF system significantly improved soil vegetative cover (Paper III). The practice of relay-cropping, for example, can prolong the growing season and improve soil cover, thereby increasing light interception by cultivated components. Alternatively, farmers can switch to a long-life crop such as cassava or sugar cane (Ghosh et al., 1989; Skocaj et al., 2013) or introduce another crop after the first. However, water scarcity during the dry season may limit the feasibility of adding new crops and must be considered when introducing a crop during the dry season. In addition, to reduce grass competition with the crop downslope, farmers could increase the sowing distance between crops and the grass strip (Paper III).

Further exploration of the legume-maize relay-cropping option in the APSIM model showed a higher overall system productivity with legume than without, due to the additional legume yield. The effect varied between longan-AF and mango-AF models and among legumes (Paper IV), reflecting the diverse interactions between legumes and the main tree/crop similar to a review by Tanveer (2017). In the current model, the tree module was only calibrated with tree size and root length density at different depths and slope positions, whilst the nutrient absorption coefficient and N demand of the trees were set as random values in APSIM. Therefore, the main difference between longan-AF and mango-AF APSIM models were related to the shading area and the water and nutrients captured by trees and grass roots. Consequently, in these AF models, the performance and impact of the legume were driven by their response to the microclimatic conditions and competition for resources. The higher shade levels and more extensive root length and distribution in mango-AF, compared with longan, likely affected the modelled interaction between the legume and maize.

The modelling outcomes demonstrated that maize with legume relay-cropping could also provide several ecological benefits, particularly in enhancing resource use in fruit tree-based AF system. Legumes could also prolong the cropping season by nearly three months (Paper IV). The simulated results were supported by recent studies (e.g. Gesch et al., 2023; Jabran et al., 2020) when legumes sowing was delayed, whereas their life cycle was longer compared to the main crops. In addition, relay-cropping legumes could optimise water use (Baldé et al., 2011) as the rainfall during the maize season generally exceeded the demand (Paper II). Increased vegetative soil cover could also reduce evaporation from the soil surface, thus reducing water lost in the dry season (Ilstedt et al., 2016; Tietjen et al., 2010). Furthermore, legume relay-cropping has the potential to provide N (Punyalue et al., 2015), reduce N leaching (Tanveer et al., 2017), and nutrient losses by erosion (Tuan et al., 2014).

6.3.3 Management

The pruning and/or thinning of fruit trees may not only considered steady fruit-set, fruit quality, and management simplification, but also serve to manage the competition (for light, water and nutrients) with crop components (Kang et al., 2008; Kishore et al., 2021; Meloni & Sinoquet, 1997; Pezzopane et al., 2021). These techniques can alter root distribution, thereby reducing belowground competition (Jones et al., 1998). Moreover, practising deep-planting (Seo et al., 2017) and root pruning (Luedeling et al., 2016) may enhance tree root distribution in deeper soil layers, thus reducing the trees´ water and nutrient consumption in the topsoil (Li et al., 2021). In longan-mango-maize-AF and plum-coffee-AF, farmers performed pruning/thinning 3 – 4 times a year, with the most extensive pruning carried out during the winter and the other 2-3 thinnings conducted in spring, summer, and autumn. In fruit-coffee-AF experiment, farmers only pruned the sontra trees once during the winter season by cutting the lower branches/twigs to a 1.5 – 1.7 m height, mainly to prevent branches from collapsing onto the coffee shrubs and to facilitate management practices such as cutting grass, fertilisation, and weeding. Theoretically, more pruning should be practised for the sontra trees. However, farmers in the study area did not apply this because the market benefits could not offset the labour costs of pruning. Developing a market for higher quality sontra could therefore incentivise pruning. However, before extending such recommendations to farmers, locally wild species such as sontra should be investigated regarding their phenology, nutrient requirement, and response to different horticultural practices including pruning.

The three studied agroforestry experiments demonstrated that the integrated grass strips effectively used the nutrients available in the systems. Whilst this is beneficial in terms of preventing nutrient losses, grass management needs to focus on reducing their potential competitions with the main crops. Paper III highlighted the concerns regarding soil nutrient imbalances in the current fruit tree-based AF systems. The grass strips and legumes were not fertilised and consumed a significant amount of nutrients, which were harvested and removed from the field (as grass, stylo shoots, and peanut pods) or bound in the perennially living tissues (pintoi). To reduce competition, farmers could cut grass and legumes earlier, particularly before the sensitive stages of the main crops (Cabral et al., 2017; Jose, 2012; Macharia et al., 2010). For farmers with a low demand for forage/fodder, who cannot bear the labour requirements or the cost of “cut and carry” practices, or those practicing traditional free grazing (Do et al., 2020), grass strips could be replaced by leguminous strips (Tuan et al., 2014; Rodríguez et al., 2022), or even weed strips (Lenka et al., 2017). However, those strip types still must be managed in a good manner. For example, grass cutting and mulching would reduce the labour requirement for weed control (Pfeiffer et al., 2016). Additionally, other conservation measures could alternate the function of grass strips, such as stone bunds (Vancampenhout et al., 2006), sediment ponds or ditches (Mekonnen et al., 2015). Legume biomass could be used as green manure mulch (De Sousa et al., 2024) or incorporated into the soil to recycle nutrients. Further, also fertilising the grass strips and legumes, particularly when they are harvested as forage, could help maintain nutrient balance and reduce nutrient competition (Krapfl et al., 2016), especially during the early stage of the system, when the effective nutrient cycles are not well established. For effective fertilisation, a thorough understanding of the nutrient requirements for grass, legume, and other components (Ram et al., 2020), along with soil nutrients status (Assefa et al., 2014) is essential.

The high rain intensity during the rainy season caused erosion and nutrient losses (Do et al. 2023), whereas the long dry season posed a challenge for fruit trees and the planting of a dry season-crop, especially as access to irrigation is restricted on these sloping lands. Improving the soils´ infiltration rate and water-holding capacity by mulching (Anderson et al., 2009) and application of soil amendments (Minasny & McBratney, 2018) can increase plant-available soil water stocks and increase the proportion of rainwater used by crops. Additionally, farmers should consider storing water in the rainy season for use in the dry season. Building artificial water storage structures is a potential option. We observed that individual farmers in the region practice rainwater harvesting for different purposes (e.g. spraying fertilisers or plant protection compounds) by digging retention structures in their fields (Figure 34). However, the limited volume of the structures may only be sufficient for point irrigation of particularly sensitive trees and crops. Farmer groups or cooperatives can also build lagger rainwater-harvesting systems to collect runoff flow or store rainfall as observed in a nearby commune and reported in comparable regions (Landicho et al., 2022). However, this may require investments and consent from multiple farmers because land is often fragmented with several farmers on the same slope.

Figure 34. A small water retention structure built by farmers in a demonstration fruit tree-coffee agroforestry system on sloping land. The limited storage capacity may not provide sufficient water for the entire dry season, resultingly requiring farmers to construct multiple small ponds. Additionally, covering those structures could help reduce water loss through evaporation. Photo was taken in July 2022.

7. Conclusion and recommendations

In this PhD thesis, I assessed the influence of slope on resource distribution in fruit tree-based agroforestry on sloping uplands and the potential options to improve resource utilisation and system productivity. The key conclusions and recommendations are as follows:

- Resource distribution was affected by slope positions, more resources were available upslope of the fruit tree rows and grass strips compared to downslope.
- Incident light to the crop canopy was significantly reduced on the downslope side of fruit trees, limiting light interception by crops compared to the upslope. Light utilisation in the system overall was poor after maize harvest, suggesting the potential of additional crop(s) to optimise the use of this resource.
- Slope effects on soil water were small during the rainy season when rainfall generally exceeded tree and crop water demand but became pronounced in the dry season.
- Soil nutrients were significantly depleted within and below the grass strips, indicating strong competition in these zones. The low nutrient concentration in the grass strips reflected their effective nutrient uptake and show that the grass must be fertilised to maintain the soil fertility and productivity of the AF system.
- Nutrient availability was the most limiting factor affecting crop growth and yield. Integrating understory legumes into the agroforestry system improved soil fertility (SOC, N), but decreased plant available P and K. Improving fertilisation strategies of all system components is necessary to mitigate this negative interaction.
- Fruit tree characteristics (e.g., size and phenology) played a crucial role in resource utilisation and distribution. These factors should be carefully considered when selecting system components with different resource requirements and when planning tree management practices such as spacing and pruning.
- The APSIM model showed a potential for simulating fruit tree-based agroforestry systems on sloping land. Relay-cropping scenarios with legumes showed potential for improving system productivity and resource utilisation. The model could be useful for agroforestry

simulation and to design and explore different options, providing a scientific base for technical support in local decision-making.

8. Implications and future perspectives

- The light study was conducted on a west-southwest slope and relatively uniform gradient at each experimental site. Future research should investigate the effect of other facing directions and slope gradients to strengthen the findings on light distribution.
- Further studies are needed to examine various fruit tree and grass, and management (e.g., pruning, fertilisation), and their effects on resource distribution, crop yield, and fruit quality.
- Investigations into water retention structures should be carried out at different scales to identify which options are best suited to local conditions.
- The understory legume integration in fruit tree-coffee-grass agroforestry is still in its early stages. Long-term monitoring and assessment are necessary to evaluate their impact on soil health, tree and crop performance, market profitability, and farmers' acceptance.
- Current APSIM AF models showed potential to simulate crop yield, biomass, and resource distribution in fruit tree-based agroforestry system on sloping land. However, several challenges remain for future research:
    - Incorporating factors that drive microclimate conditions within tree rows and grass strips, which caused the large underestimation of soil water during the dry season.
    - Developing a more dynamic tree model which includes productivity of the trees, e.g. fruit yield, and enables the overall AF system productivity to be simulated.
    - Calibrating the grass species to improve the accuracy of grass simulation.

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Popular science summary

The world population is increasing rapidly and may reach 10 billion by 2050. Consequently, global agriculture must produce more than the current production to feed everyone. However, arable flat land is limited and decreasing, mainly due to urbanisation. Sloping lands, which account for one-fifth of the total global land area and host more than 900 million people, have been increasingly exploited for agriculture and play a crucial role in global food security. However, agriculture on sloping land face severe challenges, including soil erosion, nutrient depletion, ecosystem degradation, and landslides. Agroforestry, which integrates trees, shrubs, and crops, can offer more sustainable land-use on sloping lands.

This thesis assesses the distribution of key resources in agriculture, including sunlight, plant-available soil water, and plant nutrients in 3–6-year-old fruit tree-based agroforestry systems on sloping land (15-35°) in Northwest Vietnam. These systems encompass fruit trees, maize/coffee, and forage grass established along the contour line. The study also evaluates and proposes system redesigns that incorporate understory legumes to improve resource use and enhance productivity.

The results presented in Paper 1 indicate that light distribution differed above and below tree rows and grass strips. The trees shaded the crops (maize or coffee) more below the tree rows than above, but the effect decreased farther from the tree rows. Taller trees and wider canopies resulted in more shading on crops. However, light was not a limiting factor during the cropping season. The deciduous tree species, sontra, which was intercropped with coffee, dropped its leaves during the fall. As a result, the light reaching the coffee during winter was similar in both agroforestry and sole coffee system.

According to Paper 2, fruit trees and grass strips in agroforestry contributed to enhanced rainwater infiltration. The water use by the trees and grass may still reduce water availability for the other crops during dry periods. Throughout the rainy season, this effect was small due to an oversupply of rainfall, except during short dry spells. The influence of trees and grass on soil water distribution was more pronounced in the dry season, varying by tree species. The dry conditions can be mitigated by additional measures to increase water storage in the soil and reduce evaporation from the soil surface, as well as by storing excess precipitation during rainy periods for irrigation during dry periods.

The results of Paper 3 indicate that integrating understory legumes with fruit trees and coffee shrubs enhanced the positive effects of agroforestry systems on sloping land by increasing soil organic carbon and total nitrogen. However, the legumes competed with the trees and coffee for available phosphorus and potassium. This competition may have contributed to decreased coffee growth and yield during the early stages of the experiment. All experiments in my study showed lower yield and lower nutrient concentration closely below the grass strip compared to other positions within the systems. This indicates high effectiveness of the non-fertilised grass strips in capturing nutrients. Nutrient deficiency was likely the primary growth limiting factor in this study. Fertilising also the grass strips and legumes may decrease competition and enhance system productivity.

The model simulations in Paper 4 showed the potential of grain legume relay-cropping for resource optimisation and productivity improvement in fruit tree-based agroforestry systems on sloping land. Integrating relay-cropped legumes extended the growing season by two to three months, thereby improving vegetative soil cover and enhancing the utilisation of sunlight and water within the systems. Although crop yield was at times slightly reduced, the models indicated higher system productivity due to additional legume yield. Among the scenarios tested, adding relay-cropped peanut performed best, followed by mungbean, with soybean being least beneficial.

This study concluded that fruit tree-based agroforestry with contour cropping on sloping land influences resource distribution and crop productivity. This knowledge can be used to optimise the use of light and water and develop suitable nutrient management strategies.

Populärvetenskaplig sammanfattning

Världens befolkning ökar snabbt och kan komma att uppgå till 10 miljarder år 2050. Följaktligen måste det globala jordbruket producera mer än nu för att mätta alla. Den odlingsbara plana marken är dock begränsad och minskande på grund av urbanisering. Jordbruksmark på sluttningar utgör en femtedel av världens totala landyta och hyser mer än 900 miljoner människor. Sluttningar har i allt högre grad utnyttjats för jordbruk och spelar en avgörande roll för den globala livsmedelsförsörjningen. Dessa regioner står dock inför allvarliga utmaningar, bland annat jorderosion och skred, utarmning av näringsämnen och försämring av ekosystemen. Agroforestry där träd integreras med (örtartade) grödor eller buskar kan vara en hållbar markanvändning för att motverka markförstöring och uppnå ett mer hållbart jordbruk på sluttande mark.

