Farmers' Motivation and Biophysical Impact of using C*ordia africana* and *Albizia coriaria* on Coffee-Bean Intercrops in the Mt Elgon Region (Uganda)

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Acronyms and abbreviations

ACIAR	Australian Centre for International Agricultural Research
ANOVA	Analysis of Variance
ATT	Attitude
AVE	Average Variance Extracted
BS	Base Saturation
CFA	Confirmatory Factor Analysis
CFI	Comparative Fit Index
CGIAR	Consultative Group on International Agricultural Research
CHPM	Compensation Heat Pulse Method
CIS	Combined Instrument Software
CMIN/DF	Ratio of Confirmatory Fit Index to degrees of freedom
CR	Composite Reliability
DAES	Directorate of Agricultural Extension Services
DAES	Directorate of Agricultural Extension Services
DBH	Diameter at Breast Height
FAO	Food and Agricultural Organization of the United Nations
FLROA	Forest Landscape Restoration Opportunity Assessment
GOF	Goodness of Fit
HRM	Heat Ratio Method
ICRAF	International Centre for Research in Agroforestry
IDR	Interdisciplinary approach to Research
IFI	Incremental Fit Index
INT	Intention
JAFel	John Alwright Fellowship
MAAIF	Ministry of Agriculture, Animal Industry and Fisheries
MM	Measurement Model
MoH	Ministry of Health
MTEF	Medium Term Expenditure Framework
NAADS	National Agricultural Advisory Services
NaFORRI	National Forestry Resources Research Institute
NARO	National Agricultural Research Organization
NSW	New South Wales

PAUF	Process of Agricultural Utilisation Framework
PBC	Perceived Behavioural Control
RMSEA	Root Mean Square Error of Approximation
SEM	Structural Equation Modeling
SFM1	Sap Flow Meter
SFT	Sap Flow Tool software
SN	Subjective Norms
SOPs	Standard Operating Procedures
T4FS	Trees for Food Security
TAM	Technology Acceptance Model
TDI	Theory of Diffusion of Innovations
TLI	Tucker-Lewis Index
TPB	Theory of Planned Behaviour
TRA	Theory of Reasoned Action
TTD	Transient Thermal Dissipation
UCDA	Uganda Coffee Development Authority
VSW	Volumetric Soil Water Content
ZARDIs	Zonal Agricultural Research and Development Institutes

Abstract

Farmers in developing countries are struggling to feed families due to low crop yields resulting from land degradation, land use pressures and unsustainable use of water resources. While deliberate integration of trees into farming systems (agroforestry) has been practiced traditionally in the Mt. Elgon region of Uganda since time immemorial, with modernisation of society and commercialisation of agriculture, many farmers are motivated to dismantle agroforestry systems in favour of monocultural farming systems. The science needed to improve agroforestry in the Mt Elgon region should focus on tree-crop water interactions because the competition for light and water is one of the main reasons that farmers remove trees in favour of annual crops. Additionally, long-term adoption of agroforestry has been negatively affected by an underlying culture of financial expectancy and highly subsidized extension by research and development programmes, leading to ‘pseudo adoption’. I contend that modernised agroforestry practices, informed by science generated in a participatory manner, have the promise of improving household food security, livelihoods and resilience.

The study is aligned to a pragmatic interdisciplinary research approach to embrace the domains of both biophysical science (tree-water use and crop productivity studies) and social science (farmer motivations and perceptions). It generally demonstrates effective application-oriented research and farmer decision-making, with a specific case of managing trees in a relevant agroforestry system. The study seeks to understand how farmers’ knowledge and attitudes towards agroforestry change in response to exposure to the generation of scientific information from biophysical experiments. The four central research questions for this research are: (i) what influences the intentions of smallholder farmers in Mt. Elgon region to plant and retain trees on their farms?; (ii) what factors influence farmers’ perceptions of the impact of trees on common bean and coffee productivity?; (iii) what are the impacts of trees and their

management on crop productivity and water use across a range of farm contexts?, and; (iv) what is the impact of biophysical information on farmers' perceptions about agroforestry tree management in coffee-bean systems?

A conceptual framework integrating the biophysical and social components of the study has been developed to inform the key agricultural technology adoption pathways of smallholder farmers. The study had an initial phase of in-depth, semi-structured farmer interviews and generation of biophysical information on impact of tree canopy pruning on tree water use and crop productivity from two selected farms with *Cordia africana* and *Albizia coriaria* trees integrated with coffee and common beans. The information from the biophysical data (collected over a 20-month period) was then reported to farmers through a series of extension events that were followed by a second phase of farmer interviews. Lastly, all the data and information collected from the second phase of farmer interviews and the biophysical experiment were used to establish the potential impact of incorporating *C. africana* and *A. coriaria* on soil water resources and sustainable crops productivity that would result from farmer adoption of biophysical information.

Results from the biophysical component of the study show that *C. africana* and *A. coriaria* exhibit contrasting patterns of seasonal tree water use across leaf shedding stages, characterised by episodes of reverse flow in *A. coriaria* at specific periods of the year. While tree canopy pruning altered the synchrony in the vegetative phenology of Albizia trees, the pruned Cordia and Albizia trees respectively used 22.8% and 50.1% less water than unpruned trees whose average daily water use was 76.5L day^{-1} and 133.7L day^{-1}. Coffee trees growing under pruned Cordia and Albizia trees used more water than coffee growing under unpruned trees, which could have resulted from more transpiration pull in coffee resulting from increased radiation with reduced shading. Canopy pruning also reduced the water demand of the tree component and resulted in recharge in the crop-rooting zone. In terms of crop productivity, yields of parchment coffee were highest under pruned Albizia (949 kg/ha), followed by coffee under unpruned Albizia (792 kg/ha*)*. Unshaded coffee produced the least yield at 402 kg/ha and 422 kg/ha in the Albizia and Cordia sites, respectively. The highest common beans yields (708 and 688 kg/ha) were obtained from common beans planted in open field sites, followed by those grown under unshaded coffee sites. The low yields from coffee and common beans under unpruned trees is attributed to below and above ground competition consistently outweighing the benefits of shade.

The social component of the study applied a Structural Equation Modeling (SEM) technique to assess the psychological drivers of smallholder farmers' intention and their motivation to integrate trees in their farming systems based on the Theory of Planned Behavior (TPB). The findings indicate that psychological factors are key drivers to the farmers' internal decision-making process in agroforestry technology adoption and can be context specific. The adoption behaviour of smallholder farmers is mainly shaped by existing community social norms and beliefs that tend to promote knowledge exchange, as opposed to the conventional knowledge transfer extension approaches. While I provide evidence that attitude and perceived behavioural control are reliable predictors of farmer tree planting behaviour, farmer perceptions and knowledge of the impact of trees on farm and their management varies across the farmer categories studied, where the intended purpose of trees on farm is perceived differently.

This study argues that bridging local and scientific knowledge through participatory research and extension is fundamental to enhance agricultural technology adoption among smallholder farmers. Therefore, the final phase of the study drew upon knowledge generated from biophysical component on impact of pruning on tree water use and crop productivity to assess farmers' perceptions and willingness to adopt practices emanating from the study following exposure of 394 farmers to the research outputs. The extension events facilitated dialogue between the researcher and the farmers, and the results show that the information delivered through extension events was better understood by majority of the farmers directly interacting with the project. However, overall, only 184 farmers of the 394 participants (47%) were convinced that higher coffee yield could be obtained from shaded coffee. Therefore, over 50% of these farmers are still hesitant to change, as the majority of them prune their trees only when there is need for fuelwood and or poles.

In the African context, agroforestry is strongly promoted via development projects, that provide incentives to farmers in form of free planting materials, tree nursery inputs and capacity building on planting and management of agroforestry components. There is always a likelihood that what appears as adoption is in fact trialling of the new practice, which masks actual long-term adoption. I therefore suggest that adoption information exchange through social networks and general community interactions may enhance long-term agroforestry adoption. These complex interaction processes should be applied at the early stages of technology adoption and would facilitate introduction of socially and biophysically appropriate agroforestry interventions into local realities.

In conclusion, the results from the biophysical component of the study have demonstrated that agroforestry tree canopy pruning is an important on-farm management decision for controlling competition and subsequently increasing crop yields, while prolonging the period of intercropping in intensive farming systems. However, farmers may be hesitant to adopt such useful information due to an underlying culture of financial expectancy leading to ‘pseudo adoption’, underutilization of existing social networks during research and extension, limitations in the period of exposure to a technology, and constraints in measuring and predicting adoption. The study has generally demonstrated that adoption is not merely related to the technology, socio economic and behavioural factors, and the research and extension methods applied, but also a result of complex interactions between people, technologies and institutions. For effective extension, there needs to be a lot more visibility of the research itself and over a long period of time rather than the formal short-term interactions between farmers and extension agents. The impacts resulting from effective application-oriented research, understanding farmer decision making and successful adoption of biophysical information can be essential for informing policy decisions relating to agricultural technology adoption pathways of smallholder farmers and household food security.

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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Joel Buyinza

11th October 2021

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List of publications

Published peer reviewed articles

Buyinza, J., Muthuri, C. W., Downey, A., Njoroge, J., Denton, M. D., & Nuberg, I. K. (2019). Contrasting water use patterns of two important agroforestry tree species in the Mt Elgon region of Uganda. *Australian Forestry*, 1-9. doi: 10.1080/00049158.2018.1547944

Buyinza, J., Nuberg, I. K., Muthuri, C. W., & Denton, M. D. (2020). Psychological Factors Influencing Farmers' Intention to Adopt Agroforestry: A Structural Equation Modeling Approach. *Journal of Sustainable Forestry*, 1-12. doi: 10.1080/10549811.2020.1738948

Buyinza, J., Nuberg, I. K., Muthuri, C. W., & Denton, M. D. (2020). Assessing smallholder farmers' motivation to adopt agroforestry using a multi-group structural equation modeling approach. *Agroforestry Systems*, *94*(6), 2199-2211. doi: 10.1007/s10457-020-00541-2

Buyinza, J., Nuberg, I.K., Muthuri, C.W., & Denton, M. D. (2021). Farmers' Knowledge and Perceptions of Management and the Impact of Trees on-Farm in the Mt. Elgon Region of Uganda. *Small-scale Forestry*, https://doi.org/10.1007/s11842-021-09488-3

Poster presentations

Buyinza, J., Muthuri, C. W., Denton, M. D., & Nuberg, I. K. (2019). Contrasting water use patterns of two agroforestry tree species in Mt. Elgon region of Uganda: Implication on management, at the 4th World Congress on Agroforestry (Montpellier, France, May 2019; Appendix I). https://www.worldagroforestry.org/publication/contrasting-water-use-patterns-two-agroforestry-tree-species-mt-elgon-region-uganda-0

Buyinza, J., Muthuri, C. W., Denton, M. D., & Nuberg, I. K. (2020). A practice for managing agroforestry trees increases coffee and common beans yields, presented during farmers extension events (Mt. Elgon region of Uganda, October 2020).

Buyinza, J., Muthuri, C. W., Denton, M. D., & Nuberg, I. K. (2020). Save water for agriculture by pruning trees, presented during farmers extension events (Mt. Elgon region of Uganda, October 2020).

Blog stories and Speeches

Buyinza, J. (2020). The art of Pruning. New pruning techniques in Uganda are showing farmers that trees are more valuable in the ground than on the woodpile. https://aciar.gov.au/media-search/blogs/art-pruning

Australia Awards Completion Event at the University of Adelaide. Student speech by Joel Buyinza, streamed live on May 18, 2021. https://www.youtube.com/watch?v=reakTNwQmN8

Chapter one: General Introduction

1.1 Overview

Farmers in developing countries are struggling to feed families due to land degradation and land use pressures (Winterbottom et al., 2013). Eighty percent of the chronically hungry in Africa are smallholder farmers (Fan & Rue, 2020; FAO, 2015) and their hunger is related to low crop yields linked to land degradation, loss of soil fertility and periodic drought. With scarcity and unsustainable degradation of water resources around the world, food demands have been projected to increase (Descheemaeker et al., 2013). Improving farmers' ability to produce food from their small land holdings demands adoption of innovative approaches in managing agricultural lands.

Developing lasting solutions to food insecurity requires knowledge, ideas and research methodologies from different disciplines. This is mainly because it involves interactions between humans (smallholder farmers) and their environment (Tobi & Kampen, 2017). The spatial and temporal interactions between trees and agricultural crops, usually influenced by farmers, makes agroforestry adoption complex, calling for an interdisciplinary analysis at farm and landscape levels. Use of an interdisciplinary approach to research has been identified to be necessary for addressing complex problems, especially where both the human and natural components exist and interact (Frodeman, 2011). This study was therefore interdisciplinary, integrating farmers' knowledge on agroforestry with a range of data from biophysical experiments involving trees, coffee and common beans.

Creating linkages between biophysical and social economic data provided a more detailed understanding and comprehension of existing farming systems. Integration of data from social science and natural science also allowed improved understanding of perceived relationships between variables (Neuman, 2014). The study generally sought to understand how farmers respond to science. Farmers' underlying perceptions of the impact of trees on crop yields were documented to inform agricultural technology adoption pathways of smallholder farmers in the Mt. Elgon region of Uganda.

1.2 Research background

1.2.1 The promise of agroforestry

The concept of agroforestry is based on development of an interface between agriculture and forestry where trees are deliberately integrated with agricultural crops on the same land management unit (Van Noordwijk 2019). Agroforestry has been recognized as one of the most promising farming systems that can guarantee sustainable use of water and nutrient resources (Pinho et al., 2012). It is an important climate-smart agricultural approach, that supports food and nutritional security through provision of food, contributing to household incomes and fuel needs. Agroforestry can increase soil organic matter through leaf fall. While trees provide a cheap alternative for restoring degraded lands through agroforestry (Pinho et al., 2012), most smallholder farmers with trees on-farm have failed to realize the co-benefits due to poor management of the tree component. These farmers also lack knowledge of tree selection and arrangement of the agroforestry components. Success in agroforestry systems is primarily based on selecting the right tree-crop combinations that exploit spatial and temporal complementarities in resource use (Descheemaeker et al., 2013). Therefore, research should support interventions that maximize soil water and nutrient use in agroforestry systems to improve yields and complementarity in farming systems.

1.2.2 Tree water use in agroforestry systems

Soil water has been found to be the main resource limiting productivity in agroforestry systems (Namirembe et al., 2008). This is attributed to competition from tree-crop combinations selected by farmers. Given the huge amounts of water used in agroforestry systems, even minute improvements in agricultural water productivity could have large implications for local water budgets. While overlapping growth cycles of trees and agricultural crops may increase competition for resources, adequate tree management and high leaf litter recycling can reduce the competition (Ndoli et al., 2017). Therefore, studies that seek to maximise complementarities of agroforestry systems should be supported. However, most of the studies on water use relations in agroforestry trees have not been able to monitor individual tree water use due to technological limitations. Studying the movement and dynamics of sap through a plant is key to progress scientific knowledge about plant hydraulic function and growth in a given environment (Steppe et al., 2015).

While many of these studies have been done on station, the use of sapflow technology allows monitoring of individual tree water relations under field conditions. Field-based experiments provide more viable conclusions and enhance modelling of field scenarios (Steppe et al., 2015). This study applied the sapflow technology, which uses the Heat Ratio Method (HRM) of measuring sapflow (Burgess et al., 2001), which has the ability to measure both day-time and nocturnal sapflow (Forster, 2014) and reverse-flows (Burgess, 2011; Burgess et al., 1998), which are important in understanding the overall tree-water use dynamics.

1.2.3 Role of tree management and farmer perceptions in agroforestry adoption

While agroforestry offers cheap alternatives for restoring degraded lands (Sales et al., 2016), the majority of smallholder farmers with trees on-farm have failed to realize the multiple benefits due to poor tree management. Agriculturalists need a high level of flexibility to manage available water if they are to successfully allocate it to agricultural crops (Evans & Sadler, 2008). Shoot pruning has been demonstrated as one practical method to manage the quantity and timing of tree water use and shade in agroforestry systems (Namirembe et al., 2008; Ndoli et al., 2017) where trees and agricultural crops compete for the same resources.

Apart from shoot pruning, the spatial and temporal arrangement of the tree and crop components is also fundamental to maximizing the co-benefits of agroforestry (Atangana et al., 2013). However, this requires adoption of innovative land management approaches whose success may be influenced by farmers' knowledge, attitudes and perceptions (Meijer et al., 2015). Therefore, farmers need knowledge of selection, management and appropriate arrangement of the agroforestry components to sustain land productivity. Most of these studies have widely acknowledged resource constraints and socio-economic factors, with limited focus on the cognitive and psychological constraints in adoption. Therefore, the drivers of farmer motivations and perceptions towards adoption of innovations are complex and contingent on multiple factors including biophysical, social and psychological. These can be best understood by using an interdisciplinary approach to research (IDR) that integrates biophysical and social economic components, an approach adopted by this study.

1.3 Research Questions

This study was guided by the following research questions:

- What influences the intentions of smallholder farmers in Mt. Elgon region to plant and retain trees on their farms?
- What factors influence farmers' perceptions of the impact of trees on common bean and coffee productivity?

- What are the impacts of trees and their management on crop productivity and water use across a range of farm contexts?
- What is the impact of biophysical information on farmers' perceptions about agroforestry tree management in coffee-bean systems?

1.4 Overall research aim

The study aimed at assessing the impact of biophysical information on the motivation of farmers to adopt key species (*Cordia africana* and *Albizia coriaria*) in coffee-bean agroforestry systems in the Mt. Elgon region of Uganda.

1.5 Objectives

The objectives of this study were to:

- Characterize farmers' motivations for incorporating trees in coffee and beans systems in Mt. Elgon region
- Assess the effect of *Cordia africana* and *Albizia coriaria* on coffee and bean productivity on farmers' fields in the Mt. Elgon region
- Assess tree water use of *Cordia africana* and *Albizia coriaria* under different management regimes and phenology in coffee-bean agroforestry systems
- Assess changes in farmers' perceptions after exposure to biophysical information on agroforestry tree water use and management in coffee-bean systems

1.6 Overall conceptual framework

The study had an initial phase of in-depth, semi-structured farmer interviews and generation of biophysical information on impact of tree canopy pruning on tree water use and crop productivity from two selected farms with *Cordia africana* and *Albizia coriaria* trees integrated with coffee and common beans (Figure 1). Biophysical information generally relates to influences on the physical production processes associated with farming (Pattanayak et al., 2003). Interviews established farmers' underlying perceptions and motivations towards adoption of trees in their farming systems, while the biophysical experiment assessed the impacts of trees and their management on crop productivity and tree water use. The information from farmer interviews and biophysical data was then reported to farmers through a series of extension events. The extension events were also used to highlight the relevance of the findings to the farmers and design potential implementation (scaling out) strategies.

The extension events were then followed by a second phase of interviews. The second phase assisted in determining the accuracy of the qualitative findings and provided additional rigour to the research. This process involved revisiting participants and presenting findings so that they can provide additional feedback, comments and perceptions on the results. Farmers did not have to necessarily agree with the findings of the initial interviews and the biophysical component of the study as the project was also interested in collecting the views of the dissenting farmers for documentation and further inquiry.

Lastly, all the data and information collected from the second phase of farmer interviews and the biophysical experiment were used to establish the potential impact of incorporating *Cordia africana* and *Albizia coriaria* on soil water resources and crops productivity. The potential impacts resulting from adoption of biophysical information have been documented and are essential for informing policy decisions relating to agroforestry and household food security.

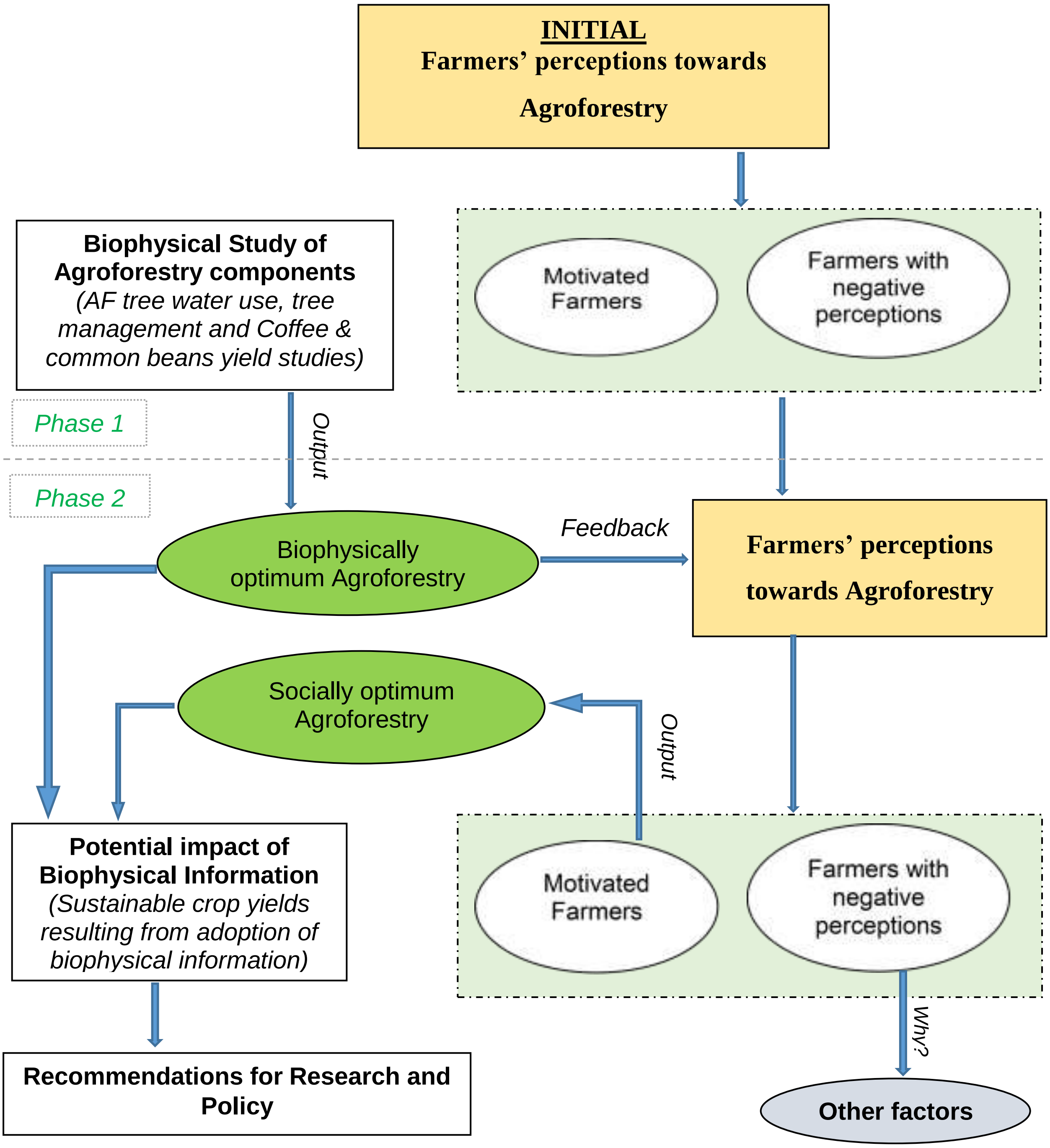

Figure 1: Overall conceptual framework for the study

1.7 Significance

Agroforestry is a complex farming system involving deliberate use of trees with agricultural crops and or animals on the same land management unit. There are both negative and positive interactions among these components that may arise from their temporal and spatial arrangement (normally influenced by the farmer). Therefore, understanding these interactions requires both the knowledge of the farmers and the biophysical knowledge generated by the researchers. This study assessed the water use patterns of *Cordia africana* and *Albizia coriaria* trees under different management regimes. Given the huge amounts of water used in agroforestry systems, it is thought that even minute improvements in agricultural water productivity could have large implications for local water budgets (FAO, 2011). Such improvements would allow higher agricultural production with the same amount of water (Descheemaeker et al., 2013). It has also been urged that the same amount of agricultural production could be attained with less water (Evans & Sadler, 2008), thus saving water that could be allocated to other higher-value uses. While there is substantive evidence that increasing tree density and diversity on-farm leads to more resilient livelihoods (Iiyama et al., 2017), smallholder farmers need to make the right selection of trees and appropriate tree management regimes to enhance productivity. Incorporating trees in farming systems and subjecting them to appropriate management regimes can build soil health, sustain crop yields and ensure water use efficiency. However, the impacts vary with different tree-crop combinations, management practices and environmental conditions. Therefore, this study explored research interventions that would maximize water use in agroforestry systems to improve yields and complementarity (spatial and temporal) in smallholder farming systems in the Mt. Elgon region of Uganda.

1.8 Thesis structure

This thesis is structured into ten chapters (Figure 2). **Chapter 1** provides the general research background, research objectives, significance of the research and the structure of the thesis. As this study embraces the domains of both biophysical science (tree-water use studies) and social science (farmer motivations and perceptions), **Chapter 2** provides a critical review of literature on the interdisciplinary research methodology. This chapter justifies interdisciplinary research (IDR) in agriculture comprising qualitative social research and quantitative natural science as a valuable and valid research approach suited to understanding studies that have both social and biophysical components. This chapter also provides an argument for a pragmatic IDR paradigm in this project.

Chapter 3 provides an assessment of the contrasting water use patterns of two important agroforestry tree species in the Mt. Elgon region of Uganda. The two tree species (*Cordia africana* and *Albizia coriaria*) present contrasting seasonal water use patterns across leaf shedding stages characterised by episodes of reverse flow in *A. coriaria* at specific periods of the year. The information generated provides critical insight for developing successful long-term tree monitoring and management programs in agroforestry systems. It is observed that the science needed to improve agroforestry in the Mt Elgon region should focus on tree-crop water interactions because the competition for light and water is one of the main reasons why farmers remove trees in favour of annual crops. Therefore, **Chapter 4** evaluates the impact of tree pruning on water relations in tree-coffee systems on smallholder farms in Eastern Uganda. Canopy pruning can reduce the water demand of the tree component and result in recharge in the crop-rooting zone. These findings demonstrate that agroforestry tree canopy pruning can regulate water use in smallholder agroforestry systems, the benefits of other tree products notwithstanding.

Chapter 5 assessed the impact of tree management on coffee and common bean productivity in smallholder agroforestry systems in Mt Elgon of Uganda. The results of this study show that agroforestry tree canopy pruning is an important on-farm management decision for controlling competition in coffee-bean agroforestry systems and subsequently increasing crop yields, while prolonging the period of intercropping in such intensive farming systems. However, even if we can develop agroforestry systems where the tree components are favourably integrated with other crops, farmers' perceptions may still be negative towards agroforestry. So, to get the science message across we need to better understand what influences farmers' perceptions and motivations to adopt innovations; for this purpose, **Chapter 6** evaluates the psychological factors influencing farmers' intention to adopt agroforestry using a structural equation modeling approach. The intention of farmers to integrate trees in coffee plantations is mainly driven by their evaluation of the benefits of shaded coffee (attitude) followed by beliefs about their own capability (perceived behavioural control). This renders attitude and perceived behavioural control as reliable predictors of farmer tree planting behavior, especially in the context of developing countries.

Chapter 7 further provides an assessment of smallholder farmers' motivation to adopt agroforestry using a multi-group structural equation modeling approach. In this study, about 40% of the variation in farmer motivation to integrate trees in their coffee plantations is explained by 'attitude' and 'perceived behavioural control' among farmers actively participating in the Trees for Food Security (T4FS) project since 2014. However, the neighbours of participating farmers and farmers who had never interacted with the project are only motivated by 'attitude' and 'social norms' respectively. Farmer motivation resulting from social pressure is strongest among farmers who had never interacted with the project, and in the absence of project interventions, rely on existing social structures to drive change in their community. The adoption behaviour of smallholder farmers is mainly shaped by existing community social norms and beliefs that tend to promote knowledge exchange, as opposed to the conventional knowledge transfer extension approaches. Norms are therefore an inherent part of social systems and can create distinct farming practices, habits and standards within a social group. **Chapter 8** evaluates farmers' knowledge and perceptions of management and impact of trees on-farm in the Mt. Elgon region of Uganda. Farmer perceptions and knowledge of the impact of trees on farm and their management varied across the farmer categories studied. This study shows the importance of context-specific design of research and development projects aiming for local impact.

Chapter 9 establishes reasons why farmers are hesitant to adopt what appears good on the basis of science: Understanding farmers' perceptions of biophysical research. The study draws upon knowledge generated from biophysical experiments on tree water use, shade tree planting and management in smallholder coffee-bean agroforestry systems to assess farmers' perceptions and willingness to adopt practices emanating from the study following exposure to the research outputs. It is hypothesized that smallholder farmers are hesitant to adopt innovations due to an underlying culture of financial expectancy leading to 'pseudo adoption', underutilization of existing social networks during research and extension, the period of exposure to a technology, and limitations in measuring and predicting adoption. This therefore calls for the need to align different farmer categories to the Process of Agricultural Utilisation Framework (PAUF) criteria, leading to a better understanding of the impact of research and development projects on smallholder farmers adoption pathways.

Finally, **Chapter 10** discusses the major findings of the entire study, the general conclusions and policy implication of the study.

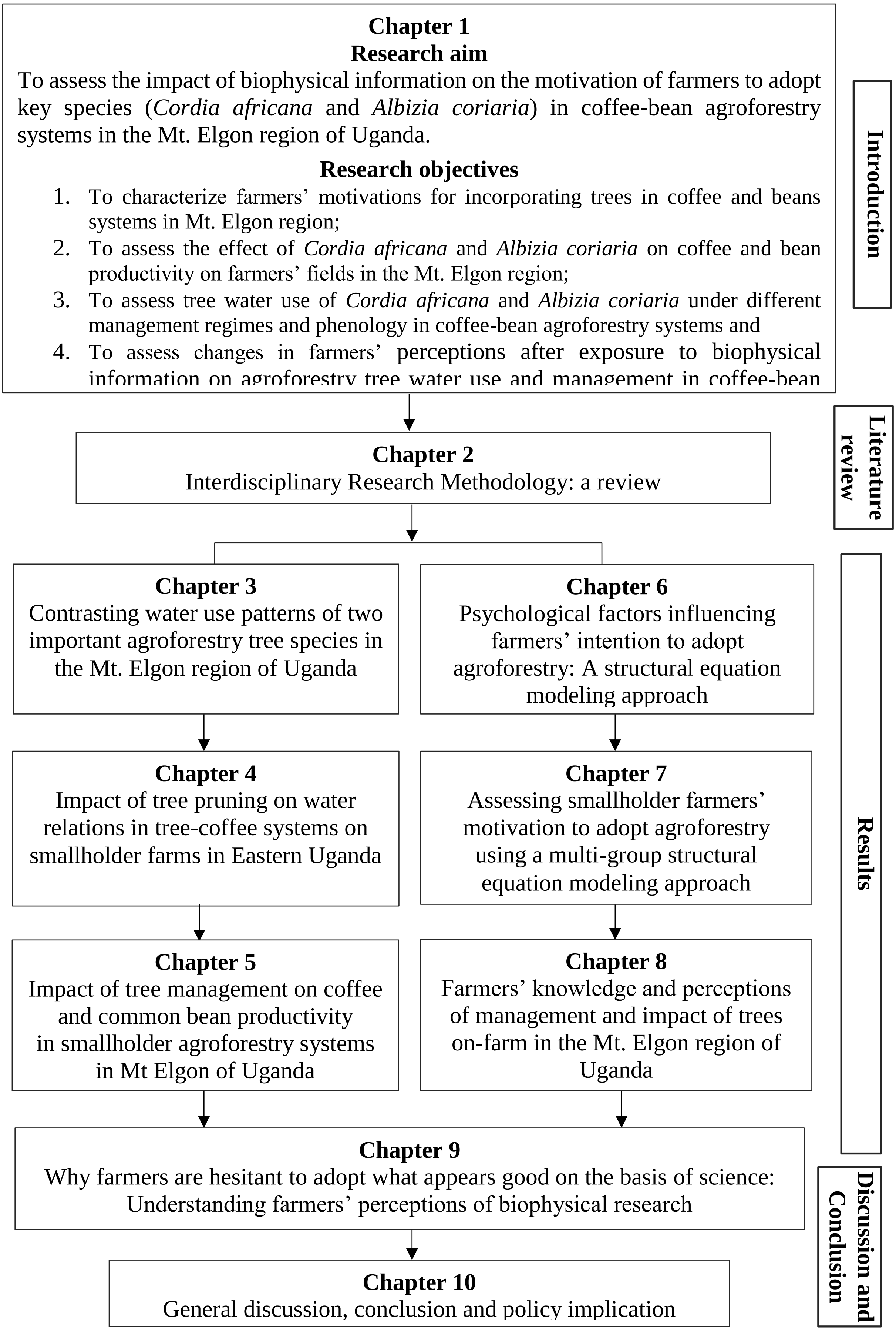

Figure 2: Thesis structure showing the sequence of chapters

1.9 References

Atangana, A., Khasa, D., Chang, S., & Degrande, A. (2013). Major Agroforestry Systems of the Humid Tropics (pp. 49-93). Dordrecht: Springer Netherlands.