Denna avhandling utvärderar den rumsliga fördelningen av viktiga resurser för växter, inklusive solljus, växttillgängligt markvatten och växtnäringsämnen, i 3–6-åriga fruktträdsbaserade agroforestry-system på sluttande mark (15-35°) i nordvästra Vietnam. Dessa system omfattar fruktträd, majs/kaffe och fodergräs som etablerats i rader längs fältens nivåkurvor (s.k. konturodling). Studien utvärderar och föreslår också systemändringar där lågväxande baljväxter odlas som bottengrödor för att optimera resursanvändningen och förbättra systemens produktivitet.

Artikel 1 visar att ljusfördelningen skiljde ovanför och nedanför trädraderna och gräsremsorna. Träden skuggade grödorna (majs/kaffe) mer nedanför fruktträdsraderna än ovanför, men effekten minskade på större avstånd från trädraderna. Högre träd och vidare trädkronor resulterade i större skuggning av grödorna. Ljuset var dock inte en begränsande faktor under majsens odlingssäsong. Den lövfällande trädarten, sontra, som samodlades med kaffe, fällde sina löv under hösten, vilket gjorde att den ljusmängd som nådde kaffeplantorna under vintern inte skilde mycket med eller utan träd.

Fruktträden och gräsremsorna bidrog enligt artikel 2 till att mer regnvatten infiltrerade i marken. Trädens och gräsets egen vattenförbrukning kan ändå minska vattentillgången för övriga grödor under torra perioder. Under regnperioden var denna effekt liten på grund av ett överflöd av nederbörd utom under korta perioder, medan den var mer uttalad under torrperioden och varierade beroende på trädart. Torkan kan mildras genom ytterligare åtgärder för att öka inlagringen av vatten i jorden och minska avdunstningen från markytan, samt genom att lagra nederbördsöverskottet under regnperioden för bevattning under torrperioden.

Resultaten från artikel 3 visar att integrering av baljväxter som bottengröda under fruktträd och kaffebuskar förstärkte de positiva effekterna av agroforestry-systemet på sluttande mark genom att öka markens kol- och kvävehalt. Baljväxterna konkurrerade dock med träden och kaffet om fosfor och kalium. Denna konkurrens kan ha bidragit till minskad tillväxt och avkastning hos kaffet under experimentets tidiga stadier. Alla experiment i min studie visade lägre skördar och lägre näringskoncentration nära nedanför gräsremsorna, jämfört med övriga positioner inom systemen. Detta visar de ogödslade gräsremsornas höga effektivitet när det gäller att fånga upp näringsämnen.Näringsbrist var sannolikt den primära begränsande faktorn för tillväxt i denna studie. Gödsling även av gräsremsorna och baljväxterna kan minska konkurrensen och förbättra systemens produktivitet.

Modellsimuleringarna i artikel 4 visade att reläodling av baljväxter för humankonsumtion har potential att bidra till resursoptimering och produktivitetsförbättring i fruktträdsbaserade agroforestry-system på sluttande mark. Genom att integrera reläodlade baljväxter förlängdes växtsäsongen med två till tre månader, vilket ökade grödornas marktäckning och förbättrade utnyttjandet av solljus och vatten i systemen. Även om skörden av majs ibland minskade något, visade modellerna på högre systemproduktivitet tack vare den extra skörden av baljväxter. Av de scenarier som testades visade integrering av jordnötter bäst resultat, följt av mungbönor, medan sojabönor var mindre fördelaktiga.

Slutsatsen från denna studie är att fruktträdsbaserad agroforestry med konturodling på sluttande mark påverkar resursfördelningen och grödornas produktivitet. Kunskapen kan användas för att optimera ljus- och vattenutnyttjande och för att utveckla lämpliga strategier för gödsling.

Tóm lược khoa học phổ thông

Dân số toàn cầu đang gia tăng nhanh chóng và có thể đạt mốc 10 tỷ người vào năm 2050, đòi hỏi nền nông nghiệp thế giới phải sản xuất nhiều hơn sản lượng hiện nay để đủ nuôi sống tất cả mọi người. Tuy nhiên, các diện tích đất canh tác ở đồng bằng bị giới hạn và thậm chí đang giảm dần do ảnh hưởng bởi quá trình đô thị hóa. Trước áp lực đó, con người khai thác nhiều hơn diện tích đất dốc để sản xuất nông nghiệp. Đất dốc là nơi sinh sống của hơn 900 triệu người, chiếm khoảng 1/5 diện tích đất trái đất và đóng vai trò ngày càng quan trọng trong an ninh lương thực toàn cầu. Tuy nhiên các khu vực này đang phải đối mặt với những thách thức to lớn, bao gồm xói mòn đất, suy giảm dinh dưỡng đất, suy thoái hệ sinh thái, và sạt lở đất. Nông lâm kết hợp là loại hình canh tác tích hợp cây thân gỗ vào các cánh đồng trồng trọt, có thể cung cấp giải pháp sử dụng đất dốc bền vững.

Luận án này nhằm đánh giá sự phân bố của các nguồn tài nguyên chính trong nông nghiệp, bao gồm ánh sáng, nước trong đất mà cây trồng có thể sử dụng, và dinh dưỡng đất trong các hệ thống nông lâm kết hợp dựa vào cây ăn quả. Các hệ thống thí nghiệm từ 3–6 tuổi và được thiết lập trên đất dốc (15-35°) ở Tây Bắc, Việt Nam. Các thành phần cây trồng bao gồm cây ăn quả, ngô/cà phê, và cỏ chăn nuôi. Nghiên cứu cũng đánh giá và đề xuất giải pháp cải thiện hệ thống kết hợp với các loại cây họ đậu dưới tán cây để tối ưu hóa việc sử dụng tài nguyên và tăng năng suất.

Kết quả nghiên cứu chỉ ra rằng sự phân bố ánh sáng phụ thuộc vào vị trí của cây trồng trên đất dốc và khoảng cách đến hàng cây và băng cỏ. Ánh sáng chiếu tới cây trồng và lượng ánh sáng cây trồng hấp thụ (ngô/cà phê) thấp hơn ở sườn dốc phía dưới so với phía trên của hàng cây. Tác động của cây ăn quả đối với ánh sáng bên dưới tán giảm dần khi khoảng cách đến hàng cây xa hơn. Kích thước cây (chiều cao và rộng tán) tỉ lệ thuận với mức độ che bóng. Tuy nhiên ánh sáng không phải là yếu tố hạn chế năng suất của ngô và cà phê. Cây sơn tra rụng lá vào mùa thu, cho phép ánh sáng chiếu đến cà phê tương tự với công thức trồng cà phê không có cây che bóng.

Cây ăn quả và các băng cỏ trong nông lâm kết hợp góp phần tăng tốc độ thấm nước mưa vào đất. Tuy nhiên, nhu cầu nước của cây ăn quả và cỏ có thể làm giảm lượng nước cung cấp cho cây trồng trong các thời kỳ khô hạn. Trong mùa mưa, sự cạnh tranh của cây và cỏ không đáng kể do lượng mưa nhiều hơn nhu cầu của cây trồng trừ khi có khô hạn xảy ra. Ảnh hưởng của cây và cỏ trong mùa khô thể hiện rõ rệt và phụ thuộc vào loài cây. Tình trạng khô hạn có thể được giảm bớt bằng các cách tăng cường khả năng giữ nước của đất, hạn chế sự bốc hơi nước từ đất, và tích trữ nước dư thừa trong mùa mưa để tưới cho cây trồng trong các thời kỳ khô hạn.

Kỹ thuật trồng xen cây họ đậu dưới tán cây ăn quả giúp tăng cường các tác động tích cực của canh tác nông lâm kết hợp, làm gia tăng hàm lượng carbon hữu cơ và tổng nitơ trong đất. Tuy nhiên, các loài cây họ đậu cũng cạnh tranh lân và kali với cây ăn quả và cà phê, làm giảm tốc độ sinh trưởng và năng suất cà phê trong giai đoạn đầu của thí nghiệm. Tất cả các thí nghiệm đều cho thấy năng suất cây trồng và hàm lượng các chất dinh dưỡng ở phía dưới dốc gần băng cỏ thì thấp hơn so với các vị trí khác trong mô hình. Điều này cho thấy băng cỏ có khả năng hấp thụ chất dinh dưỡng hiệu quả trong hệ thống nông lâm kết hợp. Các kết quả nghiên cứu chỉ ra rằng sự suy giảm chất dinh dưỡng trong đất là yếu tố hạn chế chính đối với năng suất cây trồng trong nghiên cứu này. Bón phân cho băng cỏ và cây họ đậu có thể làm giảm sự cạnh tranh dinh dưỡng và tăng năng suất của hệ thống.

Nghiên cứu mô hình hóa cho thấy tiềm năng của việc trồng xen gối vụ cây họ đậu để tối ưu hóa tài nguyên và cải thiện năng suất trong các hệ thống nông lâm kết hợp dựa trên cây ăn quả trên đất dốc. Cây họ đậu kéo dài mùa vụ thêm hai đến ba tháng, do đó duy trì lớp phủ đất thực vật và tăng cường sử dụng hiệu quả ánh sáng mặt trời và nước. Mặc dù năng suất cây trồng đôi khi giảm nhẹ, các mô phỏng chỉ ra tổng năng suất hệ thống cao hơn do có thêm sản phẩm từ cây họ đậu. Trong số các kịch bản mô phỏng, việc trồng xen gối vụ cây lạc cho thấy hiệu quả cao nhất, tiếp theo là đậu xanh, trong khi đậu nành cho hiệu quả thấp nhất.

Nghiên cứu kết luận nông lâm kết hợp canh tác theo đường đồng mức dựa vào cây ăn quả trên đất dốc ảnh hưởng đến sự phân bố tài nguyên và năng suất cây trồng. Các tri thức khoa học từ nghiên cứu có thể được sử dụng để tối ưu hóa việc sử dụng tài nguyên ánh sáng và nước, cũng như phát triển chiến lược quản lý chất dinh dưỡng phù hợp.

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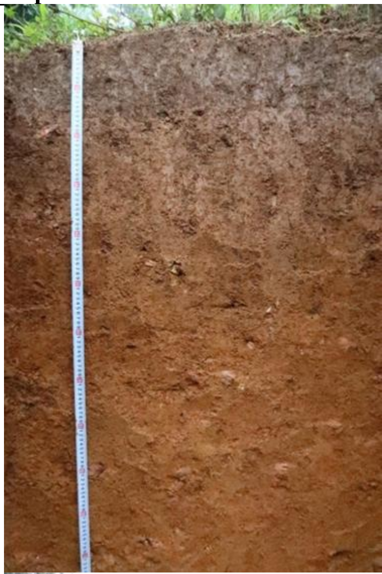
Appendix

Appendix 1A. Soil profile at plum-coffee-grass-understory legume agroforestry

Criterion	Experimental Field 1
Location	Hua Sa A village, Toa Tinh commune, Tuan Giao, Dien Bien, Vietnam
Farmer name	Lau A Sinh, Hang Thi Manh
GPS	N: 21,57695; E: 103,496974
Elevation	1150 (masl)
Slope/aspect	28.4^{o}, West
Vegetation	Coffee, fruit trees, weeds
Historical cultivation	Before 2020: annual crop From 2020: fruit-coffee AF
Date ofobservation	29 July 2023
Soil layer	Ap; 0-16 cm; 7.5 YR 4/3 moist; 7.5 YR 5/4 dry; light sticky; very low fine porosity; many very fine roots; clear smooth boundary. B1; 16-24 cm; 7.5 YR 4/4 moist; 7.5 YR 5/6 dry; light sticky; very low very fine porosity; common very fine roots. B2; 24-69 cm; 7.5 YR 4/6 moist; 7.5 YR 5/8 dry; light sticky; very low fine porosity; few very fine roots. BC; 69-120 cm; 7. 5 YR 5/8 moist; 7.5 YR 6/8 dry; light sticky; very low fine porosity; very few very fine roots; few coarse gravels (platy).
Soil name *	Humic Rhodic Ferralsol

Criterion	Experimental Field 1
Photo of soil profile	
Vegetation	

* Source: Nguyen & Vu, (2019)

Appendix 1B. Soil profile at plum-coffee-grass-understory legume agroforestry

Criterion	Experimental Field 2
Location	Hua Sa A village, Toa Tinh commune, Tuan Giao, Dien Bien, Vietnam
Farmer name	Giang A Mua, Lau Thi Sinh
GPS	N: 21,57696; E: 103,496501
Elevation	1110 (masl)
Slope/aspect	29.0^{o}, West
Vegetation	Coffee, fruit trees, weeds
Historical cultivation	Before 2020: annual crop From 2020: fruit-coffee AF
Date ofobservation	28 July 2023

Criterion	Experimental Field 2
Soil layer	Ap; 0-20 cm; 7.5 YR 4/3 moist; 7.5 YR 5/6 dry; sticky; very low fine porosity; many fine roots. B1; 20-43 cm; 7.5 YR 4/4 moist; 7.5 YR 5/6 dry; light sticky; very low very fine porosity; many very fine roots. B2; 43-81 cm; 7.5 YR 4/6 moist; 7.5 YR 5/8 dry; light sticky; very low very fine porosity; common very fine roots. BC; 81-120 cm; 7.5 YR 5/8 moist; 7.5 YR 6/8 dry; light sticky;no porosity; few very fine roots; common coarse gravel (subangular blocky).
Soil name *	Humic Rhodic Ferralsol
Photo of soil profile	
Vegetation	

* Source: Nguyen & Vu, (2019)