Burgess, S. S. O. (2011). Can hydraulic redistribution put bread on our table? *Plant and soil*, 341(1/2), 25-29. doi: 10.1007/s11104-010-0638-1

Burgess, S. S. O., Adams, M. A., Turner, N. C., & Ong, C. K. (1998). The redistribution of soil water by tree root systems. *Oecologia*, 115(3), 306-311. doi: 10.1007/s004420050521

Burgess, S. S. O., Adams, M. A., Turner, N. C., Beverly, C. R., Ong, C. K., Khan, A. A. H., & Bleby, T. M. (2001). An improved heat pulse method to measure low and reverse rates of sap flow in woody plants †. *Tree Physiology*, *21*(9), 589-598. doi: 10.1093/treephys/21.9.589

Descheemaeker, K., Bunting, S. W., Bindraban, P., Muthuri, C., Molden, D., Beveridge, M., . . . Jarvis, D. I. (2013). *Increasing water productivity in Agriculture*.

Evans, R. G., & Sadler, E. J. (2008). Methods and technologies to improve efficiency of water use. *Water Resources Research*, *44*(7), n/a-n/a. doi: 10.1029/2007WR006200

Fan, S., & Rue, C. (2020). The Role of Smallholder Farms in a Changing World. *In: Gomez y Paloma S., Riesgo L., Louhichi K. (eds) The Role of Smallholder Farms in Food and Nutrition Security*: Springer, Cham. doi:10.1007/978-3-030-42148-9_2.

FAO. (2011). *The state of the world's land and water resources for food and agriculture : managing systems at risk* (1st ed. ed.). Milton Park, Abingdon. New York, NY: Earthscan.

FAO. (2015). The economic lives of smallholder farmers. An analysis based on household data from nine countries. Food and Agriculture Organization of the United Nations (pp. 48). Rome.

Forster, M. A. (2014). How significant is nocturnal sap flow? *Tree Physiology, 34*(7), 757-765. doi: 10.1093/treephys/tpu051

Frodeman, R. (2011). Interdisciplinary research and academic sustainability: managing knowledge in an age of accountability. *Envir. Conserv., 38*(2), 105-112. doi: 10.1017/S0376892911000038

Iiyama, M., Derero, A., Kelemu, K., Muthuri, C., Kinuthia, R., Ayenkulu, E., . . . Sinclair, F. (2017). Understanding patterns of tree adoption on farms in semi-arid and sub-humid Ethiopia. *An International Journal incorporating Agroforestry Forum, 91*(2), 271-293. doi: 10.1007/s10457-016-9926-y

Meijer, S. S., Catacutan, D., Ajayi, O. C., Sileshi, G. W., & Nieuwenhuis, M. (2015). The role of knowledge, attitudes and perceptions in the uptake of agricultural and agroforestry innovations among smallholder farmers in sub-Saharan Africa. *International Journal of Agricultural Sustainability, 13*(1), 40-54. doi: 10.1080/14735903.2014.912493

Namirembe, S., Brook, R. M., & Ong, C. K. (2008). Manipulating phenology and water relations in Senna spectabilis in a water limited environment in Kenya. *Agroforestry Systems, 75*(3), 197. doi: 10.1007/s10457-008-9169-7

Ndoli, A., Baudron, F., Schuta, A. G. T., Mukuralinda, A., & Gillera, K. E. (2017). Disentangling the positive and negative effects of trees on maize performance in smallholdings of Northern Rwanda. *Field Crop Research, 213*, 11. doi: 10.1016/j.fcr.2017.07.020

Neuman, W. L. a. (2014). *Social research methods : qualitative and quantitative approaches* (Seventh edition, Pearson New International Edition. ed.): Pearson.

Pattanayak, S., Evan Mercer, D., Sills, E., & Yang, J.-C. (2003). Taking stock of agroforestry adoption studies. *An International Journal incorporating Agroforestry Forum, 57*(3), 173-186. doi: 10.1023/A:1024809108210

Pinho, R. C., Miller, R. P., & Alfaia, S. S. (2012). Agroforestry and the Improvement of Soil Fertility: A View from Amazonia. *Applied and Environmental Soil Science, 2012*. doi: 10.1155/2012/616383

Sales, E., Rodas, O., Valenzuela, O., Hillbrand, A., & Sabogal, C. (2016). On the way to restore Guatemala's degraded lands: Creating governance conditions. *World Development Perspectives, 4*, 16-18. doi: 10.1016/j.wdp.2016.11.010

Steppe, K., Vandegehuchte, M. W., Tognetti, R., & Mencuccini, M. (2015). Sap flow as a key trait in the understanding of plant hydraulic functioning. *Tree Physiology, 35*(4), 341-345. doi: 10.1093/treephys/tpv033

Tobi, H., & Kampen, J. K. (2017). Research design: the methodology for interdisciplinary research framework. *Quality & Quantity*. doi: 10.1007/s11135-017-0513-8

Van Noordwijk M (2019). Sustainable development through trees on farms: agroforestry in its fifth decade. World Agroforestry Centre (ICRAF), Bogor

Winterbottom, R., Reij C, Garrity D, Glover J, Hellums D, Mcgahuey M, & Scherr S. (2013). Improving land and water management. WRI Working Paper *Installment 4 of Creating a Sustainable Food Future* (pp. 44). Washington, DC: World Resources Institute. http://www.worldresourcesreport.org.

Chapter Two: Interdisciplinary Research Methodology: a review

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2.2 Abstract

This paper aims to justify interdisciplinary research (IDR) in agriculture comprising qualitative social research and quantitative natural science as a valuable and valid research approach suited to understanding studies that have both social and biophysical components. After a thorough review of main scientific paradigms, IDR was conducted in agriculture within the pragmatic paradigm, where inquiry is problem-centred and practice-orientated. From the reviewed literature, we suggest a framework for IDR in agriculture in the context of developing countries by modifying Tobi and Kampen (2017) IDR framework to include extension and feedback. The suggested framework provides for social relevance and generation of data for informing policy decisions relating to sustainable agriculture. The review highlights the main barriers as well as the opportunities for implementing IDR in agriculture. A significant barrier to addressing farmers' problems is that farmers think in interdisciplinary terms while researchers are still ruled by disciplinary boundaries. The current and future global complex agricultural challenges require disciplinary experts with an interdisciplinary experience. Thus, interdisciplinary research in agriculture must increasingly become the standard rather than the exception because the approaches required and the implications of agricultural research are by their very nature interdisciplinary.

Key words: *interdisciplinarity, transdisciplinarity, agriculture, paradigms, framework*

2.3 Introduction

Current global challenges such as water scarcity, food insecurity and urbanization involve the interaction between humans and their environment, rendering a single disciplinary approach inadequate to solve them. The study of the interaction between humans and their environment requires knowledge and research methodology from different disciplines (Tobi & Kampen, 2017) such as the natural sciences, the social sciences, and the humanities (Kagan, 2009;

Rutting et al., 2016). There has been a longstanding call for interdisciplinary research involving the social and the natural sciences to manage complex societal issues (Fischer et al., 2011; German et al., 2010; Lee, 2011). This is mainly because most real-life problems are multifaceted, with different determining factors, that can effectively be addressed with different disciplinary methods (Rutting et al., 2016). The collaboration between natural and social sciences is needed due to an increasingly intricate interweaving between the socio-economical context that drives the people living in the environment and their impact on the biophysical environment (Fischer et al., 2011).

Over the years, different forms of collaboration have been labelled variously as multidisciplinary, interdisciplinary and transdisciplinary research. Although these terms can be theoretically distinguished, in practice researchers often switch between these approaches – sometimes within the same research project. Multidisciplinary research is research that involves more than one discipline, but without integration of disciplinary insights (Rutting et al., 2016). Interdisciplinary research has operationally been defined as a mode of research by teams or individuals that integrates perspectives/concepts/theories and/or tools/techniques and/or information/data from two or more bodies of knowledge (National Academies, 2005). It requires the interaction of two or more disciplines in: communication of ideas and organization of knowledge, using methods, procedures, theories and data between members of a group or by an individual to solve a single problem (Butler, 2011). However, transdisciplinary research is where different academic disciplines work together with non-academic collaborators to integrate knowledge and methods to develop and meet shared research goals (Hirsch-Hadorn et al., 2008; Kelly et al., 2019)

Transcending the social and natural science divide throws open the field of inquiry and the range of possible solutions (Bromham et al., 2016). For example, many of the great research triumphs, such as human genome sequencing, the Green Revolution, and manned space flight are products of interdisciplinary inquiry and collaboration (NationalAcademies, 2005). Elsewhere, IDR has been used to establish a linkage between socio-economic factors and land-cover changes in the marginal rural landscape of the German highlands (Hietel et al., 2005), which generated a better knowledge of land-cover history. IDR has also been used to study the management of infectious animal and plant diseases in the UK (Wilkinson et al., 2011). Another project conducted an interdisciplinary assessment of alternative food networks in Italy (Corsi et al., 2018). One of the fundamental outputs of the project was that economists became more aware of the social implications of transactions and were thus spurred to explicitly include symbolic and intangible attributes of food as determinants of consumers' preferences in their empirical models. This is contrary to a widespread view that economists only deal with monetary variables.

In Africa, IDR has been applied in the conservation and use of the wild populations of *Coffea arabica* in the montane rainforests in Ethiopia (Callo-Concha et al., 2017). However, the study was both inter and transdisciplinary, considering ecological and socioeconomic aspects, and involving stakeholders at local, national and international levels. To address complexity in food systems in developing countries, a study conducted an interdisciplinary and triangulation analysis of divergent conceptual frameworks (Foran et al., 2014). The analysis found notable tensions and synergistic interactions between agroecology, agricultural innovation systems, social–ecological systems, and political ecology. While existing institutional structures and practices to support interdisciplinary research are still developing (Kelly et al., 2019), there is such a great need for the science workforce to collaborate across cultural backgrounds and disciplines (Borrego & Newswander, 2010). IDR has been highly regarded and predicted as an important factor in future research (Rutting et al., 2016).

2.3.1 Purpose of interdisciplinary research

Interdisciplinary research (IDR) integrates concepts and information from two or more bodies of knowledge (Porter et al., 2007). It is suitable for addressing complex problems, especially where both human and natural components exist and interact (Fischer et al., 2011; Frodeman, 2011; Rutting et al., 2016). The purpose of IDR is to provide a framework across multiple disciplines (Porter & Rafols, 2009) and allows improved understanding of perceived relationships between variables (Neuman, 2014). IDR also increases the policy relevance and impact of research (Wilkinson et al., 2011). Interdisciplinary research is motivated by a general belief that by drawing information from different fields and employing different methodologies, a broad understanding of an existing issue can be achieved (Rutting et al., 2016). The choice for IDR is often driven by the inherent complexity of nature and society, the drive to explore basic research problems at the interfaces of disciplines, the stimulus of generating technologies and need to solve societal problems (Rutting et al., 2016). There have also been cases where interdisciplinary approaches to research have been adopted when the traditional disciplinary approaches no longer adequately answered research questions (Butler, 2011).

2.3.2 Interdisciplinarity in agricultural research

Interdisciplinary research in agriculture is premised on the ever-growing societal desire for attaining agricultural sustainability (Hanson et al., 2008) rather than simply increased production. For agriculture, sustainability refers to the concept that production can occur on a given land management unit on an indefinite basis. For example, while use of inorganic fertilizers can increase production over a short period of time, it is regarded unsustainable given the short period of fertilizer efficiency, and the negative land and environmental effects associated with use of inorganic fertilizers. It has been argued that thinking beyond biophysical technologies could foster farmer institutions to adopt agricultural technologies (Descheemaeker et al., 2013) and facilitate natural resource management and development practice (German et al., 2010). Failure to incorporate the views of the farmers excludes them from the scientific discourse of agriculture and from shaping its outcomes. Indeed, a significant barrier to addressing farmers' problems is that farmers think in interdisciplinary terms, while researchers are still ruled by disciplinary boundaries (Galmiche-Tejeda, 2004). This calls for agricultural researchers to build collaborative relationships and develop a shared language and perspective beyond disciplinary boundaries.

Interdisciplinary research (IDR) is suitable to addressing modern requirements on agriculture given the complex nature that combines social and environmental factors (Morse et al., 2007). In addition, IDR is useful in providing a valuable opportunity for engagement with the user communities of the research outputs thus making it socially relevant (Lee, 2011; Lowe & Phillipson, 2006). Low engagement with user communities (for example farmers) often results in research outcomes that lack sufficient relevancy to the intended user community. Farmers think in a cross-disciplinary perspective about their enterprises and not simply distinct 'silos' (Galmiche-Tejeda, 2004). Where traditional agricultural research is conducted, for example collection and analysis of tree management and associated crop yield data which may appear acceptable to the research community, it may not be suitable or usable to the farmer for social reasons not researched in the study.

IDR provides a valuable opportunity for engagement with the user communities of the research, thus making it socially relevant (Lowe & Phillipson, 2006). Low engagement with research beneficiaries often results in research outcomes that lack sufficient relevancy to the intended user community. Agricultural research systems must therefore take more steps towards integrating social, cultural, and political lines of inquiry into their core mandates to effectively address the needs and realities of vulnerable communities. It is not surprising that international institutes for agricultural research such as the members of the Consultative Group on International Agricultural Research (CGIAR) have already adopted a changed discourse on farmers' knowledge by negotiating space for interdisciplinary collaboration (German et al., 2010). In the same vain, the current review seeks to document a framework for interdisciplinary research methodology in agriculture along scientific paradigm alignment.

2.4 Interdisciplinary Research (IDR) Methodology

2.4.1 Scientific Paradigms in IDR

A paradigm can be defined as a general organizing framework for theory and research that guides the orientation to inquiry including what questions to ask, what methods to use and what knowledge claims to strive for (Ogundari, 2014; Morgan, 2007). It is generally a set of assumptions, values, methods, theories and practices that are shared by a certain community of scientists. Paradigms have ontological (nature of reality) and epistemological (nature of truth) positions that contribute to how research is conducted, data analysed and findings presented (Rutting et al., 2016). While paradigms do not necessarily govern exactly which types of data or tools for data analysis should be used, they can greatly influence the way tools are used and analysis is done (Neuman, 2014). There are four main schools of knowledge claims within the sciences and social science, namely: positivism, constructivism, advocacy/participatory and pragmatism (Lenzholzer et al., 2013) summarized in Table 1 below.

Table 1: Categorization and summary of the major scientific paradigms

Paradigm	Positivism	Constructivism	Advocacy	Pragmatic
Aim	Determinative, theory verification	Subjective understanding, theory generation	Political, change oriented	Problem centered, practice orientated
Ontology	Reality is measured	Reality is constructed	Reality is constructed	Reality is discernable but not perfectly
Epistemology	Findings are true and value free	Findings are constructed and value laden	Findings are constructed and value laden	Findings are applicable, value aware
Methods	Quantitative	Qualitative	Qualitative	Quantitative and qualitative

Adapted from (Creswell, 2018)

Positivism is predominantly associated with natural science or quantitative social sciences (Aboelela et al., 2007; Lenzholzer et al., 2013) and is based on the belief that an absolute truth can be found and that a single reality exists that is measurable (Healy & Perry, 2000). It is a representative of pure science that typically tests specific hypotheses using stringent methods involving collection of quantitative data (Lenzholzer et al., 2013). The hypotheses are tested rigorously and then verified or falsified, leading to formally considered 'absolute truths' (Fischer et al., 2011). Research conducted within the positivist paradigm is said to be 'value free' in that the position or values of the researcher do not impact on how the research is conducted.

Constructivism also referred to as interpretivism or naturalism has its focus on qualitative research in social science (Petersen & Gencel, 2013). It is a mode of inquiry in which reality is experientially based, historically shaped, and its understanding is only relative in nature (Aboelela et al., 2007; Lenzholzer et al., 2013). The major aim of this form of inquiry is to seek an understanding of the world in which the researchers are operating and typically generates multiple views about complex subjective topics (Schwartz-Shea & Yanow, 2012). The underlying ontology is that reality is constructed based on attitudes, beliefs, interaction and experiences within a specific context (Lenzholzer et al., 2013). Constructivists do not start with a theory but use an inductive method to generate theory or meaning. Research conducted within the constructivism paradigm tends to focus on ideological and subjective topics rather than topics associated with production or economics. The main criteria in constructivism are authenticity, originality, credibility, transferability and dependability (Lenzholzer et al., 2013).

Advocacy or participatory paradigmatic position is associated with critical theory and is also referred to as a transformative-emancipatory perspective (Lenzholzer et al., 2013). Research within the advocacy paradigm is typically focused on social justice and equality type of issues with an aim of advocating for marginalized groups on topics within the political, ethnic or gender issues (Farley et al., 2010). Often, the researcher helps to 'voice' the (often marginalized) research participants of the research to bring about changes in actual situations and raise awareness of the participants. The research is qualitative in nature and builds on the constructivism paradigm in that the researchers advocate for the participants they study, hence the research is value laden, and results are influenced by the beliefs and perspectives of the researcher.

Pragmatism is recognized as the middle ground between positivism and the qualitative orientated paradigms (Johnson & Onwuegbuzie, 2004). Pragmatists have a pluralistic approach around the concept of 'what works' such that the focus of the research is on applications of techniques to solve a problem. This is the foundation of many studies that have combined multiple approaches. Porter et al., (2007) suggest that interdisciplinary research should be defined by its ability to borrow from other fields, particularly in the area of tools, methods, concepts, models and paradigms which is also in keeping with a pragmatic approach to research. It has been emphasized that, with regard to research quality in a qualitative research, it is more important to select appropriate methods rather than be governed by a particular theoretical position.

Pragmatists conduct research using a range of methods to build the most comprehensive answer available to complex questions. In pragmatist mixed-methods procedures the underlying assumptions may be mixed (Creswell, 2018; Lenzholzer et al., 2013). A pragmatic position has practicality, is contextually responsive and has a degree of consequence such that the researcher is aware of and understands the demands, opportunities, and constraints within which the inquiry is taking place (Greene, 2008). Knowledge claims from a pragmatist perspective are based on factors including accuracy, scope, consistency, simplicity, and comprehensiveness. The pragmatic paradigm has been criticized by some scholars because of its tendency to avoid philosophical issues (Johnson & Onwuegbuzie, 2004). Pragmatic research typically aims to ground the methods of inquiry and reporting in the nature and context of the phenomena being investigated.

2.4.2 Paradigm recommended for IDR in agriculture

We recommend that IDR in agriculture be conducted within the pragmatic paradigm, especially where the nature of research is applied research with desired practical outcomes and recommendations. Pragmatists agree that research always occurs in dynamic social, historical, political and other contexts (Lenzholzer et al., 2013). With a pragmatic philosophical approach, assumptions are less important than ensuring the study meets its practical demands in relation to data collection and interpretation (Tobi & Kampen, 2017). Therefore, from the pragmatic position, potential contradictory ontological and epistemological assumptions are less important than situational responsiveness. This would ensure that the study is more focused on achieving practical outcomes intended while designing the study (Tobi & Kampen, 2017).

Pragmatic research has great appeal because it provides the researcher with the scope to find methods that are best suited to answering the question, essentially adopting a 'what works' approach.

Pragmatists embrace the use of both qualitative and quantitative research methods and recognize the limitations of both approaches in being able to address research questions (Fischer et al., 2011). Therefore, interdisciplinary teams need be pragmatic, since the research questions and hypotheses that are agreed on take precedence in the study design instead of traditional approaches (Tobi & Kampen, 2017). However, Tobi and Kampen, (2017) warn that the so-called ''paradigm war'' between neopositivist versus constructivists within the social and behavioural sciences (Onwuegbuzie & Leech, 2005) may complicate pragmatic collaboration. This is because natural sciences tend to adopt a positivist, reductionist approach looking for the 'truth', while in the social science, a more social constructivist approach is taken. These perceived differences lead to barriers as this prevents relevant interpretation of the results and approaches from natural sciences in the social sciences, and vice versa (Fischer et al., 2011). Having an interdisciplinary team aligned to pragmatic claims would allow a middle ground for teams to focus on beyond the scope of their own approaches and work to achieve a shared research goal, rather than emphasizing paradigmatic differences. Therefore, successful interdisciplinary projects place the goal of managing a complex issue above disciplinary tradition (Fischer et al., 2011).

2.4.3 Framework for interdisciplinary research in agriculture

The general interdisciplinary research framework developed by Tobi & Kampen (2017), involves five major components: 1) conceptual design of the study, 2) technical design, 3) execution of work, 4) an interdisciplinary synthesis and 5) integration. In addition to a few aspects from the University of Amsterdam's Institute for Interdisciplinary Studies (IIS) model (Rutting et al., 2016), we have suggested extension and feedback as an additional component to the framework, involving biophysical and social components especially in the context of developing countries (Figure 1). It is, however, important to note that the interdisciplinary research framework proposed here should not serve as a strict protocol, as research processes differ in practice.

Conceptual design

The conceptual design is the orientation stage of the interdisciplinary process (Rutting et al., 2016), during which the common goals required for interdisciplinary collaboration are ascertained (Fischer et al., 2011). This stage contains the 'why' and 'what' of the research. Through activities such as thinking, exchanging interdisciplinary knowledge, reading and discussing, key aspects including research objectives, theories and research questions are developed (Tobi & Kampen, 2017). Where the project is being implemented by an interdisciplinary team, the teams are expected to come together during project development to identify the research problem, while ensuring that each relevant discipline is reflected in the choice and wording of the research problem (Rutting et al., 2016).

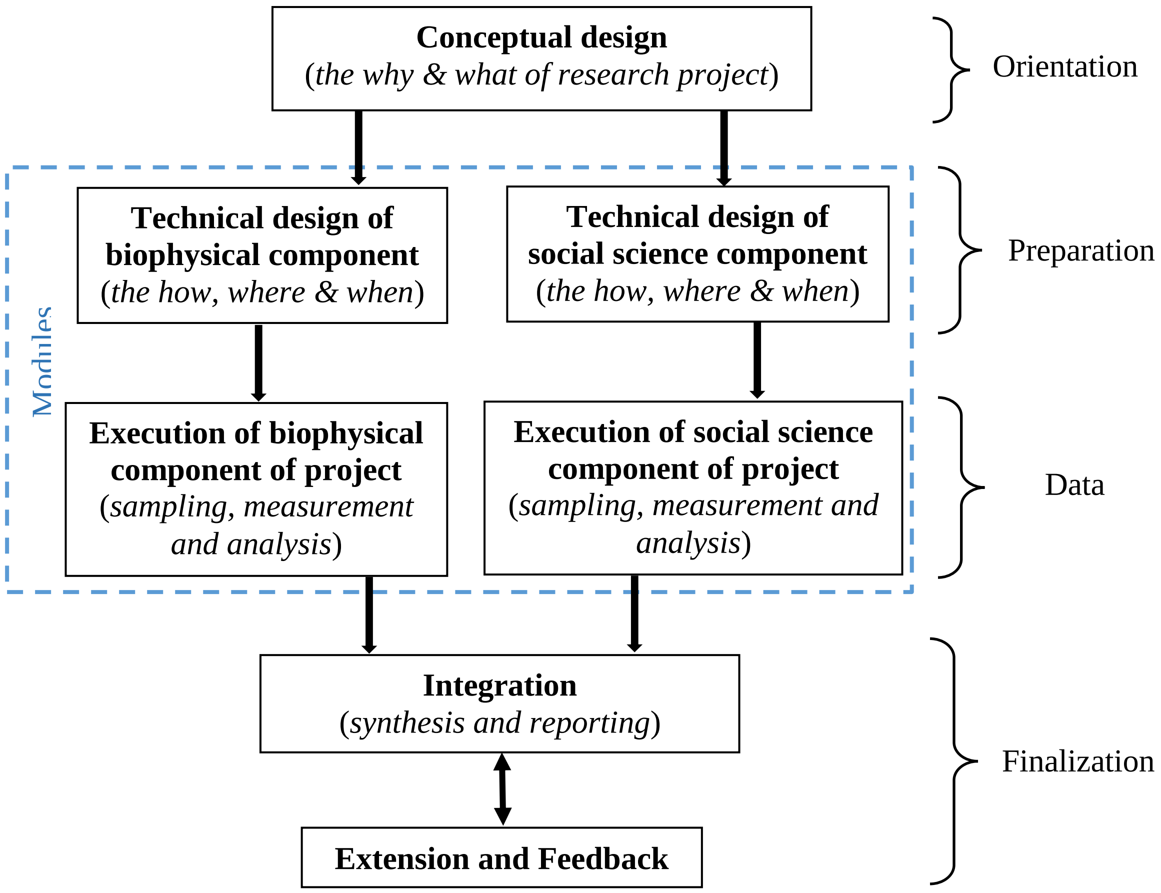

Fig. 1 A framework for interdisciplinary research in Agriculture (*Adapted from Tobi & Kampen, 2017 with author modifications*)

Technical design

The technical design stage addresses the 'how', 'where' and 'when' of the research by identifying how measurements will proceed, and designs the sampling and analysis plans (Tobi & Kampen, 2017). The preparation phase of an interdisciplinary research process involves a thorough literature research from different disciplines (Rutting et al., 2016). At the technical stage, the teams or the individual undertaking the study are expected to be pragmatic to ensure that the study meets its practical demands in relation to data collection and interpretation (Kumar, 2011). The role of the researcher is often a source of misunderstanding at this stage (Tobi & Kampen, 2017). For example, in a biophysical experiment, the researcher is usually considered a neutral outsider while reading a standardized instrument (e.g a sapflow gauge measuring tree water use). In contrast, for a social scientist, the researcher and the interviewee are part of the measurement instrument, while the researcher is eliminated where an online questionnaire is used. It is also important to set the rules for deciding on data saturation. Such contrasts need to be harmonized at the preparation stage of an interdisciplinary research framework.

Execution of the project

This stage involves the actual fieldwork to generate the required data for the project. The respective team members may do their disciplinary components of fieldwork (sampling, measurement and data analysis) on a modular basis (separately). For each interdisciplinary component, the researchers are expected to have criteria for detecting data saturation and how to analyse the collected data (Rutting et al., 2016), following all the necessary scientific data quality and ethical considerations (Tobi & Kampen, 2017). Paying attention to data quality and ethical considerations, researchers can appreciate each disciplinary concerns for good quality research and could recognize certain commonalities. Ethical issues generally run through all the components of the interdisciplinary research framework.

Integration

This involves synthesis of the information collected from the different disciplines and reporting the outputs. At this stage, the modules need to be brought together and these may rely on quantitative, qualitative, or mixed methods approaches (Tobi & Kampen, 2017) to integrate results and insights related to the research goal. Integration of information may be convergent (done parallel and integrated after completion), sequential (done after one another and the first modules inform the latter ones) or embedded, where modules depend on one another for data collection and analysis, and synthesis may be planned both during and after completion of the embedded modules (Creswell, 2018). Another key component of this finalization stage is extension and feedback mechanisms with non-academic collaborators.

Extension and feedback

Although Tobi and Kampen (2017) did not include extension and feedback in their interdisciplinary framework, these are important in generating information essential for informing policy decisions relating to sustainable agriculture. It has been argued that interdisciplinarity should not only involve individual disciplinary specialists working together, but also allowing others' perspectives and methods to influence their understanding of problems (Sillitoe, 2004). This can be effectively achieved through extension and feedback mechanisms. There could be arguments that including extension and feedback would make the framework transdisciplinary rather than interdisciplinary, because it involves non-academic collaborators such as farmers. We argue that for interdisciplinary research in agriculture to be successful, there must be a transdisciplinary aspect integrated in the research framework.

Feedback has been regarded as a fundamental bridging concept for advancing transdisciplinary sustainability research (Blythe et al., 2017). There have also been calls to transcend interdisciplinarity and move towards transdisciplinarity in order to achieve sustainability (Jeder, 2014; Takeuchi, 2014). We therefore contend that interdisciplinary research in agriculture should not end at synthesizing and reporting project outputs. It should also allow others' (usually non-academic collaborators, such as farmers) perspectives to better understand the problem and generate more conclusive and impactful knowledge from the study. Engaging non-academic collaborators would also render the project socially relevant (Lowe & Phillipson, 2006), while bridging science and development in the long-term (Callo-Concha et al., 2017).

2.5 Barriers to implementation of IDR in Agricultural research

We characterise the barriers in terms of time and effort requirements, human resource factors, and institutional and policy related barriers.

2.5.1 Time and effort requirements

A key challenge in interdisciplinary work is to develop expertise in more than one area. It requires investment of a significant amount of time in building collaborative relationships, developing a shared language and a common perspective from disparate viewpoints (Bromham et al., 2016). IDR would therefore require more time and resources than monodisciplinary research (Davé et al., 2016) and funders who wish to support IDR must consider how the additional resource requirements could be fulfilled. Interdisciplinary researchers reportedly work under considerably more stress than their disciplinary counterparts, especially in terms of time management, anxiety, and inadequate interdisciplinary literature (NationalAcademies, 2005; Spanner, 2001). A researcher undertaking an interdisciplinary study would require additional training in a new field, which may reduce their apparent productivity relative to that of a scholar who focuses on a single discipline.

2.5.2 Human resource factors

Most of the challenges faced by interdisciplinary research teams result from differences in training and scientific culture (Tobi & Kampen, 2017). Researchers in one discipline often have a strained relationship with a researcher from another discipline (Cox, 2015), much to the detriment of the farmer, who is often the beneficiary of the information generated from this type of research. Interdisciplinary teams are often put together by proximity and convenience rather than expertise and need (Butler, 2011). A shared understanding on how best to develop effective interdisciplinary researchers (particularly at early career stages) is lacking (Kelly et al., 2019), as specialized scientists tend to lack knowledge about other domains (Cox, 2015; Fischer et al., 2011). Learning something new, especially outside of one’s major discipline, is disempowering and can create anxiety among interdisciplinary research teams (Butler, 2011; Davé et al., 2016). Building bridges between disciplines goes beyond just putting together an interdisciplinary team and charging them with solving a problem (Lele & Norgaard, 2005). For interdisciplinarity to work well, cross-fertilization and cooperation are paramount. A significant barrier to addressing farmers' problems is that farmers think in interdisciplinary terms, while researchers are still ruled by disciplinary boundaries.

2.5.3 Institutional and policy related challenges

Existing institutional structures and practices to support interdisciplinary research are still developing (German et al., 2010; Kelly et al., 2019). However, effective solutions demand that we transcend institutional boundaries (Farley et al., 2010). It has been argued that disciplines lose meaning outside of the academic institutions, and that interdisciplinarity in real world problems should take that into account (Liu et al., 2010). Funding agencies play a key role in shaping interdisciplinary research (German et al., 2010; Lyall et al., 2013), with both positive influence, such as dedicated programmes for interdisciplinary projects, and negative impacts, as perceived biases can discourage submission of interdisciplinary proposals to open funding calls.