Appendix 1C. Soil profile at plum-coffee-grass-understory legume agroforestry

Criterion	Experimental Field 3
Location	Hua Sa A village, Toa Tinh commune, Tuan Giao, Dien Bien, Vietnam
Farmer name	Giang A Ho, Vang Thi Sinh
GPS	N: 21,573269; E: 103,496258
Elevation	1167 (masl)
Slope/aspect	34.2^{o}, West
Vegetation	Coffee, fruit trees, weeds
Historical cultivation	Before 2020: annual crop From 2020: fruit-coffee AF
Date ofobservation	28 July 2023
Soil layer	Ap; 0-23 cm; 7.5 YR 4/3 moist; 7.5 YR 5/4 dry; very sticky; very low medium porosity; many very fine roots; clear smooth boundary. B1; 23-47 cm; 7.5 YR 4/6 moist; 7.5 YR 5/6 dry; sticky; very low fine porosity; few very fine roots; very few medium gravels. B2; 47-72 cm; 7.5 YR 5/6 moist; 7.5 YR 5/8 dry; light sticky; low fine porosity; few very fine roots; very few medium gravels. B3; 72-120 cm; 7.5 YR 5/8 moist; 7.5 YR 6/8 dry; light sticky; very low fine porosity; none roots; very few fine gravel (platy).
Soil name *	Humic Rhodic Ferralsol

Criterion	Experimental Field 3
Photo of soil profile	
Vegetation	

* Source: Nguyen & Vu, (2019)

Appendix 2. Soil parameters used for modelling sole maize and agroforestry systems in Paper IV

Soil properties		Soil depth (cm)			
		0-20	*20-40*	*40-60*	*60-100*
Water content [a]	*Air dry ($cm*cm^{-3}$)*	0.065	0.113	0.128	0.080
	Drained lower limit [b] ($mm\ mm^{-1}$)	0.130	0.226	0.256	0.160
	Drained upper limit [c] ($mm\ mm^{-1}$)	0.276	0.361	0.388	0.257
	Saturated ($mm\ mm^{-1}$)	0.484	0.489	0.502	0.413
	Maize lower limit [d] ($mm\ mm^{-1}$)	0.130	0.226	0.256	0.160
	KS ($mm\ day^{-1}$)	553.9	127.4	87.6	219.8
PAWC [a], (mm)		28.2	27.4	26.6	38.4
Fractional water extraction [a] ($mm*mm^{-1}*day^{-1}$)					
F_{biom} [a,e]		0.035	0.020	0.015	0.015
F_{Inert} [a,f]		0.4	0.5	0.7	0.95
pH (water)		5.0	5.0	4.8	4.9
NH_4 initial		10.0	13.6	13.5	13.2
NO_3 initial		20.0	24.7	23.3	18.5

[a] These parameters were adjusted during model tuning. [b] equal to Permanent Wilting Point. [c] equal to Field Capacity. [d] the lowest soil water content that Maize can extract and assuming as Permanent Wilting Point. KS = Saturated Hydraulic Conductivity. PAWC = plant available water content. [e] F_{Biom} = fraction of carbon in microbial biomass. [f] F_{Inert} = fraction of inert carbon

Appendix 3. Fertilization parameters in sole maize and agroforestry models (Paper IV)

Sowing and applying basal fertilizer:

2017-06-15 [Fertiliser].Apply(Amount: 30, Type: Fertiliser.Types.UreaN, Depth: 100)
2018-06-03 [Fertiliser].Apply(Amount: 30, Type: Fertiliser.Types.UreaN, Depth: 100)
2019-06-20 [Fertiliser].Apply(Amount: 30, Type: Fertiliser.Types.UreaN, Depth: 100)
2020-05-30 [Fertiliser].Apply(Amount: 30, Type: Fertiliser.Types.UreaN, Depth: 100)
2021-06-09 [Fertiliser].Apply(Amount: 30, Type: Fertiliser.Types.UreaN, Depth: 100)
2022-05-14 [Fertiliser].Apply(Amount: 30, Type: Fertiliser.Types.UreaN, Depth: 100)
2023-06-16 [Fertiliser].Apply(Amount: 30, Type: Fertiliser.Types.UreaN, Depth: 100)

Topdressing:

2017-07-07 [Fertiliser].Apply(Amount: 80, Type: Fertiliser.Types.UreaN, Depth: 0)
2017-08-16 [Fertiliser].Apply(Amount: 80, Type: Fertiliser.Types.UreaN, Depth: 0)
2018-07-07 [Fertiliser].Apply(Amount: 80, Type: Fertiliser.Types.UreaN, Depth: 0)
2018-08-04 [Fertiliser].Apply(Amount: 80, Type: Fertiliser.Types.UreaN, Depth: 0)
2019-07-13 [Fertiliser].Apply(Amount: 80, Type: Fertiliser.Types.UreaN, Depth: 0)
2019-08-22 [Fertiliser].Apply(Amount: 80, Type: Fertiliser.Types.UreaN, Depth: 0)
2020-07-03 [Fertiliser].Apply(Amount: 80, Type: Fertiliser.Types.UreaN, Depth: 0)
2020-08-09 [Fertiliser].Apply(Amount: 80, Type: Fertiliser.Types.UreaN, Depth: 0)
2021-07-11 [Fertiliser].Apply(Amount: 80, Type: Fertiliser.Types.UreaN, Depth: 0)
2021-08-24 [Fertiliser].Apply(Amount: 80, Type: Fertiliser.Types.UreaN, Depth: 0)
2022-06-15 [Fertiliser].Apply(Amount: 84, Type: Fertiliser.Types.UreaN, Depth: 0)
2022-07-15 [Fertiliser].Apply(Amount: 42, Type: Fertiliser.Types.UreaN, Depth: 0)
2023-07-14 [Fertiliser].Apply(Amount: 84, Type: Fertiliser.Types.UreaN, Depth: 0)
2023-08-11 [Fertiliser].Apply(Amount: 42, Type: Fertiliser.Types.UreaN, Depth: 0)

Appendix 4. Maize phenology calibration (Paper IV)

[Phenology].Juvenile.Target.FixedValue = 220
[Phenology].Photosensitive.Target.XYPairs.X = 0, 12.4, 24
[Phenology].Photosensitive.Target.XYPairs.Y = 0, 0, 90
[Phenology].GrainFilling.Target.FixedValue = 502
[Structure].Phyllochron.Phyllochron.Phyllochron.XYPairs.X = 1, 4, 4.2, 10.5, 11
[Structure].Phyllochron.Phyllochron.Phyllochron.XYPairs.Y = 26, 26, 46, 46, 70
[Grain].WaterContent.FixedValue = 0.12
[Grain].MaximumGrainsPerCob.FixedValue = 580
[Grain].MaximumPotentialGrainSize.FixedValue = 0.35

I

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Research article

Light distribution at the fruit tree-crop interface and consequences for yield in sloping upland agroforestry

Huu Thuong Pham [a,b,*], Nguyen La [b], Ingrid Öborn [a], Göran Bergkvist [a], Rachmat Mulia [b], Sigrun Dahlin [a]

[a] *Department of Crop Production Ecology, Swedish University of Agricultural Sciences (SLU), Sweden*
[b] *World Agroforestry (CIFOR-ICRAF Vietnam) Viet Nam*

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Light distribution
Light interception
Sloping land

ABSTRACT

Agroforestry can improve soil conservation and overall farm productivity compared with sole-crop systems, but its benefits are limited by competitive interactions between tree and crop components. Studies on light competition have been performed on relatively flat land, but slope can influence light distribution. Little is known about optimizing light utilization and enhancing system productivity and/or income from agroforestry on sloping land.

This study examined how slope influences light distribution and performance of maize and coffee crops in fruit tree-crop agroforestry. Starting hypotheses were that 1) crops upslope of tree rows receive and intercept greater amounts of light than those downslope; and 2) position of the crop is more important for light interception and yield when fruit trees have a large, dense canopy.

Five-year-old fruit-crop agroforestry experiments on west-southwest facing slopes were revisited. Each agroforestry treatment was divided into nine zones relative to the tree rows (zone 5), with zones 1–4 upslope and 6–9 downslope of the fruit tree row. Light distribution was assessed using Hemiview and SunScan and compared with that in sole-maize and sole-coffee systems. Crop growth and yield were also recorded.

Incident light to the crop was higher in the sole-crop system than in agroforestry. In agroforestry, incident light to the crops was lower downslope of trees than upslope but increased with increasing distance from the tree rows. On average, 0.40–0.50 fraction of total light reached the soil surface. Downslope had a stronger negative effect on light distribution and crop yield than upslope. The available light at the soil surface provides scope for additional components. Further studies on the light demands of different crops during the season could improve system design.

Abbreviations

AF	Agroforestry
Longan-AF	Longan-maize agroforestry sub-treatment
Mango-AF	Mango-maize agroforestry sub-treatment
Fruit-maize-AF	Fruit tree-maize-grass agroforestry
Fruit-coffee-AF	Fruit tree-coffee-grass agroforestry

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* Corresponding author. Department of Crop Production Ecology, Swedish University of Agricultural Sciences (SLU), Sweden.
E-mail address: huu.thuong.pham@slu.se (H.T. Pham).

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(*continued*)

LAI	Leaf area index
SM	Sole maize
SC	Sole coffee
SS1	SunScan probe
BF5	Sunshine sensor
PDA	Handheld computer
D10	Tree trunk diameter at 10 cm height above the ground
D15	Coffee stem diameter at 15 cm height above the ground
LA	Plant leaf area

1. Introduction

Sloping uplands play a vital role in sustainable development of the global economy to meet human food demand and reduce poverty [1,2], with rapid population increase creating pressure to expand agriculture onto sloping land. Sloping uplands are especially important in tropical regions, where they account for approximately 50 % of total land area [3]. Shifting cultivation has been the traditional use of sloping land for annual crop production, but population growth, land use laws, and lack of suitable land are leading to shorter fallow periods or continuous cultivation. Farmers on sloping land are facing serious problems, e.g., soil erosion, nutrient depletion, water shortage, some of which are accentuated by climate change [1] and limited road access [4]. These problems are affecting agricultural productivity, farmers' livelihoods, and sustainable development of communities on sloping land.

Agroforestry (trees on farms and in agricultural landscapes) can increase and diversify farm production and income, increase productivity, and preserve the environment [5–7]. The benefits of agroforestry derive from the combined interaction of many factors over the long-term [8]. They include higher biodiversity [9], improved soil fertility [10], increased nutrient cycling [11] and soil conservation [6], improved microclimate [12], higher soil cover [13], and pest, disease, and weed control e.g., by increasing natural enemies, distancing between plants of the same species, and trapping or outcompeting harmful agents [14,15]. Disadvantages of agroforestry include competition between trees and crops for water [16], nutrients [17,18], and light [19], and increased pest and disease pressure if one component tree or crop hosts organisms can cause damage to another component crop [20–22]. Hence, proper design and management are necessary to ensure the sustainability of agroforestry.

Incident light to the crop canopy is one of the most important natural resources that is modified in agroforestry compared with sole cropping [23,24]. Much research has been carried out in agroforestry systems to gain a better understanding of light distribution and use by trees and understory plants. Tree canopies can intercept 10–90 % of incident light [25] The remaining light is reflected (<10 %) or available to be absorbed by crops and weeds [25]. The proportion of light intercepted by tree and crop components depends on the canopy structure [26,27], the distance between trees [19], and the ability of crops to fill and utilize gaps. Biomass production by both trees and crops is correlated with light interception [28,29]. The responses to light modified by trees differ between crop species. Positive effects of reduced light intensity include increased nutrient uptake and chlorophyll content in leaves, and more favorable microclimate close to tree canopies, in some cases resulting in increased growth rate and leaf area index (LAI) of crops [22,26,30,31].

Research on light incidence and utilization in agroforestry has focused on improving system productivity by minimizing competition between components and optimizing light capture, i.e., preventing light reaching the soil surface [30,32]. Incident light to crops and crop productivity may be reduced for crops growing close to fruit tree rows [30,33–35]. On flat land, the sun's direction controls incident light in the system and trees/crops can be arranged in a north-south orientation to optimize light capture and growth [36]. On sloping land, incident light is also affected by slope gradient, slope length, and slope aspect. For example, a west- or east-facing slope reduces day length. The impact increases when slope length and slope gradient increase [37]. However, it is unclear how these general factors translate into light distribution and spatial variation in growth and yield in agroforestry on sloping land. Selecting a planting arrangement to minimize slope effects is difficult, since the slope direction largely determines the planting direction (perpendicular to the slope). Enhanced knowledge of light incidence and interception on sloping land would help promote establishment of fruit trees on sloping uplands of north-west Vietnam, which cover 254,200 ha [38]. Large numbers of fruit trees are now being introduced to cropping systems that previously consisted of sole maize or coffee. Different fruit tree species differ in terms of morphology, phenology, or physiology, and companion crops can be chosen based on market opportunities or shade tolerance. This calls for knowledge and science-based recommendations on how to optimize design and management of fruit tree-crop agroforestry systems on sloping land to meet both short- and long-term sustainability and profitability goals.

The overall aim of this study was to determine how slope influences light distribution and performance of maize and coffee crops in two semi-mature fruit tree-crop agroforestry systems on land sloping to the west-southwest, to provide evidence and experimental support for system redesign and adjustment of management practices. The hypotheses tested were that 1) crops upslope of the tree rows receive and intercept greater amounts of light than that downslope; and 2) the position of the crop is more important for light interception and yield when the fruit trees have developed a large, dense canopy.

2. Materials and methods

2.1. Site descriptions

The research was carried out in two fruit tree-crop agroforestry experiments established by the AFLi project [39] in 2017 [40]. The experiments comprised of fruit tree-maize agroforestry (fruit-maize-AF) in Mai Son district, Son La province (21.10°N, 104.06°E; 566 masl) and fruit tree-coffee agroforestry (fruit-coffee-AF) in Tuan Giao district, Dien Bien province (21.33°N, 103.30°E; 1104 masl) (Fig. 1). Both sites are characterized by a subhumid tropical climate with mean annual temperature of 21.5 °C and 18.6 °C in Mai Son and Tuan Giao, respectively. The sites have a rainy season from May to October and a dry season from November to April. Annual rainfall during the period 1989–2022 was on average 1380 mm in Mai Son and 1680 mm in Tuan Giao, mostly falling from May to August. Sole cropping was the typical practice at both sites before the establishment of agroforestry, with farmers mainly planting annual crops such as upland rice and maize in Mai Son and upland rice, maize, and coffee in Tuan Giao.

The fruit-maize-AF system has 15–26° slope (mean 21°), while that in the fruit-coffee-AF system is 24–34° (mean 29°). These ranges are representative of sloping lands in Northwest Vietnam. Both fields face west-southwest. The soils in both experiments are classified as Acrisols and have 1.8 % (Mai Son) and 2.0 % (Tuan Giao) soil organic carbon (SOC) in the Ap-horizon. The soil texture varies with depth, with clay content of 18 % (Mai Son) and 17 % (Tuan Giao) % in the Ap-horizons increasing to 42 and 30 %, respectively, in the B2 horizon (around 45–55 cm depth), and decreasing to 25 and 22 %, respectively in the BC horizon. Nutrient concentrations (especially K and P) are low at both sites and soil pH (H_2O) is low in fruit-maize-AF (5.5) and very low (4.0) in fruit-coffee-AF. Detailed information about the soil characteristics of both sites is given by Do et al. [40].

2.2. Field experiments, study design, and management

2.2.1. Field experiments

The field experiments had a randomized complete block design with four replicates and two treatments: agroforestry and sole cropping (Fig. 2). In fruit-maize-AF, longan (*Dimocarpus longan* Lour. 'PHM-99-1-1') and mango (*Mangifera indica* L. 'GL4') were intercropped with maize (*Zea mays* L. 'PAC999Super') and guinea grass (*Panicum maximum* Jacq. 'Mombasa'). All trees and crops were planted as single-species rows along the contour lines considering both environmental and economic aspects, and the farmers' management techniques. Also following the dominating farmer management, the trees were free-standing and pruned as described in section 2.2.3. The distance between two rows of the same fruit species was 20 m and the distance within rows was 4 m (125 trees/ha). The longan and mango fruit species were planted in alternate rows, so that the distance between two tree rows was 10 m (i.e. in total

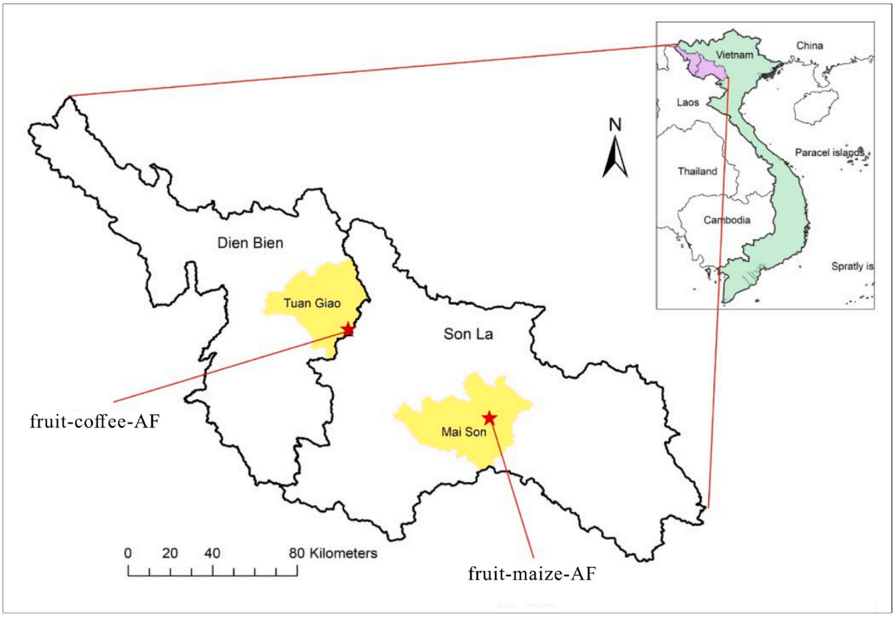

Fig. 1. Location of the fruit tree-maize agroforestry (fruit-maize-AF) system in Mai Son district, Son La province, and fruit tree-coffee agroforestry (fruit-coffee-AF) system in Tuan Giao District, Dien Bien province.

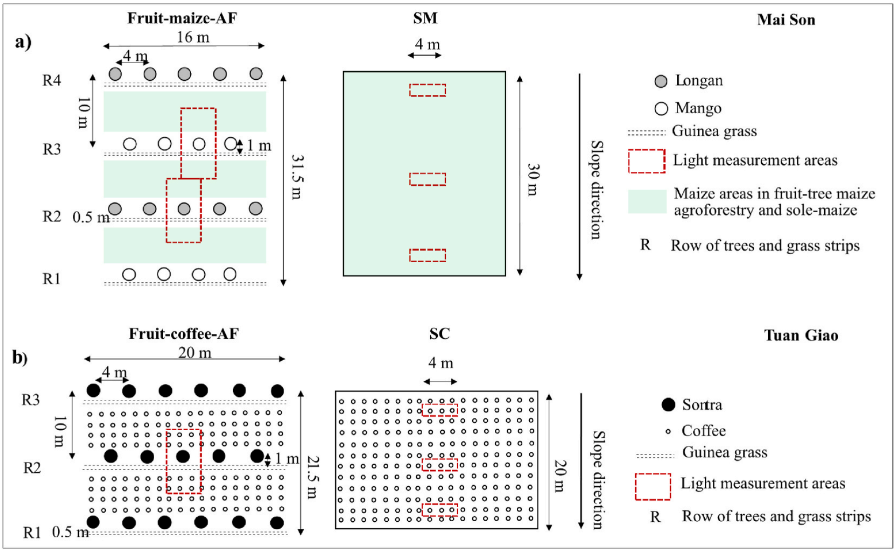

Fig. 2. Field experiment design and data collection areas at (a) Mai Son: fruit tree-maize agroforestry (fruit-maize-AF) and sole-maize (SM) treatments and (b) Tuan Giao: fruit tree-coffee agroforestry (fruit-coffee-AF) and sole-coffee (SC) treatments. Adjusted from Do et al. [40].

250 trees/ha). Double grass strips were planted at the downslope side of the tree rows, with a distance to the tree row of 1 m and a distance between two grass strips of 0.5 m. In 2022 (season six of the agroforestry system), maize was sown with 0.7 m between rows and 0.3 m within rows. The closest maize row upslope of the trees was planted 1.2 m from the tree trunks, while on the downslope it was planted 1.25 m from the center of the grass strips. Due to the increased tree canopies, maize was not sown in the fruit trees rows as done during earlier stages of the experiment [40]. Fruit trees and grass strips accounted for approximately 30 % of the land in the fruit-maize-AF system in 2022. In the sole-maize treatment, maize was sown as in the agroforestry system, but on 100 % of the land, giving a density of 71,000 plants/ha.

In fruit-coffee-AF, sontra (*Docynia indica* (Wall.) Decne.) was intercropped with coffee (*Coffea arabica* L. 'Catimor') and guinea grass (*Panicum maximum* Jacq. 'Mombasa'), all planted along the contour line (Fig. 2) similar to the fruit-maize-AF. The distance between two sontra rows was 10 m and the within-row distance was 4 m (250 trees/ha). Double grass strips were planted as in fruit-maize-AF. Between two sontra rows, four coffee rows were planted with 2 m between rows and 1.4 m within rows. The nearest coffee row on the upslope of the trees was 1.5 m from the sontra row, while on the downslope it was 1.25 m from the center of the grass strip. In the sole-coffee (SC) system, coffee was planted with the same distance between and within coffee rows as in the agroforestry system.

2.2.2. *Study design*

In fruit-maize-AF, the agroforestry plots were divided into two AF sub-treatments with longan-maize-grass (longan-AF) and mango-

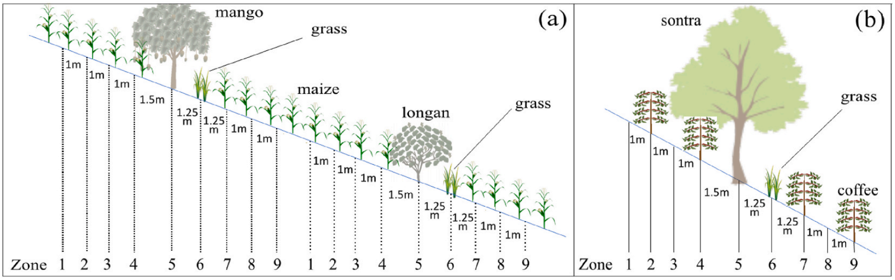

Fig. 3. Center of zones in longan-maize-grass (longan-AF) and mango-maize-grass (mango-AF) sub-systems in (a) the fruit tree-maize agroforestry (fruit-maize-AF) and (b) fruit tree-coffee agroforestry (fruit-coffee-AF) systems. The general shape and size of the tree canopies is indicated by the size of the icons. Icon sources: https://depositphotos.com/vectors/tree.html.

maize-grass (mango-AF) sequences, respectively. To test the hypothesis on light distribution, nine zones were identified along the slope of all agroforestry plots in both experiments: zones 1 to 4 on the upslope side and zones 6 (grass strips) to 9 on the downslope side of tree row (zone 5). The width of each crop zone (1–4 and 7–9) was 1 m, as the center of two neighboring crop zones was 1 m apart. The center of zone 4 was 1.5 m from the tree trunks. The center of zone 6 and zone 7 were located 1.25 m from the tree trunks and zone 6 center, respectively (Fig. 3).

2.2.3. *Management of experimental treatments*

Maize was sown on May 14, 2022, following application of NPK (5:10:3) basal fertilizer. The maize was weeded and then top-dressed with urea and potassium at 6–7 leaves and silking stages. The total amount of nutrients applied to maize in the agroforestry sub-treatments was 192 kg N, 18 kg P, 63 kg K, and 40 kg S ha^{-1}, which was 30 % lower than in sole-maize, treatment reflecting the smaller maize area (details in Tables S1 and S3 in Supplementary Data). Fruit trees were fertilized three times (in March, June, September), with a total amount of 0.32 kg N, 0.091 kg P, 0.207 kg K, and 0.035 kg S $tree^{-1}$. In the 2022 season, fall armyworm (*Spodoptera frugiperda* (J.E. Smith)) was controlled by emmabectin benzoate active ingredient twice in June. Fipronil active ingredient was applied once, in September, to protect the fruit tree buds against young twig borer (*Niphonoclea albata*) and leaf-eating insects (*Adoretus* sp.). In fruit-coffee-AF, sontra and coffee were fertilized three times (in March, June, September), with a total of 200 kg N, 61.5 kg P, 204.6 kg K ha^{-1} and 0.18 kg N, 0.135 kg P, 0.075 kg K $tree^{-1}$, respectively (details in Tables S2 and S4). Coffee shrubs were sprayed with acetamiprid and chlorpyrifos ethyl active ingredients twice in March to control coffee scale bug (*Coccus viridis*). No fertilizer was applied to the grass in any of the experiments.

At the time of the light measurements, the trees were five years old and were bearing fruits. The mango and longan trees were pruned three times during the growing season and once after harvest according to common practice. The major pruning was in winter (November-early December) when approximately 20 % of the canopy was removed, while some gentle pruning to manage twig density was done during the summer (May–June) and autumn (August–September). After harvesting fruits in June (mango) or in September (longan), farmers cut all dead branches and fruited twigs. The sontra trees in fruit-coffee-AF were only pruned during the winter, and the pruning then restricted to removing lower branches and twigs to avoid them weighing down on the coffee shrubs. The coffee shrubs were pruned regularly in spring and summer by the host farmers, as they wanted to maintain a height of 1.6–1.7 m.

Weeding was performed several times in both experiments. In fruit-maize-AF, farmers hand-hoed before the sowing of maize as part of land preparation for maize cultivation, and again at the 6–7 leaf and silking stages, immediately before fertilization. Farmers weeded again, after harvest, in December, using a strimmer. All weed and maize residues were left in the field. In fruit-coffee-AF, farmers weeded the plots three times, by strimmer in March and September and by glufosinate ammonium in June. Details of field management in previous years (2017–2021) are given by Do et al. [40].

2.3. *Data collection*

In order to explore the distribution of light in the agroforestry systems, we collected weather data and measured incident light at crop level and light interception by the crop layer once every third month, starting in March and finishing in December. Additional measurements of light were carried out in fruit-maize-AF at the maize growing stages of 3–4, 6–7, 10–11 leaves, and silking. The growth and yield performance of crops and trees were monitored to test the relationship between crops and light distribution.

2.3.1. *Total incident light, rainfall, and temperature at the study sites*

A mini-weather station (ATMOS 41, METER Group, Inc.) was installed in the middle of fruit-maize-AF to determine incident light, rainfall, and air temperature. Incident light to fruit-coffee-AF was estimated from daily temperature [41,42], using temperature data from a nearby weather station. Rainfall was recorded manually in another experiment approximately 2 km from the fruit-coffee-AF experiment.

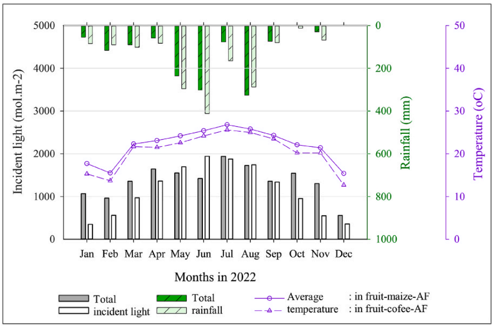

Fig. 4. Monthly total incident light, rainfall, and average temperature in the fruit tree-maize-agroforestry (fruit-maize-AF) and fruit tree-coffee-agroforestry (fruit-coffee-AF) systems in 2022.