Interdisciplinary research is often encouraged at policy level but poorly rewarded by funding instruments (Woelert & Millar, 2013). There have been reports that many interdisciplinary research proposals face dismissal because they are scrutinized by academics who are discipline based (Bromham et al., 2016; NationalAcademies, 2005) and have difficulty understanding or seeing the merit of interdisciplinary research (Butler, 2011). Policy-makers need to recognize the benefits of a broader range of expertise in decision-making and incorporate social science into policy to complement the more established sources of natural science advice related to the agricultural sector. Collaboration with the social sciences can bring different perspectives and methodologies to help reframe agricultural problems and reveal multiple or disputed understandings and thus expose diverse possibilities and alternative meanings.

2.6 Opportunities for implementation of IDR in agriculture

There has been a general longstanding call for interdisciplinary research between the social and the natural sciences to manage complex societal issues (Fischer et al., 2011; German et al., 2010), regardless of the many barriers that remain. Opportunities for collaboration occur when researchers are willing to adapt, with a strong interpersonal focus and interest in engaging in discussions with others while looking to broaden their horizon and step outside their own field (Kelly et al., 2019). We propose that agricultural sustainability can successfully be achieved by ensuring that disciplinary experts have an interdisciplinary experience. We review two opportunities that can expose disciplinary experts to interdisciplinary experiences that would foster agricultural sustainability.

2.6.1 Increasing demand for interdisciplinary teams

The complex problems society is currently facing (e.g., global food insecurity, climate change) demand innovative solutions that combine knowledge from different scientific disciplines (NationalAcademies, 2005). This is mainly because research carried out by interdisciplinary teams contributes to bridging multiple disciplinary concepts, theories and methods to solve problems that a single discipline cannot solve (Perez-Vazquez & Ruiz-Rosado, 2005). Since agriculture is conceived as a system formed by different elements (including institutions, society, biotic and abiotic resources), IDR can contribute to better understanding of the complex problems of agriculture. There have been calls for increased support for interdisciplinary research in agriculture and life sciences higher education (Miller, 2016; Spelt et al., 2010). Indeed, to achieve the interaction among different dimensions (e.g social and biophysical) and its goals, interdisciplinary research has been considered as the right approach (Perez-Vazquez & Ruiz-Rosado, 2005).

2.6.2 The potential of IDR to address global agricultural technology adoption barriers

Global agriculture demands increased food production to meet the projected global population by the year 2050 to feed an estimated 9 billion world human population (Miller, 2016; Ray et al., 2013). At the same time, available land is not increasing and agricultural production must be intensified on the available land while reducing environmental impacts (Miller, 2016). Addressing these global challenges requires adoption of innovative agricultural interventions, especially by smallholder farmers (under 2 ha of land) that produce 28-31% of global food production (Ricciardi et al., 2018). We anticipate that the use of collaborative approaches such as interdisciplinary and transdisciplinary approaches will be central to addressing global food security challenges. These approaches have been reported to be socially engaging (Lowe & Phillipson, 2006) while facilitating the bridging of science and development in the long-term (Callo-Concha et al., 2017).

2.7 Conclusion

In an attempt to review and document interdisciplinary research in agriculture, We recommend that IDR in agriculture be conducted within the pragmatic paradigm as a middle ground between positivism and the qualitative orientated paradigms. We promote a pluralistic approach around the concept of 'what works' such that the focus of the research is on applications of techniques to solve a problem. We suggest an interdisciplinary research framework in agriculture that involves six major components: 1) conceptual design of the study, 2) technical design, 3) execution of work, 4) an interdisciplinary synthesis, 5) Integration and 6) extension and feedback.

From the reviewed literature, there is evidence of an ever-increasing demand for interdisciplinary teams to solve complex global challenges. It is anticipated that the use of IDR will be central to addressing global food security challenges by bridging science and development in the long term. The current and future global complex agricultural sustainability challenges will require disciplinary experts with an interdisciplinary experience. We believe that interdisciplinary research in agriculture must increasingly become the standard rather than the exception because the approaches needed, and the implications of agricultural research, are by their very nature interdisciplinary. While IDR should not be incentivised at the expense of good quality monodisciplinary agricultural research, we anticipate that IDR can contribute to better understanding of the complex problems of agriculture.

2.8 References

Aboelela, S. W., Larson, E., Bakken, S., Carrasquillo, O., Formicola, A., Glied, S. A., . . . Gebbie, K. M. (2007). Defining Interdisciplinary Research: Conclusions from a Critical Review of the Literature. *Health Services Research, 42*(1p1), 329-346. doi: 10.1111/j.1475-6773.2006.00621.x

Blythe, J., Nash, K., Yates, J., & Cumming, G. (2017). Feedbacks as a bridging concept for advancing transdisciplinary sustainability research. *Current Opinion in Environmental Sustainability, 26-27*, 114-119. doi: 10.1016/j.cosust.2017.05.004

Borrego, M., & Newswander, L. (2010). Definitions of Interdisciplinary Research: Toward Graduate-Level Interdisciplinary Learning Outcomes. *Review of Higher Education, 34*(1), 61-84. doi: 10.1353/rhe.2010.0006

Bromham, L., Dinnage, R., & Hua, X. (2016). Interdisciplinary research has consistently lower funding success. *Nature, 534*(7609), 684-687. doi: 10.1038/nature18315

Butler, L. (2011). Barriers and enablers of interdisciplinary research at academic institutions. In K. Shelley (Ed.), (pp. 157): ProQuest Dissertations Publishing.

Callo-Concha, D., Denich, M., Lamers, J. P. A., Schwachula, A., Hornidge, A. K., Khamzina, A., & Borgemeister, C. (2017). Bridging science and development: lessons learnt from two decades of development research.(Report). *Agroforestry Systems, 91*(5), 799. doi: 10.1007/s10457-016-0008-y

Corsi, A., Barbera, F., Dansero, E., & Peano, C. (2018). *Alternative Food Networks An Interdisciplinary Assessment* (1st ed. 2018. ed.). Cham: Springer International Publishing.

Cox, W. J. (2015). *An Interdisciplinary Approach Is Critical for Successful Crop Management Research in the Northeast*. Madison, WI, USA: American Society of Agronomy.

Creswell, J. W. (2018). *Research design : qualitative, quantitative, and mixed methods approaches* (Fifth edition. ed.). Thousand Oaks, California: SAGE Publications, Inc.

Davé, A., Hopkins, M., Hutton, J., Krčál, A., Kolarz, P., Martin, B., . . . Stirling, A. (2016). Landscape Review of Interdisciplinary Research in the UK. Report to HEFCE and RCUK by Technopolis and the Science Policy Research Unit (SPRU) (pp. 184): University of Sussex.

Descheemaeker, K., Bunting, S. W., Bindraban, P., Muthuri, C., Molden, D., Beveridge, M., . . . Jarvis, D. I. (2013). *Increasing water productivity in Agriculture*.

Farley, J., Batker, D., Torre, I., & Hudspeth, T. (2010). Conserving Mangrove Ecosystems in the Philippines: Transcending Disciplinary and Institutional Borders. *Environmental Management, 45*(1), 39-51. doi: 10.1007/s00267-009-9379-4

Fischer, A. R. H., Tobi, H., & Ronteltap, A. (2011). When Natural met Social: A Review of Collaboration between the Natural and Social Sciences. *Interdisciplinary Science Reviews, 36*(4), 341-358. doi: 10.1179/030801811X13160755918688

Foran, T., Butler, J. R. A., Williams, L. J., Wanjura, W. J., Hall, A., Carter, L., & Carberry, P. S. (2014). Taking Complexity in Food Systems Seriously: An Interdisciplinary Analysis. *World Development, 61*(C), 85-101. doi: 10.1016/j.worlddev.2014.03.023

Frodeman, R. (2011). Interdisciplinary research and academic sustainability: managing knowledge in an age of accountability. *Envir. Conserv., 38*(2), 105-112. doi: 10.1017/S0376892911000038

Galmiche-Tejeda, A. (2004). Who is interdisciplinary? Two views, two goals, professionals and farmers. *Interdisciplinary Science Reviews: Interdisciplinarity: lessons from the social sciences, 29*(1), 77-95. doi: 10.1179/030801804225012464

German, L., Verma, R., & Ramisch, J. J. (2010). *Beyond the Biophysical Knowledge, Culture, and Power in Agriculture and Natural Resource Management* (1st ed. 2010. ed.). Dordrecht: Springer Netherlands.

Greene, J. C. (2008). Is Mixed Methods Social Inquiry a Distinctive Methodology? *Journal of Mixed Methods Research, 2*(1), 7-22. doi: 10.1177/1558689807309969

Hanson, J. D., Hendrickson, J., & Archer, D. (2008). Challenges for maintaining sustainable agricultural systems in the United States. *Renewable agriculture and food systems, 23*(4), 325-334.

Healy, M., & Perry, C. (2000). Comprehensive criteria to judge validity and reliability of qualitative research within the realism paradigm. *Qualitative Market Research: An International Journal, 3*(3), 118-126. doi: 10.1108/13522750010333861

Hietel, E., Waldhardt, R., & Otte, A. (2005). Linking socio-economic factors, environment and land cover in the German highlands, 1945-1999. *Journal of Environmental Management*, *75*(2), 133-143. doi: 10.1016/j.jenvman.2004.11.022

Hirsch-Hadorn, G., Hadorn, G. H., Hoffmann-Riem, H., Biber-Klemm, S., Grossenbacher-Mansuy, W., Joye, D., . . . Zemp, E. (2008). *Handbook of Transdisciplinary Research*. Dordrecht: Springer Netherlands.

Jeder, D. (2014). Transdisciplinarity – The Advantage of a Holistic Approach to Life. *Procedia - Social and Behavioral Sciences, 137*(C), 127-131. doi: 10.1016/j.sbspro.2014.05.264

Johnson, R. B., & Onwuegbuzie, A. J. (2004). Mixed Methods Research: A Research Paradigm Whose Time Has Come. *Educational Researcher, 33*(7), 14-26. doi: 10.3102/0013189X033007014

Kagan, J. (2009). *The Three Cultures: Natural Sciences, Social Sciences, and the Humanities in the 21st Century*. Cambridge: Cambridge University Press.

Kelly, R., Mackay, M., Nash, K. L., Cvitanovic, C., Allison, E. H., Armitage, D., . . . Werner, F. (2019). Ten tips for developing interdisciplinary socio-ecological researchers. *Socio-Ecological Practice Research, 1*(2), 149-161. doi: 10.1007/s42532-019-00018-2

Kumar, R. (2011). *Research methodology : a step-by-step guide for beginners* (3rd ed. ed.). London: SAGE.

Lee, J. S. (2011). *An interdisciplinary study of maternal productivity in beef cattle.* (PhD), The University of Adelaide, South Australia.

Lele, S., & Norgaard, R. B. (2005). Practicing Interdisciplinarity. *BioScience, 55*(11), 967-975. doi: 10.1641/0006-3568(2005)055[0967:PI]2.0.CO;2

Lenzholzer, S., Duchhart, I., & Koh, J. (2013). 'Research through designing' in landscape architecture. *Landscape and Urban Planning, 113*, 120-127. doi: 10.1016/j.landurbplan.2013.02.003

Liu, S., Costanza, R., Farber, S., & Troy, A. (2010). Valuing ecosystem services: theory, practice, and the need for a transdisciplinary synthesis. *Annals of the New York Academy of Sciences, 1185*(1), 54. doi: 10.1111/j.1749-6632.2009.05167.x

Lowe, P., & Phillipson, J. (2006). Reflexive Interdisciplinary Research: The Making of a Research Programme on the Rural Economy and Land Use. *Journal of Agricultural Economics, 57*(2), 165-184. doi: 10.1111/j.1477-9552.2006.00045.x

Lyall, C., Bruce, A., Marsden, W., & Meagher, L. (2013). The role of funding agencies in creating interdisciplinary knowledge. *Science and Public Policy, 40*(1), 62-71. doi: 10.1093/scipol/scs121

Miller, J. J. (2016). The role of interdisciplinary scholarship and research to meet the challenges facing agriculture in the 21st century. In G. L. Hein, G. Adams, R. Elmore, C. Francis, & R. Wright (Eds.): ProQuest Dissertations Publishing.

Morgan, D. L. (2007). Paradigms Lost and Pragmatism Regained: Methodological Implications of Combining Qualitative and Quantitative Methods. *Journal of Mixed Methods Research, 1*(1), 48-76. doi: 10.1177/2345678906292462

Morse, W. C., Nielsen-Pincus, M., Force, J. E., & Wulfhorst, J. D. (2007). Bridges and Barriers to Developing and Conducting Interdisciplinary Graduate-Student Team Research. *Ecology and Society, 12*(2), 8. doi: 10.5751/ES-02082-120208

NationalAcademies. (2005). *Facilitating interdisciplinary research*. Washington, D.C: The National Academies Press.

Neuman, W. L. a. (2014). *Social research methods : qualitative and quantitative approaches* (Seventh edition, Pearson New International Edition. ed.): Pearson.

Ogundari, K. (2014). The Paradigm of Agricultural Efficiency and its Implication on Food Security in Africa: What Does Meta-analysis Reveal? *World Development, 64*, 690-702. doi: https://doi.org/10.1016/j.worlddev.2014.07.005

Onwuegbuzie, A., & Leech, N. (2005). Taking the "Q" Out of Research: Teaching Research Methodology Courses Without the Divide Between Quantitative and Qualitative Paradigms. *Quality and Quantity, 39*(3), 267-295. doi: 10.1007/s11135-004-1670-0

Perez-Vazquez, A., & Ruiz-Rosado, O. (2005). Interdisciplinary Research: A SWOT analysis and its role in agricultural research in Mexico. *Tropical and Subtropical Agroecosystems, 5*, 91-99.

Petersen, K., & Gencel, C. (2013). Worldviews, Research Methods, and their Relationship to Validity in Empirical Software Engineering Research (pp. 81-89): IEEE.

Porter, A., Cohen, A., David Roessner, J., & Perreault, M. (2007). Measuring researcher interdisciplinarity. *An International Journal for all Quantitative Aspects of the Science of Science, Communication in Science and Science Policy, 72*(1), 117-147. doi: 10.1007/s11192-007-1700-5

Porter, A., & Rafols, I. (2009). Is science becoming more interdisciplinary? Measuring and mapping six research fields over time. *Scientometrics, 81*(3), 719-745. doi: 10.1007/s11192-008-2197-2

Ray, D. K., Mueller, N. D., West, P. C., & Foley, J. A. (2013). Yield Trends Are Insufficient to Double Global Crop Production by 2050.

Ricciardi, V., Ramankutty, N., Mehrabi, Z., Jarvis, L., & Chookolingo, B. (2018). How much of the world's food do smallholders produce? *Global Food Security, 17*, 64-72. doi: https://doi.org/10.1016/j.gfs.2018.05.002

Rutting, L., Post, G., Keestra, M., Roo, M. d., Blad, S., & Greef, L. d. (2016). *An introduction to interdisciplinary research : theory and practice* (Vol. 2). Amsterdam: Amsterdam University Press.

Schwartz-Shea, P., & Yanow, D. (2012). *Designing for Trustworthiness: Knowledge Claims and Evaluations of Interpretive Research*: Routledge.

Sillitoe, P. (2004). Interdisciplinary experiences: working with indigenous knowledge in development. *Interdisciplinary Science Reviews, 29*(1), 6-23. doi: 10.1179/030801804225012428

Spanner, D. (2001). Border Crossings: Understanding the Cultural and Informational Dilemmas of Interdisciplinary Scholars. *The Journal of Academic Librarianship, 27*(5), 352-360. doi: 10.1016/S0099-1333(01)00220-8

Spelt, E. J. H., Biemans, H. J. A., Luning, P. A., Tobi, H., & Mulder, M. (2010). Interdisciplinary thinking in agricultural and life sciences higher education.

Takeuchi, K. (2014). The ideal form of transdisciplinary research as seen from the perspective of sustainability science, considering the future development of IATSS. *IATSS Research, 38*(1), 2-6. doi: 10.1016/j.iatssr.2014.05.001

Tobi, H., & Kampen, J. K. (2017). Research design: the methodology for interdisciplinary research framework. *Quality & Quantity*. doi: 10.1007/s11135-017-0513-8

Wilkinson, K., Grant, W. P., Green, L. E., Hunter, S., Jeger, M. J., Lowe, P., . . . Waage, J. (2011). Introduction: Infectious diseases of animals and plants: an interdisciplinary approach. *Philosophical Transactions: Biological Sciences, 366*(1573), 1933-1942.

Woelert, P., & Millar, V. (2013). The "Paradox of Interdisciplinarity" in Australian Research Governance. *Higher Education: The International Journal of Higher Education and Educational Planning, 66*(6), 755. doi: 10.1007/s10734-013-9634-8

Chapter Three: Contrasting water use patterns of two important agroforestry tree species in the Mt. Elgon region of Uganda

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Name of Principal Author (Candidate)	Joel Buyinza		
Contribution to the Paper	Field experimentation, Collected and analysed data, Interpreted the findings, Wrote the manuscript, acted as the first and corresponding author		
Overall percentage (%)	75%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
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Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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ARTICLE

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Contrasting water use patterns of two important agroforestry tree species in the Mt Elgon region of Uganda

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ABSTRACT
Lack of information on water use of key agroforestry species is an obstacle to understanding their influence on crop productivity. *Cordia africana* and *Albizia coriaria* are the dominant tree species of smallholder farming systems in the Mt Elgon region of Uganda and have multiple uses in agroforestry systems. This study deployed six sap flow meters on stems of three selected trees each of *C. africana* and *A. coriaria* on-farm. The objective of the study was to assess the daily water use patterns of these agroforestry tree species at different times of the year. We measured the daily sap flow of these two species using the heat ratio method over a period of 18 months. There was a significant main effect of the interaction between tree species and season on daily water use. The two species show contrasting patterns of seasonal water use across leaf shedding stages characterised by episodes of reverse flow in *A. coriaria* at specific periods of the year. We propose that reverse flows in *A. coriaria* were triggered by leaf shading while the zero flows in *C. africana*, which occurred during rainfall events, could have resulted from a lag phase, an indication that the two species may have different water-use strategies. Although *C. africana* uses 12–15 l day^{-1} and *A. coriaria* uses 20–32 l day^{-1} based on the study trees, *C. africana* generally uses 12% more water than *A. coriaria* on a standardised daily basis. *Albizia coriaria* exhibited radial variation of sap velocities between the inner and outer thermocouples at different periods of measurement, a phenomenon worth investigating further. The leaf shedding patterns of the two trees provide an opportunity for maximising the temporal complementarities of agroforestry systems where these trees exist. This knowledge of *C. africana* and *A. coriaria* tree water use provides critical insight for developing successful long-term tree monitoring and management programs in agroforestry systems.

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3.2 Introduction

Sustainable use of soil water resources has been associated with improved food security and livelihoods (Cai et al. 2011). Global food demands have been projected to increase as a result of scarcity, degradation and overuse of water resources (FAO 2011; Descheemaeker et al. 2013). Agroforestry is recognized as one of the most functional components of farming systems that can enhance sustainable use of water and nutrient resources and assist in the provision of global food demands (Pinho et al. 2012). It is an important component of climate-smart agriculture that supports food and nutritional security through provision of food, contributing to household income and fuel needs. While agroforestry offers effective means to restore degraded lands (Sales et al. 2016), most smallholder farmers with trees on-farm have failed to realize the co-benefits, due to poor management of the tree component. These farmers also lack knowledge of tree selection and arrangement of the agroforestry components. Success in agroforestry systems is primarily based on selecting the right tree-crop combinations that exploit spatial and temporal complementarities in resource use (Descheemaeker et al. 2013).

One of the fundamental steps towards enhancing the complementarity and stability of food production in smallholder agroforestry systems is gaining an understanding of the water use of the tree component. Understanding tree water-use physiology has received increasing research attention in response to emerging environmental issues such as land-use change (Ellison et al. 2017), degradation of agricultural land (Muthuri et al. 2005) and climate change (Linares et al. 2012; Webber et al. 2014; Strobl et al. 2017), which all impact on household food security. However, most of the studies on water use in agroforestry trees have not monitored individual tree water use in the field, due to technological limitations. Field-based experiments provide useful scientific knowledge about plant hydraulic function that can be used to better understand and model field scenarios (Steppe et al. 2015). Field monitoring also allows subsequent observations to be made on other tree physiological events including leafing phenology and response to rainfall patterns. Understanding how farmers interact with the trees on a daily basis provides an opportunity for real time measurements that can be used for improved management.

The deciduous nature of the focal tree species (*Cordia africana* and *Albizia coriaria*) provides an opportunity to improve crop productivity through temporal complementarity with crop plants. A key factor when choosing suitable agroforestry tree species is their leaf phenology, as the timing and extent of leaf shedding and replacement during the annual cycle affects the pattern and rate of soil water extraction and the effects on associated crops (Broadhead et al. 2003). Differences in leaf phenology can influence the extent of competition and complementarity in agroforestry systems (Muthuri et al. 2009). For example, Chinese red birch, *Betula albosinensis*, can adopt different water use strategies to cope with changes in soil water (Yan et al. 2018) which can influence the yield of the associated crop. Therefore, understanding water use patterns of deciduous agroforestry species such as *C. africana* and *A. coriaria* is crucial to determining the extent of competition and complementarity.

Since *C. africana* and *A. coriaria* are important components of agroforestry systems in eastern Africa, we assessed sapflow of these species in two farmers' fields using the heat ratio method, as established by (Burgess et al. 2001). It was hypothesized that the water use patterns would be seasonally influenced through leaf traits and rainfall, and that these would have important consequences to agricultural crops growing in these systems.

3.3 Materials and Methods

3.3.1 Study area

The study was conducted in Manafwa district located in Eastern Uganda, with a land area of 452 km^2, bordering the Republic of Kenya in the East, Bududa district to the North, Mbale district to the West and Tororo to the Southwest. About 98% of the human population in Manafwa is rural based, with an annual population growth rate of 3.4%. In terms of climate, the average annual rainfall is 1500 mm, with two peak rainy seasons that occur in the months of April–June and August–November. Manafwa registers a mean annual maximum and minimum temperature range between 32^{o}C - 15^{o}C.

3.3.2 Tree species under Study

Albizia coriaria Welw. ex Oliv. (locally called Mugavu in Luganda and Swahili, and Kumoluko in Lugisu) is a deciduous nitrogen fixing tree in the family Fabaceae (Katende *et al.*

1995). It is a pioneer species that grows to a height of 36 m with a distribution from West Africa through eastern, southern and parts of central Africa (Orwa *et al.* 2009). The absence of *A. coriaria* in closed canopy rainforests is largely the result of its high light requirements (Janani *et al.* 2014). Although *A. coriaria* is reportedly a slow growing tree, it is widely regarded as a multipurpose tree, providing various products and services (Tabuti and Mugula 2007). There have also been claims that the tree bark provides a useful medicine for malaria and coughs (Namukobe et al. 2011) and has dye-yielding properties for plain woven cotton fabrics (Janani *et al.* 2014). *A. coriaria* is one of the most common multipurpose tree species used in indigenous agroforestry systems of Uganda (Bukomeko et al. 2017). It was chosen for this project because it is a popular tree already widely grown by farmers in Mt. Elgon region and for its ability to fix nitrogen.

Cordia africana Lam. (commonly known as large-leaved Cordia, locally called Mukebu in Luganda and Chichikiri in Lugishu) is a deciduous tree that belongs to the family *Boraginaceae* (Katende *et al.* 1995). The species is widely distributed from South Africa to Saudi Arabia and Yemen at altitudes between 550 - 2600 meters above sea level (m.a.s.l), in warm and moist areas, often along riverbanks. The mature fruits of *C. africana* have a sweet edible pulp (Kebebew and Balemie 2006). *C. africana* was exceptionally well ranked by farmers as an important agroforestry tree species in coffee plantations in Eastern Uganda (Gram et al. 2017). Silvicultural studies of the species indicate that increased spacing of *C. africana* increases branch diameter (knot size) and crown diameter (Mehari and Habte 2006), making it a good agroforestry candidate tree species. This tree species was selected for this study because it has been widely integrated in coffee systems in Mt. Elgon region.

3.3.3 Research design and Instrumentation

Tree water use was assessed using 6 SFM1 Sap Flow Meters (ICT International, Armidale, Australia) installed on three *C. africana* and three *A. coriaria* trees existing in two farmers' fields. There were three trees of one species on one farm and three of the other species on the other farm, making 6 trees in all. The two farms are approximately 2 km from each other. The trees are spaced at a distance of 10-12 m and are integrated with coffee at a spacing of 3 x 3 m. Tree species selection was based on the fact that these two species are the most common in the farming systems in the area, predominant in coffee agroforestry systems. Sapflow instrumentation (SFM1 Sap Flow Meter) used in this study is based on the Heat Ratio Method (HRM) as it is non-destructive and has the ability to detect low and reverse flow rates over extended periods (Burgess et al. 2001).

3.3.4 Site selection and installation of Sap Flow Meters

During selection of sites and trees for installing the Sap Flow Meters, care was taken to select healthy, straight trunk representative trees, within the same diameter class. The host farmers (land and tree owners) were also fully engaged before starting the installation exercise, which ensured protection of the Sap Flow Meters and the solar panels on their farms.

Prior to installation the bark depth of each tree was measured using a bark depth gauge, and an increment borer was used to determine sap wood thickness. These parameters were then used to determine the correct radial placement of the measurement needles within the water conducting tissue of the tree at approximately 1.3m height or DBHOB (Diameter at Breast Height Over Bark) on the tree trunk. The two measurement needles were positioned 0.5 cm equidistant above and below the central heater. The three needles were lightly greased with an inert silicon vacuum grease, to improve thermal coupling between the needles and the stem.

Each needle was then inserted into the pre-drilled holes in the water conducting xylem of the tree. A solar panel was directly connected to the non-polarized charging ports to trickle charge the internal battery of each Sap Flow Meter for continuous field operation. Sapflow was continuously monitored at 30-minute temporal resolution over an 18-month period from November 2015 to April 2017. Information on tree leafing phenology was also collected by noting the months of the year when the trees shed their leaves through the sap flow measurement period.

3.4 Data analysis

The downloaded data was analysed using the Sap Flow Tool (SFT) software and the Combined Instrument Software (CIS) to obtain Daily Flows ($Lday^{-1}$) and sap velocity ($cmhr^{-1}$). A linear transformation on the heat pulse velocity was performed to obtain corrected zero flow baselines for asymmetry of installation. The daily flows were analyzed and compared with rainfall patterns using a line graph (for daily flows) and bar graphs (for rainfall data). Daily Flow data was exported from the SFT software as a .csv file and used for further analysis. Pearson's correlation coefficients between rainfall and seasonal daily sapflow in *C. africana* and *A. coriaria* were obtained using Minitab 18 (Minitab Inc., USA).

An analysis of variance- General Linear Model (Two-way ANOVA-GLM) was also performed in Minitab to assess the interaction between tree species and season on daily sapflow with 'tree species' and 'season' as the main effects at 95% confidence interval. The two-way ANOVA would establish whether either of the two independent variables (tree species and season) or their interaction are statistically significant.

A schematic representation of existing farming systems with the 2 tree species, coffee and common beans was constructed from the smallholder farmers' perspective. This was integrated with information on rainfall patterns, tree leaf phenology, coffee flowering and harvesting as well as planting and harvesting of common beans.

3.5 Results

3.5.1 Assessment of the daily sapflow of the study trees

Table 1 provides a summary of the average daily sapflow of the 6 trees that were monitored during the study. The maximum daily sapflow was 87.6 Lday^{-1} for *A. coriaria* and 52.3 Lday^{-1} for *C. africana*. *A. coriaria* trees generally used more water registering average daily flow of 20-32 Lday^{-1} against 12-15 Lday^{-1} used by *C. africana*. *A. coriaria* trees had larger diameter at breast height (DBH 41-53 cm) than *C. africana* (DBH 28-37 cm).

Table 1 Summary of maximum, minimum and average daily sapflow per tree and sapflow standardized to tree area for *A. coriaria* and *C. africana* over a 10-month period of the experiment

Tree species	Tree ID	DBH (cm)	Daily sapflow (Lday^{-1})			Daily sapflow (L.day^{-1}cm^{-2})	
			Min	Max	Average	Tree	Overall
Albizia coriaria	Tree 1	40.9	-0.8	87.6	24.8	0.019	
Albizia coriaria	Tree 2	52.5	-5.8	34.7	20.6	0.010	0.015
Albizia coriaria	Tree 3	51.4	-8.2	75.4	31.5	0.015	
Cordia africana	Tree 1	36.6	1.3	48.7	15.3	0.015	
Cordia africana	Tree 2	31.6	1.2	41.5	12.8	0.016	0.018
Cordia africana	Tree 3	28.3	0.5	52.3	15.2	0.024	

To obtain standard comparable daily sapflow in the 2 tree species, the daily flows were computed per cross-sectional area of the tree at 1.2 meters height (L.day^{-1}cm^{-2}) as shown in Table 1. The overall average daily sapflow of *C. africana* (0.018 L.day^{-1}cm^{-2}) was higher than that *A. coriaria* (0.015 L.day^{-1}cm^{-2}), an indication that *C. africana* used 12% more water than *A. coriaria*. Unlike *C. africana*, negative daily sapflow were registered in *A. coriaria*. It is however likely that other factors including soil properties and competitive relationships of the trees with the associated crops (not covered under this study) may also influence the differences in tree water use. The study therefore focused on assessing trends in daily and seasonal tree water use of the two tree species that occur within an agroforestry setting.

3.5.2 Tree water use in A. coriaria and C. africana

The study made a comparison between the daily sapflow in *C. africana* and *A. coriaria* with rainfall data. The data presented in Fig.1 is mean daily sapflow for *C. africana* and *A. coriaria* covering 10 months of sapflow measurement. *C. africana* exhibited higher daily sapflow than *A. coriaria* from the start of the experiment until early March 2016 (Fig. 1). This was followed by a gradual decline below *A. coriaria* thereafter through the rainfall season. However, daily sapflow in both trees generally increased during the dry season and declined during high rainfall days. Unlike *A. coriaria*, total daily sapflow in *C. africana* drastically decreased during the main rainfall season between April and June.