Total incident light to fruit-maize-AF and fruit-coffee-AF was approximately 16,300 and 13,300 mol m^{-2}, respectively. Light intensity showed a peak in July–August in fruit-maize-AF, and in June–July in fruit-coffee-AF (Fig. 4). Total annual rainfall was 1365 mm in fruit-maize-AF, while fruit-coffee-AF received 1676 mm. Rain was concentrated to four months (May–August), which accounted for approximately 70 % of the total annual amount. Mean monthly temperature was above 20 °C except in December–February, and higher in fruit-maize-AF than in fruit-coffee-AF.

2.3.2. Light distribution

We combined an indirect method (Hemiview) and a direct method (SunScan) to assess light distribution. Hemiview can be used to assess the incident light above the tree canopy for the measurement day using field configurations but cannot be used at the soil surface. On the other hand, SunScan can measure light at specific times and at the soil surface, but data collection is limited by time resources (labor) and ability to work above the tree canopy. A strong correlation ($R^2 = 0.949$) was found by Hale [43] when comparing measurements from the two methods. Both methods have been used in combination by other researchers to investigate light distribution, e.g. Dong et al. [44], or to validate other methods, e.g. Zhao et al. [45].

A Canon EOS 60D digital single-lens reflex camera and fish-eye lens (Sigma EX DC 4.5 mm) were connected to a HemiView frame and a monopod and used to take hemispherical images at 1.7 m height (crop level, at the approximate maximum height of the maize and coffee canopies). All images were processed by HemiView canopy analysis software to calculate the fraction of incident light reaching the crop level ($F_{incident\ to\ crop}$). Field criteria, including longitude, latitude, altitude, slope, and measurement date, were included in the software to configure the analysis model. The threshold value was adjusted by the analyzer to avoid noise from clouds. The time in the software was set to the time of image capture. The magnetic declination value was calculated using a tool made by NOAA [46]. In Skymap, the azimuth divisions were set to 8 (45-degree divisions) and the zenith divisions to 18 (5-degree divisions), the settings typically recommended for analysis of hemispherical photographs [47]. For configuring the intercepting surface, the azimuth was set as 0, since the camera was kept at constant orientation with the support of a compass attached to the HemiView frame. The zenith value was the mean of the field slope gradient. The active side was set as single, meaning light was assumed to be intercepted by the upper part of the leaves. All images were cropped to remove interference from the camera lens. The fraction of incident light to the two agroforestry treatments was assumed to be equal to that reaching the sole-crop treatments.

Photosynthetically active radiation was measured using the SunScan canopy analysis system (SS1-COM, Delta-T), which includes a SunScan probe (SS1), a Sunshine sensor (BF5), and a handheld computer (PDA). The SS1 connects to the PDA and consists of 64 PAR sensors embedded evenly in a 1-m probe. The BF5 was placed in the middle of sole-crop plots at 1.7 m height and connected to the SS1 by a cable to provide the reference for SS1 measurements in the AF plots. In each crop zone of the agroforestry sub-systems and sole-maize system, five measurements were made 1 m apart within a maize row and five in a line half-way between two maize rows, both being closest to the middle of the zone. These measurements were at two levels, i.e., at crop level (1.7 m height, level I_1) and at the soil surface (level I_2). In zones 5 and 6, measurements were taken at five points along the center of the rows (tree rows and between two grass strips, respectively). In fruit-coffee-AF, five points, 1m apart, were measured at two levels in the centerline of each zone.

At each measurement point, the soil surface was measured first and then the SS1 was quickly moved to 1.7 m height, to minimize the effect of weather conditions. Measurements were made between 10.00 and 14.00 h on a sunny day with a clear sky, according to recommendations [48], as the sun attributes would be most stable and the effect of environmental conditions such as cloud, moisture, or haze on the light fraction minimized. The SS1 was placed horizontally along the contour line. To further minimize the effect of environmental conditions, fractions (F) were calculated. The fraction of light intercepted by the crop layer ($F_{crop\ interception}$, layer between 1.7 m height and soil surface) was calculated by Eq. (1) based on incident light at crop level ($F_{incident\ to\ crop}$), I_1, and I_2:

$$F_{crop\ interception} = F_{incident\ to\ crop} \times (I_1 - I_2)/I_1 \quad (1)$$

In the crop zones (1–4, 7–9), the crop layer was mainly crops, while in the fruit tree (5) and grass strips (6) the crop layer consisted of grass, weeds, and/or a part of the tree crown.

The light reaching the soil surface ($F_{light\ reaching\ soil}$) was calculated as the difference between $F_{incident\ to\ crop}$ and $F_{crop\ interception}$) and shown in Eq. (2):

$$F_{light\ reaching\ soil} = F_{incident\ to\ crop} - F_{crop\ interception} \quad (2)$$

The difference in latitude between the two sites is very small, and according to Miller [37] would not substantially influence the solar zenith and azimuth, which determine the energy of incident light. Besides, since the slope aspect at both sites is close to 240° from North, we assumed that they had similar sunlight regime during the year. Seasonal average $F_{light\ reaching\ soil}$, $F_{incident\ to\ crop}$, and $F_{crop\ interception}$ were computed as the average of measurements during the cropping season in both fruit-maize-AF and fruit-coffee-AF.

2.3.3. Performance of trees and crops

Tree trunk diameter (D10) at 10 cm height above the ground (due to grafting and pruning practices) [49], canopy width, and tree height were measured quarterly, in March, June, September, and December, using caliper, bamboo poles, and tape measure. Similar measurements were taken on the coffee shrubs, although stem diameter (D15) was measured at 15 cm height above ground [50].

Five maize plants in each maize zone were selected randomly to measure height, SPAD, and leaf area at the 3–4, 6–7, and 10–11 leaf stages, and silking. A SPAD reader (SPAD 502 Plus Chlorophyll Meter, Spectrum Technology Inc.) was used to assess the chlorophyll concentration. Three SPAD readings were taken, at 25 %, 50 %, and 75 % along the leaf and near the leaf's midrib of the 3rd, 6th and 10th fully expanded maize leaf and the ear position leaf at the respective growing stages, and the average was calculated. In addition, the length and width of all living leaves on these maize plants were measured to calculate the leaf area of each plant (Eq. (3)):

$$LA = (L_1 \times W_1 + L_2 \times W_2 + \ldots + L_i \times W_i) \times 0.73 \text{ (cm}^2) \quad (3)$$

where L_i and W_i are the length and width (cm), respectively, of the living leaf number I and 0.73 is a shape constant of the maize leaf [51].

Maize total aboveground biomass in the field was determined by cutting and weighing all maize plants in a sample area of 3.5 m^2 in each zone. Five random plants per zone were sampled and separated into stalks, leaves, cob, grain, and ear husk. All plant samples were weighed before and after sun-drying. Coffee cherries (the fruit that contains the coffee bean) were harvested four times from September to December. Farmers picked the ripe cherries on the first three occasions, while they picked all remaining cherries on the fourth occasion. The crop yield in each zone was computed based on crop area to discuss the links with light distribution. The system productivity for the years 2017–2021 was assessed by Do et al. [49].

2.4. Statistical analysis

All data analysis was done using R software (version 4.1.1) and R-studio software (version 2022.12.0.353), applying a statistical significance level of $p < 0.05$. The statistical significance of explanatory variables was performed using ANOVA type II Wald F tests with Kenward-Roger degree of freedom to evaluate the difference between the two agroforestry sub-treatments and the sole-maize, and between zones in the agroforestry sub-treatments. In some cases, Box-Cox or square root transformation was used to fulfill the assumption of normal distribution of the residuals. Ad-hoc pairwise analysis with the Tukey adjustment method was used to compare differences between categories. A simple linear regression model with F-test was used to test the relationship between average incident light to the crop and light interception by the crop layer on the one hand, and crop growth and yield on the other hand. Another regression tested the relationship between incident light to the crop and plot slope within each experiment.

3. Results

3.1. Tree performance

In the fruit-maize-AF system, mango trees grew faster than longan. Mean mango tree height and canopy width were 3.3 and 2.9 m, respectively, almost 1.5 times greater than those of longan. The mango canopy often reached over zone 4 and zone 6, while the longan canopy rarely did. Mean stem diameter of mango (12.3 cm) exceeded that of longan (7.3 cm) (Table S5). In the fruit-coffee-AF system, the sontra trees were over 7 m tall in December 2022 and their canopy was approximately 6 m wide. The tree canopy thus reached over the nearest coffee rows in zones 4 and 7.

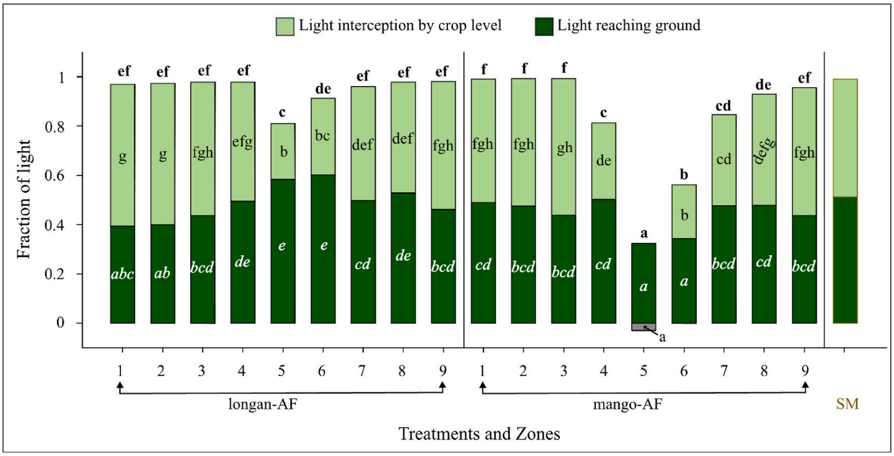

Fig. 5. Light distribution and interception in different zones in the longan-maize (longan-AF) and mango-maize (mango-AF) agroforestry sub-treatments and in sole-maize (SM), expressed as average over the maize season. Different bold, regular, and italic letters (a, b, …) indicate significant ($p < 0.05$) differences between zones within agroforestry sub-treatments in terms of incident light to maize level, light interception by maize layer, and light reaching the soil surface, respectively. The grey histogram indicates that the amount of light reaching the soil surface exceeded that reaching the 1.7 m level of the mango canopy.

3.2. Effect of slope on incident light

On each measurement occasion, fruit-maize-AF received a significantly higher fraction of light than fruit-coffee-AF, which had a steeper slope. Incident light to fruit-maize-AF was relatively similar during the year (Table S6), while incident light to fruit-coffee-AF was variable, being higher in quarter 2 than quarters 3 and 4. Within each experiment, the regression analysis between incident light and slope range showed no significant relationship ($p > 0.05$).

3.3. Light distribution in the fruit tree-maize agroforestry system

3.3.1. Incident light at maize level

Sole-maize received the highest fraction of incident light at maize level ($p < 0.01$), followed by longan-AF and then mango-AF. The fruit tree canopy five years after establishment of the agroforestry system intercepted on average 0.05 and 0.20 fraction of total incident light in longan-AF and mango-AF, respectively. Within each sub-treatment, tree light interception varied between zones. Tree canopy had a stronger effect on incident light reaching the maize downslope than upslope. Concerning the main effect of zones, zones 4 and 6 received a lower light fraction than the remaining zones. The effect of mango on incident light at maize level was significantly greater than that of longan in zones 4, 7, and 8 (Fig. 5). The influence of both fruit trees decreased when the distance from tree rows increased.

3.3.2. Light interception by the maize layer

Light interception by the maize layer differed significantly between the growth stages over the maize season ($p < 0.001$). On average, the maize intercepted 0.48 fraction at 6–7 leaves, 0.63 at 10–11 leaves, 0.51 at the silking stage, and 0.20 at harvest time. The mango trees had a greater effect than longan trees on light interception by the maize layer in zones 4 and 7, but the effect decreased with increasing distance from the tree rows (Fig. 5). The negative value of light interception in zone 5 of mango-AF shows that the incident light at the 1.7 m level of the tree canopies was less than the light reaching the ground, probably due to light coming in from the sides close to the ground.

3.3.3. Light reaching the soil surface

Before the pre-planting weeding for maize, the soil surface in sole-maize, longan-AF, and mango-AF plots received an average of 0.84, 0.83, and 0.80 fraction of total incident light, respectively. During the maize season, light reaching the soil surface did not differ between the (sub-)treatments ($p = 0.89$), but differed between maize development stages ($p < 0.001$) in the order: 10–11 leaves < silking < 6–7 leaf stages. The soil surface in the maize zones in both agroforestry sub-systems received more light than zones 5 and 6 during the off-maize season. A similar trend was found in mango-AF during the maize season, but zones 5 and 6 in longan-AF showed the opposite (Fig. 5).

3.4. Light distribution in the fruit tree-coffee agroforestry system

3.4.1. Light incidence at coffee level

Sole-coffee shrubs received a larger fraction of the incident light than coffee in the agroforestry treatment across all four measuring occasions of 2022 (Fig. 6). Incident light to the coffee increased with increasing distance from the sontra row both upslope and

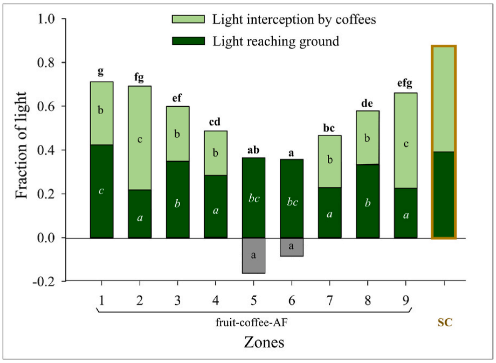

Fig. 6. Mean annual light distribution in the fruit tree-coffee agroforestry (fruit-coffee-AF) and sole-coffee (SC) systems. Different bold, regular, and italic letters (a, b, …) indicate significant differences ($p < 0.05$) between zones in fruit-coffee-AF in terms of incident light at coffee level, light interception by coffee layer, and light reaching soil surface, respectively. The grey histograms indicate that the amount of light reaching the soil surface exceeded that at the 1.7 m level in the fruit tree rows and grass strips.

downslope ($p < 0.001$). Zones on the downslope of sontra tree were slightly more impacted than upslope zones on the same distance from the tree row.