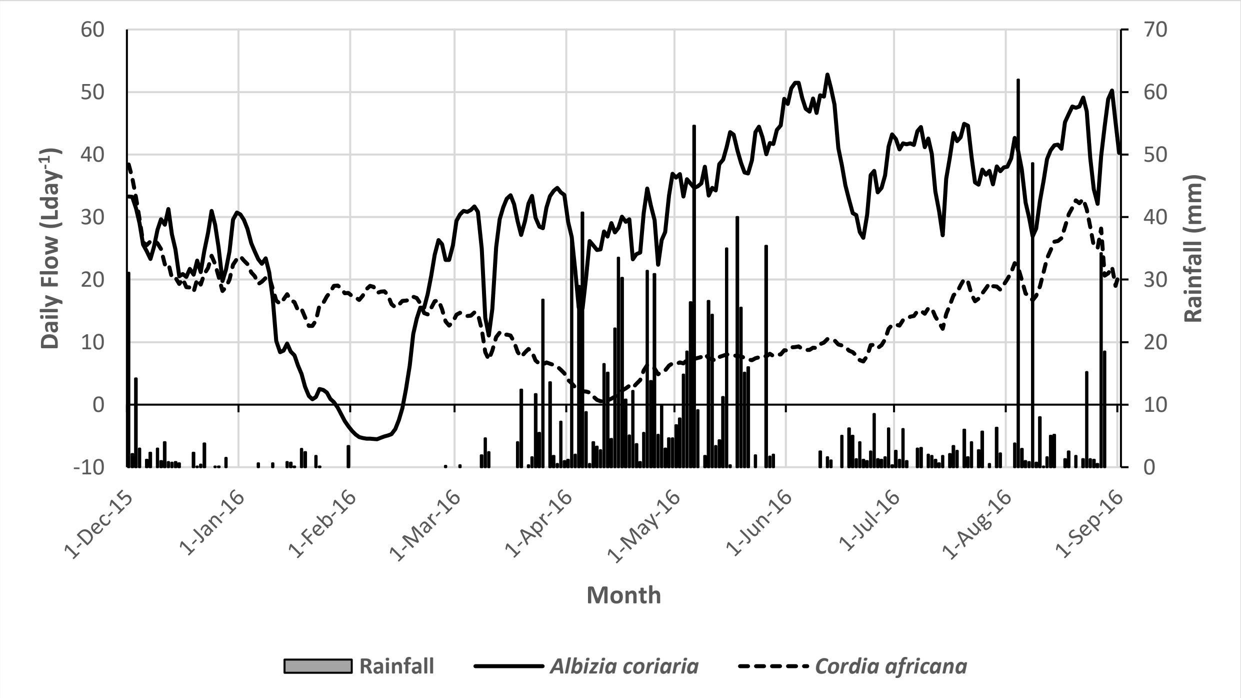

Fig. 1 Daily average sapflow in *A. coriaria* and *C. africana* over a 10 month period. Rainfall events indicate the early wet season (April to June) and the start of the late wet season (August to November)

The minimum daily sapflow for each tree was registered at different periods of the year (Fig.1). In *C. africana,* the minimum daily flows occurred between April and May (peak rainfall months), and between February and March (dry season) in *A. coriaria*, (also characterized by reverse flows). The consistent occurrence of reverse flows in *A. coriaria* between January and February were also observed following analysis of additional data covering 506 days (Fig. 2).

3.5.3 Relationship between rainfall and daily sapflow

Pearson's correlation indicated that rainfall was highly correlated (P<0.05) with daily sapflow in both *C. africana* and *A. coriaria* trees, predominantly in the dry season (Table 2). However, the positive correlation coefficients observed in *A. coriaria* in the dry season is an indication that there could be factors other than rainfall, that are influencing the daily sapflow in the tree during the dry season. The positive correlation implies that the daily sapflow increased with rainfall. The higher the rainfall the less the evaporative demand, and the more water in the soil both of which enhance transpiration. The negative correlation in *C. africana*, where water use seems to be decoupled from rainfall, may be attributed to a strong lag between the start of the wet season and recovery in tree water use following the dry season.

Table 2 Pearson's correlation coefficients between rainfall and seasonal daily sapflow in *C. africana* and *A. coriaria*

Tree species	**Pearson's correlation coefficients**		
	Dry season	**Wet season**	**All**
Albizia coriaria	0.326*	-0.107^{ns}	0.136*
Cordia africana	-0.199*	-0.149^{ns}	-0.228*

*Correlations significant, at the level of P<0.05. are indicate by *; those that are non-significant are labeled as ns*

3.5.4 Interaction between tree species and season on daily sapflow

In table 3 below, the two-way ANOVA performed shows that there was a significant interaction between tree species and season (tree species* season) on the mean daily sapflow ($F(1,548)=56.48$, $P<0.001$). While there were statistically significant differences in mean daily sapflow between *C.africana* and *A. coriaria* ($F(1,548)=275.3$, $p<0.001$), there was no statistically significant difference in mean daily sapflow between the dry and wet seasons ($F(1,548)=1.44$, $p=0.231$).

Table 3 A two-way ANOVA to assess the interaction between tree species and season on daily sapflow

Tests of Between-Subjects Effects

Dependent Variable: Daily sapflow

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	36480.043[a]	3	12160.014	103.258	.000
Intercept	255990.935	1	255990.935	2173.781	.000
Tree species	32422.605	1	32422.605	275.321	.000
Season	169.577	1	169.577	1.440	.231
Tree species* Season	6651.270	1	6651.270	56.480	.000
Error	64534.101	548	117.763		
Total	358618.298	552			
Corrected Total	101014.144	551			

a. R Squared = .361 (Adjusted R Squared = .358)

3.5.5 Radial changing of sap velocities between outer to inner thermocouples in *A. coriaria*

An analysis of the sap velocity of *A. coriaria* over an extended period (November 2015 to April 2017) showed radial changing of sap velocities between the inner and outer thermocouples (Fig 2).

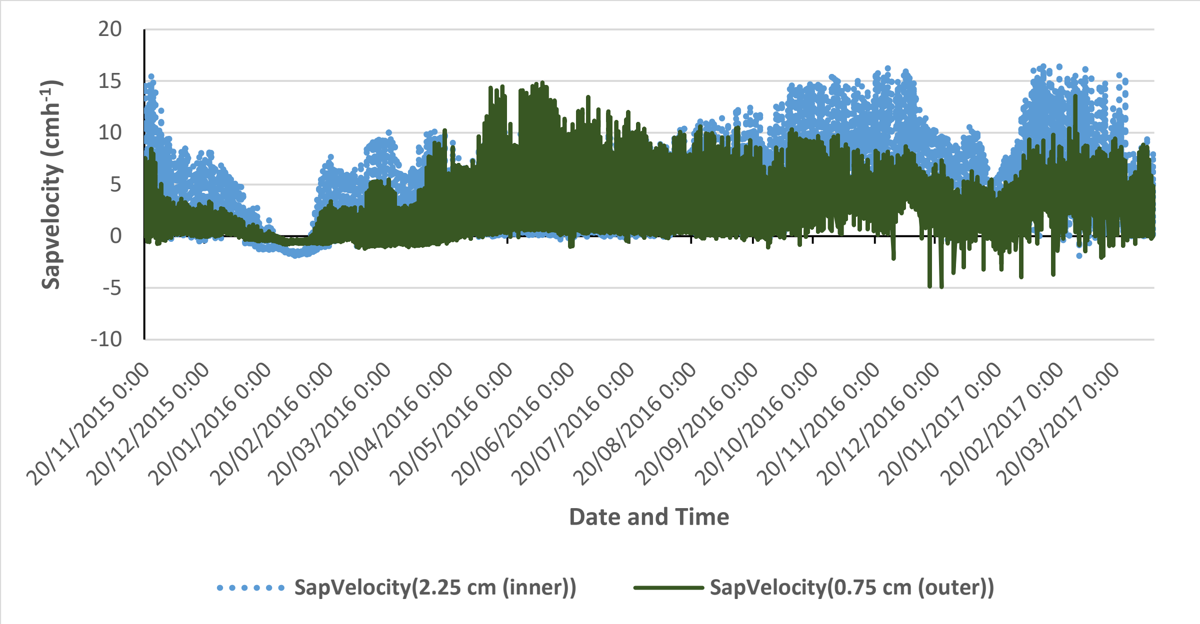

Fig. 2 Radial changing of sap velocity in *A. coriaria* registered by the inner and outer thermocouples (data presented are average values from the 3 trees)

The inner thermocouple generally registered higher sap velocities than the outer thermocouple at various stages of water stress especially between November and March in 2016 and 2017 (Fig 2). However, between the months of April and early June 2016, the outer thermocouple recorded higher sap velocities than the inner thermocouple. This scenario extended through the rainfall season until October 2016.

3.5.6 Existing agroforestry systems in Mt. Elgon region

Most farmers in Mt. Elgon region are small land holders with 1-2 acres of land, which forces them to till the land intensively throughout the year to grow multiple crops. The agroforestry systems are mainly characterized by coffee (*Coffee arabica*) and beans (*Phaseolus vulgaris*) with scattered trees, predominantly *Cordia africana* and *Albizia coriaria* (Fig. 3). Coffee normally flowers twice every year at the onset of the rain seasons, coinciding with the planting of beans.

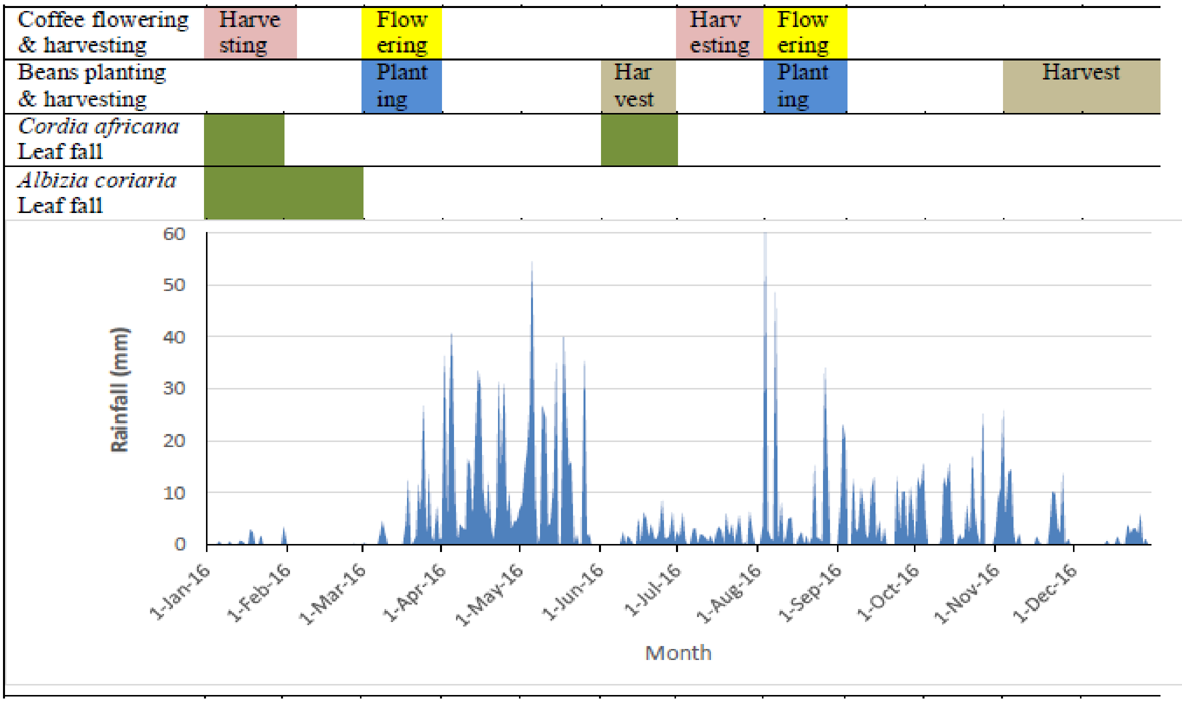

Fig. 3 Key agroforestry systems and phenological events in Mt. Elgon region of Uganda, indicated in terms of 2016 rainfall for the region.

Both tree species are deciduous, with *C. africana* shedding its leaves at the onset of the dry seasons (Fig. 3). However, *A. coriaria* is observed to have one major annual leaf fall which occurs in January, sometimes extending into February.

3.6 Discussion

3.6.1 Differences in tree water use

Water-use studies of agroforestry tree species are essential for understanding their interactions with other agroforestry components. A number of individual tree water-use studies have focused on the species *Eucalyptus grandis* (Dye 1996), *Acacia tortilis (Do et al. 2008), Eucalyptus camaldulensis (O'Grady et al. 2009)*, *Grevillea robusta* (Lott et al. 1996), *Vitellaria paradoxa* (Bazié et al. 2017) and *Senna spectabilis* (Namirembe et al. 2008) (Table 4). However, *Cordia africana* and *Albizia coriaria* are important agroforestry tree species whose water use is not well documented. Prior to standardization of the daily sapflow this study revealed that *A. coriaria* generally uses more water than *C. africana* (Fig 1), an indication that

A. coriaria exhibits a higher transpiration rate than *C. africana*. we propose a number of reasons for this contrast in tree species water use including differences in tree sizes, rooting depth, and sap wood area and density among other factors.

In terms of tree size, a study in the Republic of Panama on trees of difference trunk diameters reported a similar trend where tree size played a dominant role in determining the water use and water storage characteristics of four individual tree species (Meinzer et al. 2004). In that study, mean daily water use increased with tree size from 42 kgday^{-1} in a 34 cm diameter *Cordia alliodora* tree to 785 kgday^{-1} in a 98 cm diameter *Anacardium excelsum* (Table 4). Daily reliance on stored water was also reported to increase with tree size in two temperate coniferous and one temperate angiosperm species (Phillips et al. 2003), thus partially explaining the difference in water use between larger diameter *A. coriaria* and smaller diameter *C. africana* in the current study.

Table 4 Tree water use and tree parameters including method used for different tree species

Tree species	Method[a]	DBH (cm)	Water use	Source
Acacia aneura	CHPM	12	14 kgday^{-1}	(O'Grady et al. 2009)
Acacia tortilis	TTD	17	48 Lday^{-1}	(Do et al. 2008)
Eucalyptus camaldulensis	CHPM	18	87 kgday^{-1}	(O'Grady et al. 2009)
Eucalyptus grandis	CHPM	30	141 kgday^{-1}	(Dye 1996)
Eucalyptus pilularis	CHPM	11-14	18 Lday^{-1}	(Adrienne et al. 2013)
Grevillea robusta	CHPM	n/a	12 kgday^{-1}	(Lott et al. 1996)
Cordia alliodora	CHPM	34	42 kgday^{-1}	(Meinzer et al. 2004)
Anacardium excelsum	CHPM	98	785 kgday^{-1}	(Meinzer et al. 2004)
Vitellaria paradoxa	HRM	55.5	151 Lday^{-1}	(Bazié et al. 2017)
Senna spectabilis	CHPM	7.9	4.8 kgday^{-1}	(Namirembe et al. 2008)

[a]Methods used is indicated by compensation heat pulse method (CHPM), heat ratio method (HRM), transient thermal dissipation (TTD)

However, when daily sapflow was assessed in terms of daily sapflow per cross-sectional area of the tree at 1.2 meters height, the results showed that *C. africana* used 12% more water than

A. coriaria (Table 1). This may be due to differences in the wood biophysical properties. Sapwood properties, including wood density, have been reported to influence the water economy of trees, showing a negative correlation between species-specific water use and sapwood density (Oliva Carrasco et al. 2015). *C. africana* has been reported to have wood density of 0.40 gcm^{-3} (Buyinza et al., 2014), which is lower than *A. coriaria* at 0.59 gcm^{-3} (Ojelel et al. 2015). Trees with high wood densities have smaller xylem vessel diameters than those with low wood densities. A related study of species-specific water use in *Ceiba speciose*, deciduous tree native to the tropical and subtropical forests of South America, showed that sapflow increased exponentially with increasing sapwood density (Oliva Carrasco et al. 2015). The large quantities of discharge water into the transpirational stream were consistent with the very low wood density of *C. speciose*. This could partly explain the lower tree water use in *A. coriaria* on a standardized daily basis in this study. However, despite using more water on a daily basis, *C. africana* is more efficient in its water use (since water use expressed on an area basis relates to water use efficiency). This is because higher water use efficiency generally means less water used per carbon gained, a quality that would clearly benefit smallholder farmers in the Mt. Elgon region.

The differences in daily water of *C. africana* and *A. coriaria* during different times of the year (dry and wet season) were farther investigated by performing a two-way ANOVA with 'tree species' and 'season' as the main effects. The results show that interaction between tree species and season (tree species* season) had a significant effect on the mean daily water use (Table 3). However, there was a nonsignificant effect of season on daily water use, an indication that the dry and wet seasons may not be sufficient in explaining the differences in daily water use of *C. africana* and *A. coriaria*. However, in *C. africana,* likelihood of a lag in the recovery of tree water use following the dry and wet season traits linked to deep rooting depth and high stem capacitance may facilitate the species to maintain high rates of water use, early in the dry season.