Within sole-coffee, the difference in fraction of intercepted light between measuring occasions was small (0.84–0.92). However, in the agroforestry treatment it was lowest in quarter 3 (0.49 as averaged across all zones) and highest in quarter 4 (0.61), reflecting sontra growth and leaf-drop.

3.4.2. Light interception by the coffee layer

Light interception by the crop layer was higher in sole-coffee than in the agroforestry treatment ($p < 0.05$). It was significantly lower in quarter 3 than in quarters 1 and 4 ($p = 0.003$). In fruit-coffee-AF, the coffee layer intercepted from 0.20 to 0.50 fraction of the total incident light, which declined rapidly with shorter distance to the tree row. Grass strips and tree rows received lower light intensity at the 1.7 m (crop) level than at the soil surface (Fig. 6).

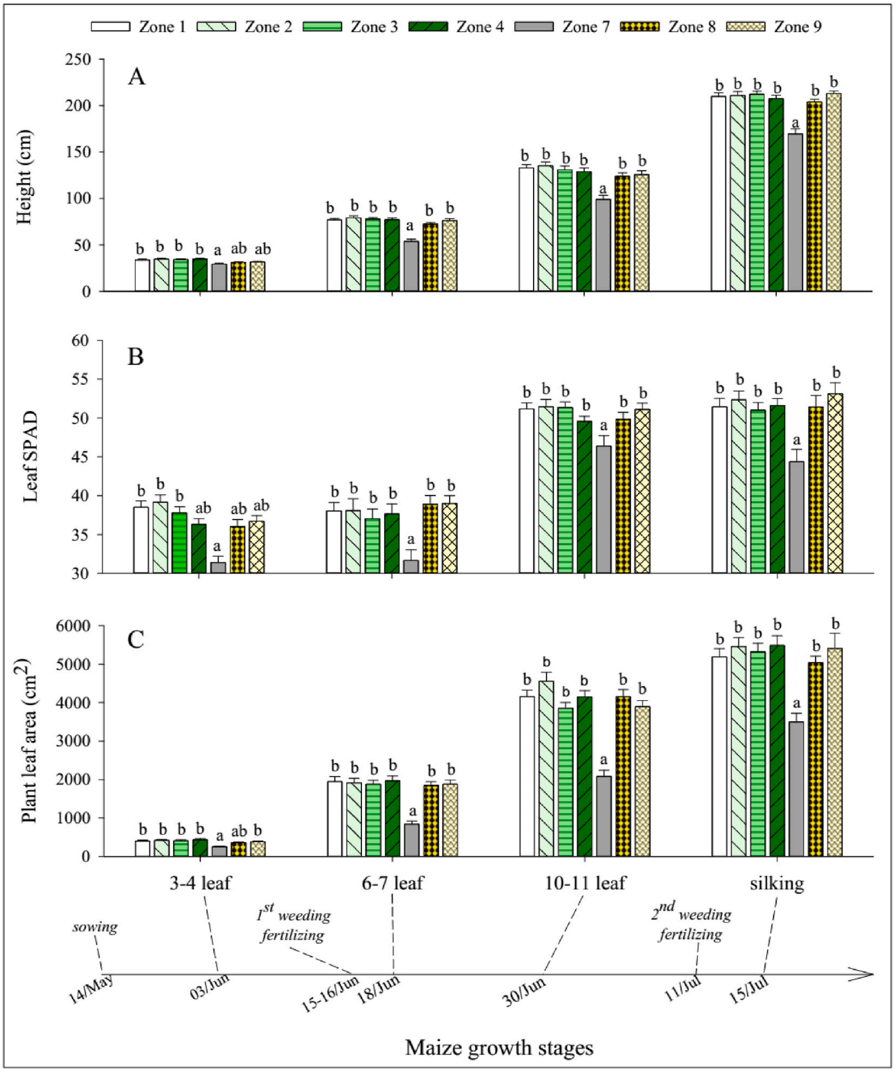

Fig. 7. (A) Maize height, (B) leaf SPAD value, and (C) leaf area in different maize zones and development stages across agroforestry sub-treatments. Different letters (a, b) indicate significant differences between zones within the respective development stage ($p < 0.05$).

3.4.3. Light reaching the soil surface

The soil surface in sole-coffee received significantly greater amount of light than that in agroforestry ($p = 0.003$). In the agroforestry treatment, light reaching the soil surface was lower within the coffee rows (zones 2, 4, 7, and 9) than between rows (zones 1, 3, and 8) ($p < 0.001$). Significantly more light reached the soil surface in the tree row than in all other zones except for grass strips and the middle alley (zone 1) (Fig. 6).

3.5. Crop growth and yield

3.5.1. Maize growth and yield in the fruit tree-maize agroforestry system

Maize showed best performance in sole-maize, followed by the plot averages of longan-AF and mango-AF sub-treatments. The maize in sole-maize was significantly taller than in the mango-AF (Fig. S1). The leaf area was also larger in sole-maize than in mango-AF at the 3–4, 6–7 and 10–11 leaf stages, but not at the silking stage. Maize height and leaf area in the longan-AF sub-treatment was intermediate and not significantly different from the others. The leaf SPAD value increased in all three (sub-)treatments from the 3 to 4 leaf stage to the silking stage, but there was no significant effect between the treatments.

The effects of competition were mainly found in the nearest maize zone on the downslope side of tree rows. Maize height (Fig. 7A), leaf SPAD values (Fig. 7B), and leaf area (Fig. 7C) in zone 7 were significantly lower than in other zones ($p < 0.001$) during all maize development stages in both longan-AF and mango-AF.

Mean maize grain yield and aboveground biomass did not differ significantly between the sole-maize and the agroforestry subsystems. Zone 7 had significantly lower yield and biomass in both agroforestry sub-systems (Fig. 8, Fig. S2). There was a tendency for grain yield and aboveground biomass to decrease with shorter distance from maize zones to the tree row on the downslope side of the trees.

3.5.2. Coffee growth and yield in the fruit tree-coffee agroforestry system

There were no significant differences between the sole-coffee and agroforestry treatments in coffee height and canopy width ($p > 0.05$). Mean coffee stem diameter tended to be slightly larger in sole-coffee than in agroforestry, with the difference being significant in December (Fig. S3). The SPAD values decreased gradually over the year and were lower in agroforestry than in sole-coffee in March.

Coffee height in zone 7 in the agroforestry treatment was significantly lower than in the other coffee zones in March (Fig. 9A). Coffee canopy width in zones 7 and 9 tended to be slightly smaller than in zones 2 and 4, but a significant difference was only found in December (Fig. 9B). Coffee stem diameter was not significantly different between the zones. Leaf SPAD values were lowest in zone 7 in March, July, and December (Fig. 9C).

Sole-coffee had significantly higher fresh cherry yield than the average of the coffee zones in agroforestry (Fig. 10). In the agroforestry treatment, coffee on the downslope of the tree row tended to have lower yield than that on the upslope, but the difference was only significant between zone 4 and zone 7.

3.6. Correlation between light and crop performance

In fruit-maize-AF, there was no significant linear relationship between incident light at maize level and maize performance ($p > 0.05$). In contrast, light interception by the maize layer was positively correlated with all maize variables, including height, SPAD value, leaf area, grain yield, and total aboveground biomass (Fig. S4). As in fruit-maize-AF, there was no correlation between incident light at coffee level, and coffee performance and yield in fruit-coffee-AF. Light interception by the coffee layer showed no significant correlation with coffee growth variables and fresh cherry yield ($p > 0.05$).

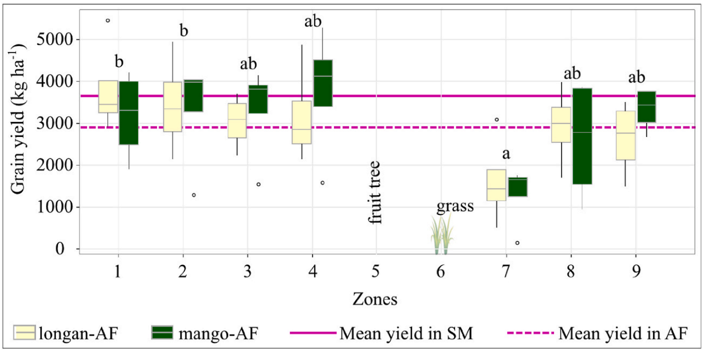

Fig. 8. Grain yield in maize zones in the longan-maize-grass (longan-AF) and mango-maize-grass (mango-AF) agroforestry sub-treatments. The main effect of zone was significant ($p < 0.001$). Different letters (a, b) indicate significant differences between maize zones ($p < 0.05$). The error bars show 95 % confidence intervals.

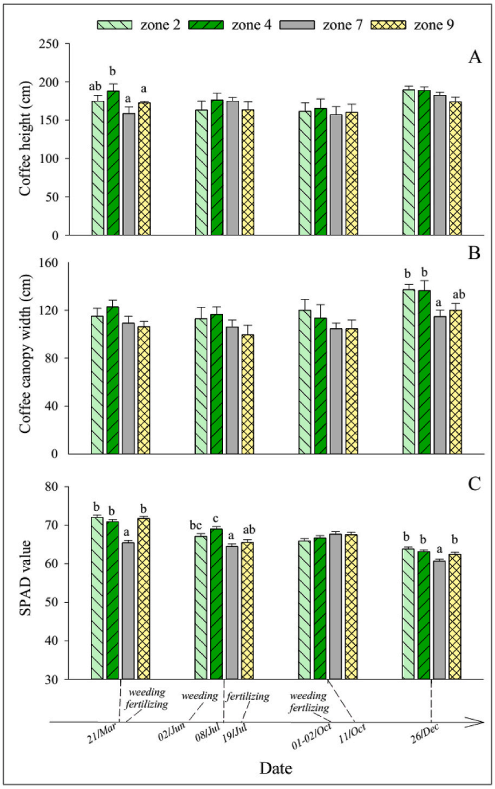

Fig. 9. (A) Coffee shrub height, (B) canopy width, and (C) leaf SPAD value in different zones of the sontra-coffee-grass (fruit-coffee-AF) agroforestry system in 2022. Error bars show 95 % confidence interval. Different letters (a–b) indicate significant differences within the respective development stage ($p < 0.05$).

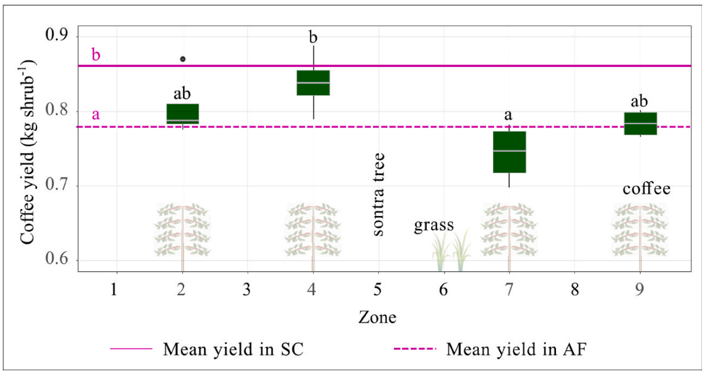

Fig. 10. Fresh coffee cherry yield in agroforestry (AF) and sole coffee (SC) plots in the sontra-coffee-grass (fruit-coffee-AF) system. Error bars show 95 % confidence interval. Different black and purple letters (a and b) indicate significant differences between zones and treatments, respectively ($p = 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. Discussion

4.1. Light distribution in the agroforestry system on sloping land

Approximately 0.99 and 0.87 fraction of total incident light reached to the crop level in sole-maize and sole-coffee, respectively. The difference was probably caused by the steeper slope in the fruit-coffee-AF experiment, which delayed the sunrise and shortened the day length [37]. Contributing factors could also have been the longer upslope hill above the fruit-coffee-AF experiment and taller trees around the experiment. This suggests that field experiments under these conditions need larger plot areas and appropriate buffer areas between treatment plots, and that all plots should be established along the same contour line to avoid the influence of upper treatment plots on downslope plots.

The seasonal average amount of fraction of incident light at crop level in different zones varied from 0.40 to 0.99 in fruit-maize-AF and from 0.40 to 0.73 in fruit-coffee-AF. The amount of incident light was lower closer to the tree rows than farther away, in agreement with findings by Nicodemo et al. [52] and Abbasi Surki et al. [19]. Fruit tree size (such as height, canopy width, and canopy structure) plays an important role in incident light at crop level [8]. Therefore, the light distribution in an agroforestry system varies depending on the system design, including the choice of tree/crop components and their allocation in the field. The experimental design in the study plots was informed by both economic and environmental targets, and therefore used a distance of 10 m between two fruit tree rows, which is suggested as optimal by the International Center for Research in Agroforestry [53]. On flat land, the lower risk of soil erosion allows farmers to use a greater distance between tree rows [54] and therefore the effect of trees on incident light can be kept lower than in agroforestry on sloping land.

The incident light at crop level was less affected upslope of the tree rows than downslope, which to our knowledge is a novel finding. The slope reduced the altitude of the tree canopy relative to the crop level on the upslope side of the trees, but increased it on the downslope side. At both sites, with west-southwest facing direction, downslope crops received a smaller proportion of the sunlight than upslope crops because of more tree shading earlier in the day. This was clearer in fruit-maize-AF, where the fruit trees were smaller with regular canopy management, than in fruit-coffee-AF, where the tree canopies were not managed and therefore larger, and shading was more similar throughout the day.

Within the fruit-maize-AF system, the soil surface in tree rows and grass strips in the longan-AF sub-treatment received a greater fraction of sunlight than the crop canopy level (1.7m), especially at the 6–7 and 10–11 maize leaf stages. A similar increase in incident light between crop canopy level and soil surface was observed in the fruit-coffee-AF system. This increase in light between the two levels could be due to reflection from other system components, diffuse light, direct sunlight in mornings and evenings when sun was low [55], and the fact that there was little vegetation below the trees in zone 5.

4.2. Crop performance in relation to light distribution under the tree canopy

Plants can adjust their organ function to adapt to changes in light availability [56]. However, their ability to adjust is weak under inhomogeneous light distribution, as in agroforestry systems, and plants experiencing inhomogeneous light can therefore be expected to be more negatively influenced than those under homogeneous low light [57]. However, shading is only a problem if light is the limiting factor for growth, and this is often not the case in agriculture [58]. Crop performance in our experiments differed between crops upslope and downslope of the tree rows. In both experiments, yields were lower on the downslope side of the tree rows than upslope. Lower yield of crops closer to the tree rows, as found on the downslope side, is in line with findings on flat land [30,33,34,59,60]. The effect of tree rows on crop performance on the downslope side was similar to their impact on incident light at crop level. This suggests that the strong effect of the trees on incident light on the downslope side was the cause of the poorer crop performance. However, it might also be caused by competition for water and nutrients [60–63] on the downslope side of the trees where double grass strips were planted to reduce soil erosion [40]. Previous studies have shown that erosion occurs below grass strips, whereas the upslope side tends to accumulate soil and water [40,64]. On the upslope side of the tree rows, we saw no trend of declining yields closer to the tree rows. The maize and coffee rows nearest above the fruit trees even tended to perform better than those farther away from the tree rows, indicating that the better performance of crops upslope than downslope of trees was not only due to less shading but most likely also competition from grass roots downslope. The crops immediately above the tree rows might also have utilized part of the nutrients applied to the trees, and might have benefited from favorable environmental conditions that trees could provide, such as lower wind velocity, better water availability, and mitigation of extreme weather events, as summarised by Nair and Garrity [65].

Incident light was thus apparently not the limiting factor for maize and coffee in our study. In fruit-maize-AF, zone 4 received an average of 0.82 fraction of total incident light and performed similarly to the middle alley (zone 1, 2), which received approximately 0.99. Maize, an annual C4 plant, has high potential photosynthetic rates at unlimited sunlight and high temperature [66], and is therefore considered to be highly sensitive to light limitation [67–69], which reduces its growth and yield [70–72]. We observed a weak correlation between light interception by maize and maize performance, so the increased light interception by the crop was probably caused by the greater maize biomass enabled by higher availability of nutrients and/or water [73,74]. In the fruit-coffee-AF system, coffee received 0.50–0.70 and intercepted 0.20–0.50 fraction of total incident light, and apparently adapted well to the shaded conditions, corroborating findings by Soto-Pinto et al. [22] that 38–48 % shade cover produces the highest coffee yield. However, Muschler [75] found that coffee performed differently when intercropped with different tree species and at reduced distance to tree rows, due to variations in competition, compatibility, weeds suppression, and disease control [76]. The reaction to shading may also vary depending on coffee cultivar [77].

4.3. System modification to optimize light capture

Management practices play a crucial role in modifying light distribution in agroforestry. Farmers usually apply cultivation techniques to accomplish particular goals, especially higher productivity and quality. One of the most common techniques is pruning woody trees and shrubs. In fruit-maize-AF, farmers carried out pruning/thinning 3–4 times a year to manage fruit tree shape and density and stimulate growth of new shoots with high-quality flower buds. Pruning and thinning also reduce the competition by the tree component in agroforestry [27,30,78,79]. In fruit-coffee-AF, farmers cut the lower branches/twigs of sontra trees once during the winter season to prevent them from collapsing onto the coffee shrubs and to facilitate other management practices such as pruning coffee shrubs, cutting grass, fertilizing, and weeding. More elaborate pruning and thinning are not usually applied to sontra trees, because farmers do not anticipate a sufficient increase in payment to offset the labor cost for pruning and they are also often unwilling to use a new practice, such as pruning of sontra, until a clear benefit has been demonstrated. Therefore, we followed the general practice and only did the minimum pruning required to facilitate other activities in the experiment. To promote quality-enhancing management strategies, there is a need to develop the market to increase price and income from quality fruit. There is a general lack of research on how sontra reacts to pruning and other management [80].

Competition can also be regulated by tree row arrangements. On flat land, north-south tree lines are recommended at high and medium latitudes to achieve homogeneous light for crops in the alley [81] while at low latitudes the direction of the rows is less important [82]. The possibility to decide row-orientation on sloping land is often limited because planting is preferably done along contours to reduce erosion and to facilitate management. However, the spacing within and between tree rows can be optimized if sufficient knowledge about resource partitioning and resource use efficiency are available [8]. To compensate for the effect of soil cultivation on soil erosion, other soil conservation measures can be integrated into the system, such as artificial terraces [83], vegetative sediment traps [84], or legume strips [85]. Changing the planting pattern such that trees and crops are assigned to the most suitable fields at landscape level would be an option, but would require consensus among farmers, and the possibilities for farmers to adapt crops to different fields are limited due to the small size of each farm.

The amount of light intercepted by the system can be increased through agroforestry practices and maintaining living vegetative cover, while ensuring that the different components are managed to achieve appropriate interactions. System modifications to achieve special goals can be made by selecting crops with suitable levels of competitive ability in time and space, managing tree and crop density, scheduling planting or sowing, fertilizing, managing weeds, pests and diseases, irrigating, and pruning tree canopy [86,87]. If fruit production is the priority, adjustments should focus on increasing tree density and applying tree management that enhances fruit yield and quality. On the other hand, if farmers prioritize understory crops or pastures giving immediate returns, managing the amount and pattern of light transmittance is more crucial [29]. Coltri et al. [88] emphasized overstory management as important to create suitable conditions for understory crops and reduce possible climate stressors. Such management depends on the architecture and seasonal growth pattern of the trees, especially for deciduous species with distinct bud bursts. Mango has a denser canopy than longan, but both are evergreen species [89,90] and maintain relatively stable light to lower levels. On the other hand, sontra is a deciduous species [80,91] with larger fluctuation in shading over the year. Our results suggest that in fruit-maize agroforestry, more severe pruning of mango trees should be implemented to reduce the shading effect and maintain a more uniform light regime. In fruit-coffee agroforestry, different pruning strategies should be tested and focused on improving sontra yield and quality.

Coffee maintains a perennial canopy, but maize has a growth cycle of only about four months at the study sites [92], leading to poor utilization of light during much of the year. Fruit-maize-AF systems should be modified to increase and prolong the vegetative cover by introducing long-life cycle crops, intercropping with e.g., leguminous species, crop rotation, or relay-cropping. For long-life cycle crops, cassava can be considered. This species takes approximately one year to complete its life cycle in the study area, and maintains living vegetative cover over the dry season [93,94]. In fact, at the fruit-maize-AF site, some farmers have replaced maize with cassava. Others have planted sugar cane, but its high competitiveness raises questions about trade-offs in light, nutrient, and water use. The long dry season during winter and subsequent water restriction is the greatest challenge for farmers who want to add more crops to prolong the season in Northwest Vietnam. Intercropping of a native crop that can survive during the dry season may be considered, e.g., we observed some native edible and medicinal species in the field, such as *Streptocaulon juventas* (Lour.) Merr., and *Gymnopetalum cohinchinensis* (Lour.) Kurz. Shade-tolerant crops such as adzuki beans (*Phaseolus calcaratus*) [64] could be introduced as understory crops close to the tree rows. In the fruit-coffee-AF system, light was not used by any crop in the space between coffee rows. An increase in light utilization can be achieved by reducing the distance between coffee rows or intercropping another crop. Although this to some degree hinders coffee management, it may help control weeds and reduce erosion as observed by the local farmers.

5. Conclusions

Both agroforestry systems studied utilized more light for biomass production than sole-crop systems and provided stable vegetative cover during the whole year, supporting light interception. Crops on the downslope side of fruit trees were more shaded than upslope crops, particularly close to tree rows. Crops' yield on the downslope also tended to be lower than in the upslope but showed a significant difference only directly below the tree and grass zones (zone 7). However, maize yield and biomass were only weakly correlated with light distribution. The impact of the trees on light distribution in the fruit tree-crop agroforestry systems varied with tree species, distance and orientation from tree rows, which should be considered when selecting system components and management strategies.

While fruit tree-crop agroforestry utilized incident light more efficiently than sole-crops, thanks to a more stable vegetative cover across the year, there were still available light resources that could be exploited in a system redesign or management plan. The lack of information about favorable light conditions for different annual and/or perennial crops calls for future studies to enable improved agroforestry design and adjustment on sloping land. The slope direction was similar at both sites in this study, so studies are needed on other slope directions. Better knowledge on canopy structures of trees depending on species and management (e.g. pruning strategies) would also benefit species selection and system design.

Ethics declarations

Review and/or approval by an ethics committee was not needed for this study because its data were collected in field experiments and involved no human participants.

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Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Huu Thuong Pham: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nguyen La:** Writing – review & editing, Supervision, Methodology. **Ingrid Öborn:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Göran Bergkvist:** Writing – review & editing, Supervision, Methodology. **Rachmat Mulia:** Writing – review & editing, Supervision. **Sigrun Dahlin:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e38655.

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Supplementary Materials

Table S1: Management activities in the fruit tree-maize (fruit-maize-AF) agroforestry system and in sole-crop maize (SM) in 2022. Details of fertilizer application are given in Table S3

Date	Treatment	Activity	Note
13-Mar-2022	AF	Fertilizing fruit trees in agroforestry (AF)	
25-Mar-2022	AF	Cutting guinea grass in AF. Thinning mango and longan flowers	
30-Mar-2022	AF + SM	Hand-hoeing weed in both AF and SM	
2-May-2022	AF	Pruning old guinea grass parts to 5 cm height in AF	For better regeneration
10-May-2022	AF + SM	Hand-hoeing weed second time before sowing maize, in both AF and SM	
14-May-2022	AF + SM	Sowing maize in both AF and SM	
29-May-2022	AF + SM	Spraying emmabectin benzoate to manage fall army worm on maize, in both AF and SM	
7-Jun-2022	AF	Cutting guinea grass in AF	
8-Jun-2022	AF	Harvesting mango	
9-Jun-2022	AF + SM	Spraying emmamectin benzoate to manage fall army worm on maize, in both AF and SM	
15-Jun-2022	AF + SM	Hand-hoeing weed first time for maize First top-dressing fertilizers for maize	Slightly late, because of the need for some sunny days for hand-hoeing
16-Jun-2022	AF	Fertilizing for fruit tree in AF	
11-Jul-2022	AF + SM	Hand-hoeing weed second time for maize. Second top-dressing fertilizer for maize	
29-Aug-2022	AF	Harvesting longan	
18-Sep-2022	AF + SM	Harvesting maize	
27-Sep-2022	AF	Fertilizing for fruit tree in AF	
29-Sep-2022	AF	Spraying fipronil to protect spring shoots of both longan and mango	
15-Oct-2022	AF + SM	Weeding and cutting maize residues by weed trimmer	
3-Nov-2022	AF	Cutting guinea grass	
4-Dec-2022	AF	Pruning longan and mango tree	

Table S2: Management activities in the fruit tree-coffee agroforestry (fruit-coffee-AF) system and in sole-coffee (SC) in 2022. Details of fertilizer application are given in Table S4

Date	Treatment	Activity	Note
9-Dec-2021	AF	Pruning sontra	
20-Mar-2022	AF + SC	Weeding 1st time (by strimmer)	
22-Mar-2022	AF + SC AF	Applying fertilizer for coffee, 1st time Applying fertilizer for fruit trees, 1st time	
25-Mar-2023	AF + SC	Spraying acetamiprid and chlopyrifos ethyl to control coffee scale	
25-Apr-2022	AF	Cutting guinea grass	
2-Jun-2022	AF + SC	Weeding 2nd time (by herbicide)	
4-Jul-2022	AF	Cutting guinea grass	
19-Jul-2022	AF + SC AF	Applying fertilizer for coffee, 2nd time Applying fertilizer for fruit trees	
10-Sep-2022	AF	Cutting guinea grass	
Sept-2022	AF + SC	Harvesting ripe coffee cherries, 1st time	
Sept-2022	AF	Harvesting sontra fruit	
1-Oct-2022	AF + SC	Weeding 3rd time (by strimmer)	
2-Oct-2022	AF + SC	Apply fertilizer for coffee, 3rd time Apply fertilizer for fruit tree	
14-Oct-2022	AF + SC	Harvesting coffee cherries, 2nd time	
17-Nov-2022	AF + SC	Harvesting coffee cherries, 3rd time	
15-Dec-2022	AF + SC	Harvesting coffee cherries, final time.	All remaining cherries (ripe and unripe)

Table S3: Fertilizer types and quantities used in the fruit tree-maize agroforestry (fruit-maize-AF) system in 2022. NPK 6.9.3.8S (6% N, 3.7% P, 2.5% K, 8%S), urea (46%N), KCl (50.6% K), NPK 13.5.10.14S (13% N, 2% P, 8.3% K, 14% S).

Date	**13 Mar 2022**	**14 May 2022**	**15 Jun 2022**		**12 Jul 2022**		**27 Sep 2022**	**Total**
Maize (kg/ha)								
Fertilizer type		*NPK 6.9.3.8S*	*Urea*	*KCl*	*Urea*	*KCl*		
Quantity		*500*	*175*	*50*	*175*	*50*		
N		30	81		81			**192**
P		18.4						**18.4**
K		12.4		25.3		25.3		**63**
S		40						**40**
Fruit tree (kg/tree)								
Fertilizer type	*NPK 13.5.10.14S*		*NPK 13.5.10.14S*				*NPK 5.10.3.8S*	
Quantity	*1.1*		*1.1*				*1.1*	
N	0.14		0.14				0.06	**0.32**
P	0.023		0.023				0.045	**0.091**
K	0.091		0.091				0.025	**0.207**
S	0.15		0.15				0.09	**0.035**

Table S4: Fertilizer types and quantities used in the fruit tree-coffee agroforestry (fruit-coffee-AF) system in 2022. NPK 5.10.3 (6.6% N, 4.1% P, 2.5% K), urea (46%N), KCl (50.6% K), supe phosphate (6.5% P).

Date	**21 Mar 2022**			**15 Jun 2022**			**12 Oct 2022**			**Total**
Coffee (kg/ha)										
Fertilizer type	*Urea*	*KCL*	*Super phosphate*	*Urea*	*KCL*	*Super phosphate*	*Urea*	*KCL*	*Super phosphate*	
Quantity	*151*	*123*	*313*	*173*	*164*	*313*	*108*	*123*	*313*	
N total	70			80			50			**200**
P			20.5			20.5			20.5	**61.5**
K		62.3			83			62.3		**204.6**
Sontra (kg/tree)										
Fertilizer type	*NPK 5.10.3*			*NPK 5.10.3*			*NPK 5.10.3*			
Quantity	*1.1*			*1.1*			*1.1*			
N	0.06			0.06			0.06			**0.18**
P	0.045			0.045			0.045			**0.135**
K	0.025			0.025			0.025			**0.075**

Table S5: Tree performance in the fruit tree-maize agroforestry (fruit-maize-AF) and fruit tree-coffee agroforestry (fruit-coffee-AF) systems. Tree stem diameter at 10 cm height from ground (D10), tree height, and tree canopy diameter (mean ± standard error). Different letters (a, b) indicate significant differences between longan and mango growth (p=0.05)

Parameter	Time	fruit-maize-AF		fruit-coffee-AF
		Longan	*Mango*	*Sontra*
D10 (cm)	Mar 2022	$6.67^{a} \pm 0.25$	$11.20^{b} \pm 0.42$	17.71 ± 0.99
	Jun 2022	$7.31^{a} \pm 0.27$	$12.12^{b} \pm 0.48$	17.00 ± 1.16
	Sep 2022	$7.50^{a} \pm 0.29$	$12.89^{b} \pm 0.54$	19.06 ± 0.87
	Dec 2022	$7.72^{a} \pm 0.34$	$12.8^{b} \pm 0.50$	23.29 ± 0.87
Height (m)	Mar 2022	$2.04^{a} \pm 0.09$	$3.07^{b} \pm 0.08$	5.83 ± 0.16
	Jun 2022	$2.08^{a} \pm 0.07$	$2.87^{b} \pm 0.12$	5.97 ± 0.15
	Sep 2022	$2.06^{a} \pm 0.08$	$3.14^{b} \pm 0.10$	6.57 ± 0.15
	Dec 2022	$2.16^{a} \pm 0.08$	$3.28^{b} \pm 0.11$	7.17 ± 0.17
Canopy (m)	Mar 2022	$2.07^{a} \pm 0.10$	$2.80^{b} \pm 0.10$	4.66 ± 0.11
	Jun 2022	$2.14^{a} \pm 0.10$	$2.53^{b} \pm 0.13$	5.33 ± 0.16
	Sep 2022	$2.10^{a} \pm 0.13$	$2.82^{b} \pm 0.13$	5.62 ± 0.14
	Dec 2022	$2.09^{a} \pm 0.09$	$2.78^{b} \pm 0.10$	5.92 ± 0.17

Table S6: Fraction of light in the fruit tree-maize agroforestry (fruit-maize-AF) and fruit tree-coffee agroforestry (fruit-coffee-AF) systems (mean ± standard error). Different letters (a, b, c) indicate significant differences between sites on four occasions (p=0.05)

Experiment	Incident light measured on:			
	Mar 2022	*Jun 2022*	*Sep 2022*	*Dec 2022*
Fruit-maize-AF	$0.995^{ab} \pm 0.002$	$0.989^{b} \pm 0.005$	$0.988^{a} \pm 0.001$	$0.990^{a} \pm 0.001$
Fruit-coffee-AF	$0.883^{c} \pm 0.022$	$0.920^{c} \pm 0.015$	$0.838^{c} \pm 0.024$	$0.858^{c} \pm 0.021$
Effect	**p-value**			
Experiment	< 0.001			
Time	0.017			
Experiment × Time	0.021			

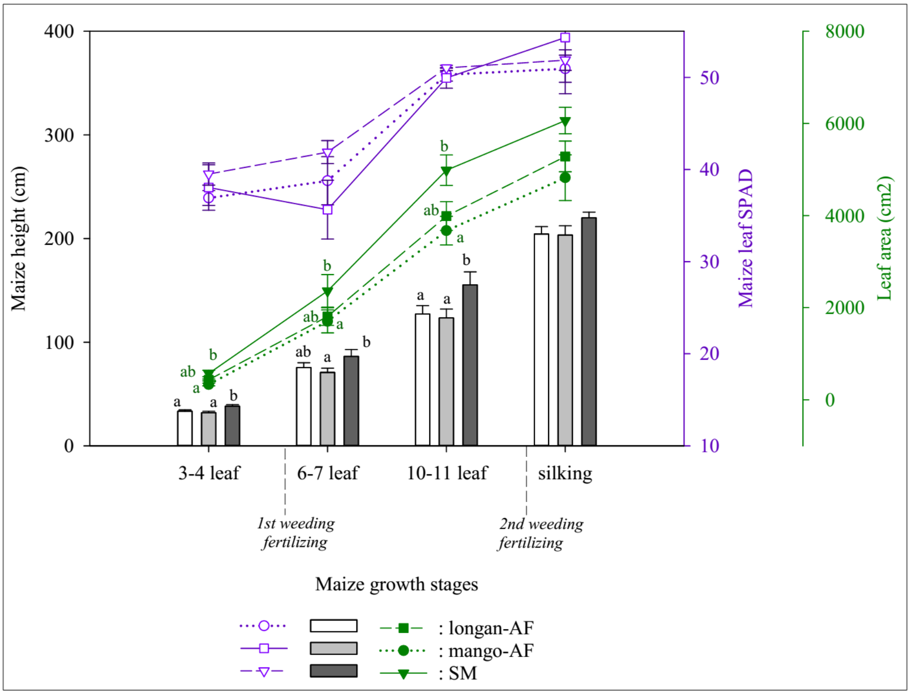

Figure S1. Mean maize height, leaf SPAD value, and plant leaf area (LA) in the longan-maize-grass (longan-AF) and mango-maize-grass (mango-AF) agroforestry sub-treatments and in sole-crop maize (SM). Different letters (a, b) indicate significant differences (p=0.05).

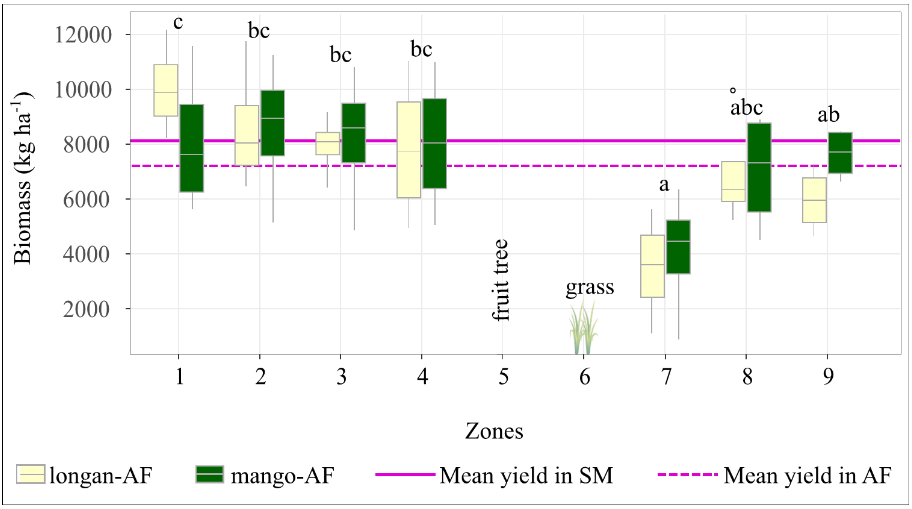

Figure S2. Maize aboveground biomass in crop zones in longan-maize (longan-AF) and mango-maize (mango-AF) agroforestry sub-treatments. Main effect of zone was significant (p<0.001). Different letters (a<b) indicate significant differences between maize zones (p=0.05). Error bars show 95% confidence interval.

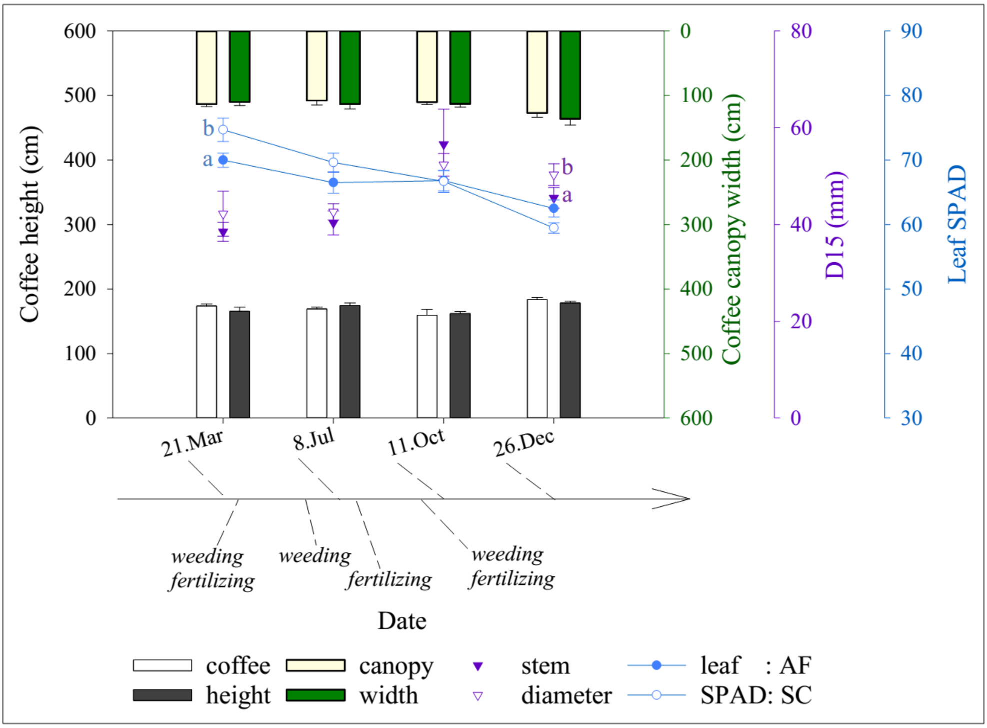

Figure S3. Coffee growth performance in agroforestry (AF) and sole-coffee (SC) treatments in fruit tree-coffee agroforestry (fruit-coffee-AF) experiment in 2022. Different letters (a, b) indicate significant differences (p=0.05) between treatments on each measurement occasion.

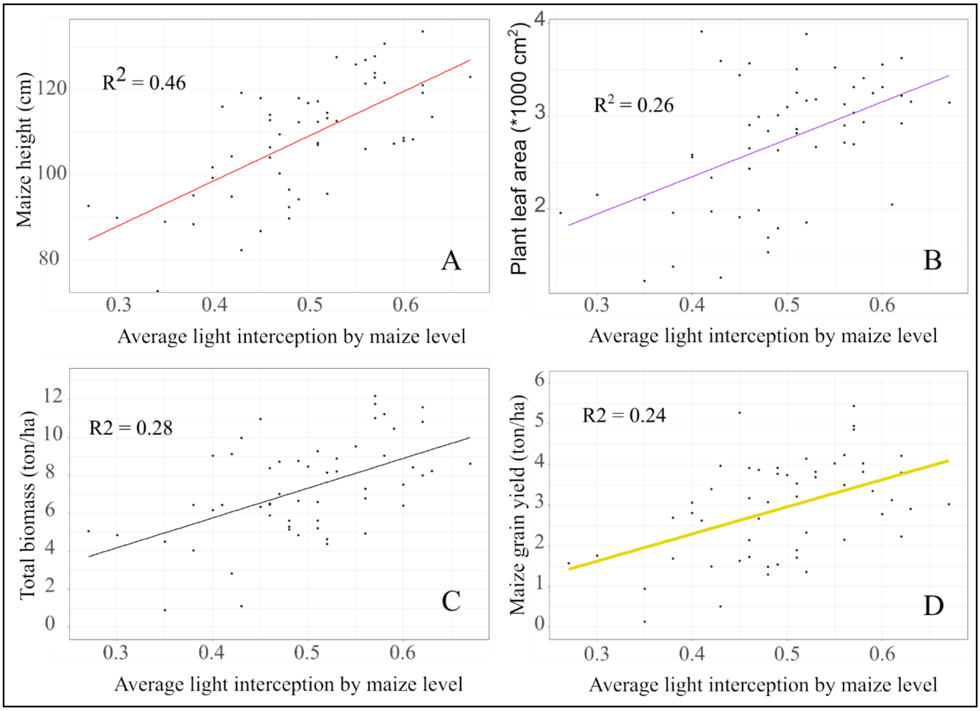

Figure S4. Correlation between average light interception by maize level and (a) maize height, (b) plant leaf area, (c) total aboveground biomass and (d) grain yield in fruit tree-maize agroforestry (fruit-maize-AF) in 2022.

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This thesis shed light on the resource availability in 3 to 6 years old fruit tree-crop agroforestry systems and the consequent crop performance on slopping land in northwest Vietnam. It also evaluated potential options for optimizing resources and enhancing system productivity. The research findings contribute to the understanding of slope effects on light availability, plant available water, and nutrient distribution, providing a way forward for designing systems and planning management strategies for sustainable agriculture on sloping land.

Huu Thuong Pham received his PhD education from the Department of Crop Production Ecology, at SLU in Uppsala in Sweden. He obtained his MSc in Crop Science at Vietnam National University of Agriculture in Hanoi in Vietnam.

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