3.6.2 Reverse flows in *A. coriaria*

Reverse flows have been reported in trees such as *Grevillea robusta* (Burgess et al. 1998; Smith et al. 1999), *Eucalyptus camaldulensis* (Burgess et al. 1998), *Fraxinus velutina* and *Juglans major* (Hultine et al. 2003) predominantly occurring when surface soils are dry. The HRM method used in this study has the capacity to detect reverse flows (Burgess et al. 2001). While this study did not measure water potential, other studies have indicated that reverse flows in trees result from low soil water potential (Smith et al. 1999). When the atmosphere is wetter than the soil, the soil will have a higher water potential than the atmosphere, so water flows to the soil. Water in a tree will always flow towards areas where the water potential is least. This can be through or across the stem, a process also referred to as hydraulic redistribution (Matimati et al. 2014; Hafner et al. 2017). A study conducted on the neotropical savanna trees of Brazil reported occurrence of reverse sapflow in deciduous and brevi-deciduous species during the dry season that was consistent with hydraulic lift (Scholz et al. 2008). In this study, reverse flows in *A. coriaria* coincided with the consistent annual tree leaf fall events between late January and February. The occurrence of reverse flows and leaf shedding during the dry season is a water saving strategy for *A. coriaria*.

A. coriaria increased its water use about one month prior to the start of the wet season, between mid-February and early March (Fig 1). This may be because *A. coriaria* trees start flushing with new leaves at that time of the year in preparation of a presumably very predictable start to the wet season.

3.6.3 Influence of tree leaf phenology on water use

The two tree species in this study also show varying patterns in water use across seasons and leaf phenology stages characterized by small reverse flows in *A. coriaria* (Fig. 1). The reverse flows in *A. coriaria* could have been triggered by leaf shedding, while the reduction in sapflow in *C. africana* occurred during rainfall events. However, there might be a lag in the recovery of *C. africana* tree water use following the dry season, hence following the wet season, traits linked to deep rooting depth and high stem capacitance may facilitate *C. africana* to maintain high rates of water use into the early part of the dry season. This is an indication that the two species may have different water-use strategies.

The leafing phenological pattern of *A. coriaria* has a greater influence on tree water use than in *C. africana*, suggesting that the consistent and predictable leaf shedding pattern in *A. coriaria* may be beneficial for planning farming activities among smallholders. The magnitude and duration of whole tree water use may be caused by reduction in photosynthetic leaf area (Adrienne et al. 2013), normally triggered by environmental variability (rain and dry seasons). The dry season is an important trigger for leaf abscission and leaf and branch emergence in seasonal tropical forest and savanna (Dalmolin et al. 2015). Deciduous species are drought avoiders: they drop their entire canopy and hence do not transpire at significant rates in the dry season – their foliage therefore avoids drought (Eamus 1999). Consequently this also reduces competition for soil water and nutrient resources. The leaf shedding pattern of *Albizia coriaria* provides an opportunity for maximizing the temporal complementarities of agroforestry systems.

Trees can reduce competition through their species-dependent differences in leafing phenology and rooting patterns and activity (Meinzer *et al*., 2001). While this study did not focus on tree rooting patterns and activity, leafing phenology has been associated with seasonal time courses for the partitioning soil moisture, where species showing the smallest seasonal variation in leaf area are able to tap deep sources of soil water during dry seasons (Meinzer *et al*. 1999). This study suggests that leafing phenology has an important role in determining the patterns and rates of soil water extraction, yet tree phenology is a neglected aspect of agroforestry research. Furthermore, the importance of studying the response of trees with differing leafing phenology to drought as such information would help provide an improved understanding of water management in agroforestry systems (Eamus 1999).

3.6.4 Variability in radial sap velocities in *A. coriaria*

The changing radial pattern in sap velocities between the outer to inner thermocouples in *A. coriaria* point to a number of factors including the microclimate, sap wood area and meteorological conditions. While it is widely reported that sap flow is essentially driven by the microclimate, especially the evaporative demand and radiation (Ford et al. 2004; Fiora and Cescatti 2006), the possible influence of climatic conditions on radial variability is yet to be thoroughly investigated. A related study showed that sap flow in *Avicennia marina* varied significantly throughout the sapwood and that radial patterns in sap flux density were dependent on meteorological conditions (Van de Wal et al. 2015). A field experiment that assessed sapflow in mature mangrove of *Avicennia germinans* trees of different sizes also observed that the shape of the radial patterns differed between the wet and dry season of their experiment (Muller et al. 2009). Essentially, the surface roots are connected to the outer region of the sapwood area while the deeper tap roots are physiologically connected to the inner region of the sapwood area. It is anticipated that when it rained and soil moisture increased, the outer thermocouple was able to access the excess moisture from the soil due to its close proximity to the moisture in the surrounding soil surfaces. The ability of the tap roots to draw water from deeper soil regions during water stress periods could suggest another water saving strategy by *A. coriaria*.

However, observing radial variations in sap velocities in the outer and inner thermocouples may also introduce errors in estimating total tree water use, especially in trees with large sapwood area. A number of studies have acknowledged that woody species with deep functional sapwood present a challenge in scaling point measurements of sap velocity to whole-stem sap flow and the need to account for radial variability of sap velocity in the stem (Wullschleger and King 2000; Nadezhdina et al. 2002; Ford et al. 2004; Fiora and Cescatti 2006). The sapwood can remain active up to a depth of 8 cm (Muller et al. 2009) which renders such a stem more susceptible to radial variations. Radial variation can account for discrepancies of up to 25 % (Van de Wal et al. 2015). Therefore, it is recommend that radial variability is determined prior to sapflow measurement by first using sensors with multiple measuring points along a stem radius followed by single-point measurement with sensors at a predetermined depth.

3.6.5 Tree water use influence from associated crops

Tree water use of the study tree species could also be influenced by the associated crops including coffee and beans that are commonly integrated in the agroforestry farming systems in the study sites (Fig. 4). Trees and agricultural crops growing together on the same piece of land may compete for available soil water, especially where soils are shallow. Studies have reported greater depletion of water at depth in the tree-crop treatments than sole tree plots (Jackson et al. 2000; Lott et al. 2003) in the upper soil layers. However, some trees have dimorphic rooting morphology which allows them to shift from predominantly shallow to deeper sources of water when water availability in the upper soil layers is low (Priyadarshini et al. 2016), an adaptive strategy employed to overcome seasonal water limitation. This was reported for *Vitellaria paradoxa* where soil moisture in the upper soil layers was significantly lower during the dry season and as a result *V. paradoxa* shifted to deeper water sources, obtaining approximately 30% of its water requirement from groundwater (Tobella et al. 2017). Knowledge about the sources and patterns of tree water use provides crucial information to better understand how trees influence the local water balance in agroforestry systems. However, in this current study, the differences between the soil and competing relationships between the two farms could have limited species comparisons and need to be considered in the subsequent studies.

3.7 Conclusion

C. africana generally uses more water than *A. coriaria* on a standardized daily basis. While both tree species exhibited low daily sapflow during at certain stages of the experiment, they occurred at different periods. The reverse flows in *A. coriaria* could have been triggered by leaf shedding which occurs in Jan-Feb. However, the period of low flows in *C. africana* coincided with the rainfall events (though this may be attributed a lag between the start of the wet season and recovery in tree water use following the dry season), an indication that the two species may have different water-use strategies. There was a significant main effect of the interaction between tree species and season on daily water use. The leaf shedding pattern of *A. coriaria* has a greater influence on tree water use than in *C. africana*, suggesting that the consistent and predictable leaf fall in *A. coriaria* may be beneficial for planning farming activities among smallholders. The study recommends further studies to monitor sapflow in the associated crop (coffee) to better understand the interactions among the different agroforestry components. Such studies should also seek to understand the underlying causes of radial changing of sap velocities between outer to inner thermocouples, a characteristic observed in *A. coriaria* under the current study.

Agroforestry has attracted considerable attention in recent years because of its potential to reduce poverty, improve food security, reduce land degradation and mitigate climate change. However, progress in promoting agroforestry is held back because decision-makers lack reliable tools to accurately predict yields from tree-crop mixtures. Further studies to establish convergence of tree traits related to plant water use such as sap wood density, photosynthetic active radiation (PAR), leaf area, xylem water potential, sapflow, sapwood area, tree diameter (stem increment) and height are recommended. Identifying convergence in water use of these important agroforestry tree species can potentially provide powerful tools for scaling physiological processes in natural ecosystems (O'Grady et al. 2009). Such information would be useful in modeling trade-offs between carbon accumulation and water loss in agroforestry systems. Understanding these factors will also facilitate development of appropriate tree management regimes for optimal utilization of soil water, thus enhancing productivity of agroforestry systems among small holder farmers.

3.8 References

Adrienne BN, Smith RGB, Ryde J, Dane ST, David IF, Philip JA, Jürgen B. 2013. Changes in Whole-Tree Water Use Following Live-Crown Pruning in Young Plantation-Grown Eucalyptus pilularis and Eucalyptus cloeziana. Forests. 4(1):106-121.

Bazié HR, Sanou J, Bayala J, Bargués-Tobella A, Zombré G, Ilstedt U. 2017. Temporal variations in transpiration of Vitellaria paradoxa in West African agroforestry parklands [journal article]. Agroforestry Systems.

Broadhead JS, Black CR, Ong CK. 2003. Tree leafing phenology and crop productivity in semi-arid agroforestry systems in Kenya [journal article]. Agroforestry Systems. 58(2):137-148.

Bukomeko H, Jassogne L, Tumwebaze SB, Eilu G, Vaast P. 2017. Integrating local knowledge with tree diversity analyses to optimize on-farm tree species composition for ecosystem service delivery in coffee agroforestry systems of Uganda [journal article]. Agroforestry Systems.

Burgess SSO, Adams MA, Turner NC, Beverly CR, Ong CK, Khan AAH, Bleby TM. 2001. An improved heat pulse method to measure low and reverse rates of sap flow in woody plants †. Tree Physiology. 21(9):589-598.

Buyinza, J., Tumwebaze, S.B., Namaalwa, J., Byakagaba, P. 2014. Above-ground biomass and carbon stocks of different land cover types in Mt. Elgon, Eastern Uganda. *International Journal of Research on Land-use Sustainability* 1: 51-61.

Cai X, Molden D, Mainuddin M, Sharma B, Ahmad M-U-D, Karimi P. 2011. Producing more food with less water in a changing world: assessment of water productivity in 10 major river basins. Water International. 36(1):42-62.

Dalmolin Â, Almeida Lobo F, Vourlitis G, Silva P, Dalmagro H, Antunes M, Ortíz C. 2015. Is the dry season an important driver of phenology and growth for two Brazilian savanna tree species with contrasting leaf habits? An International Journal. 216(3):407-417.

Do FC, Rocheteau A, Diagne AL, Goudiaby V, Granier A, Lhomme J-P. 2008. Stable annual pattern of water use by Acacia tortilis in Sahelian Africa [Article]. Tree Physiology. 28(1):95-104.

Dye PJ. 1996. Response of Eucalyptus grandis trees to soil water deficits. Tree physiology. 16(1_2):233.

Eamus D. 1999. Ecophysiological traits of deciduous and evergreen woody species in the seasonally dry tropics. Trends in Ecology & Evolution. 14(1):11-16.

Ellison D, Morris CE, Locatelli B, Sheil D, Cohen J, Murdiyarso D, Gutierrez V, Noordwijk Mv, Creed IF, Pokorny J et al. 2017. Trees, forests and water: Cool insights for a hot world. Global Environmental Change. 43:51-61.

FAO. 2011. The state of the world's land and water resources for food and agriculture : managing systems at risk. 1st ed. ed. Milton Park, Abingdon. New York, NY: Earthscan.

Fiora A, Cescatti A. 2006. Diurnal and seasonal variability in radial distribution of sap flux density: implications for estimating stand transpiration. Tree Physiology. 26(9):1217-1225.

Gram G, Vaast P, van der Wolf J, Jassogne L. 2017. Local tree knowledge can fast-track agroforestry recommendations for coffee smallholders along a climate gradient in Mount Elgon, Uganda. Agroforestry Systems.

Hafner BD, Tomasella M, Häberle K-H, Goebel M, Matyssek R, Grams TEE, Mencuccini M. 2017. Hydraulic redistribution under moderate drought among English oak, European beech and Norway spruce determined by deuterium isotope labeling in a split-root experiment. Tree Physiology. 37(7):950-960.

Hultine KR, Williams DG, Burgess SSO, Keefer TO. 2003. Contrasting patterns of hydraulic redistribution in three desert phreatophytes [journal article]. Oecologia. 135(2):167-175.

Jackson NA, Wallace JS, Ong CK. 2000. Tree pruning as a means of controlling water use in an agroforestry system in Kenya. Forest Ecology and Management. 126(2):133-148.

Janani L., Hillary L., Phillips K. 2014. Mordanting methods for dyeing cotton fabrics with dye from Albizia Coriaria Plant Species. *International Journal of Scientific and Research Publications, 4*(10), 1-6

Katende AB, Birnie A, Tengna SB. 1995. Useful Trees and Shrubs for Uganda: Identification, Propagation and Management for Agricultural and Pastoral Communities. Technical Handbook No. 10. Regional Soil Conservation Unit, Nairobi, Kenya.

Linares JC, Covelo F, Carreira JA, Merino JA. 2012. Phenological and water-use patterns underlying maximum growing season length at the highest elevations: implications under climate change. Tree Physiol. 32(2):161-170.

Lott JE, Khan AAH, Black CR, Ong CK. 2003. Water use in a Grevillea robusta–maize overstorey agroforestry system in semi-arid Kenya. Forest Ecology and Management. 180(1):45-59.

Matimati I, Verboom GA, Cramer MD. 2014. Do hydraulic redistribution and nocturnal transpiration facilitate nutrient acquisition in Aspalathus linearis?(PHYSIOLOGICAL ECOLOGY--ORIGINAL RESEARCH). Oecologia. 175(4):1129.

Mehari A, Habte B. 2006. Influence of Initial Spacing on Growth and Branching Characteristics of Cordia africana Trees Established on Eritrean Highland. New Forests. 31(2):185-193.

Meinzer FC, James SA, Goldstein G. 2004. Dynamics of transpiration, sap flow and use of stored water in tropical forest canopy trees. Tree Physiology. 24(8):901-909.

Muller E, Lambs L, Fromard F. 2009. Variations in water use by a mature mangrove of Avicennia germinans, French Guiana [journal article]. Annals of Forest Science. 66(8):803-803.

Muthuri CW, Ong CK, Black CR, Ngumi VW, Mati BM. 2005. Tree and crop productivity in Grevillea, Alnus and Paulownia-based agroforestry systems in semi-arid Kenya. Tree and crop productivity in Grevillea, Alnus and Paulownia-based agroforestry systems in semi-arid Kenya. 212:23-39.

Muthuri CW, Ong CK, Craigon J, Mati BM, Ngumi VW, Black CR. 2009. Gas exchange and water use efficiency of trees and maize in agroforestry systems in semi-arid Kenya. Agriculture, Ecosystems & Environment. 129(4):497-507.

Nadezhdina N, Čermák J, Ceulemans R. 2002. Radial patterns of sap flow in woody stems of dominant and understory species: scaling errors associated with positioning of sensors. Tree Physiology. 22(13):907-918.

Namirembe S, Brook RM, Ong CK. 2008. Manipulating phenology and water relations in Senna spectabilis in a water limited environment in Kenya [journal article]. Agroforestry Systems. 75(3):197.

Namukobe J, Kasenene JM, Kiremire BT, Byamukama R, Kamatenesi-Mugisha M, Krief S, Dumontet V, Kabasa JD. 2011. Traditional plants used for medicinal purposes by local communities around the Northern sector of Kibale National Park, Uganda. Journal of Ethnopharmacology. 136(1):236-245.

O'Grady AP, Cook PG, Eamus D, Duguid A, Wischusen JDH, Fass T, Worldege D. 2009. Convergence of tree water use within an arid-zone woodland [journal article]. Oecologia. 160(4):643-655.

Ojelel S, Otiti T, Mugisha S. 2015. Fuel value indices of selected woodfuel species used in Masindi and Nebbi districts of Uganda [journal article]. Energy, Sustainability and Society. 5(1):14.

Oliva Carrasco L, Bucci SJ, Di Francescantonio D, Lezcano OA, Campanello PI, Scholz FG, Rodríguez S, Madanes N, Cristiano PM, Hao G-Y et al. 2015. Water storage dynamics in the main stem of subtropical tree species differing in wood density, growth rate and life history traits. Tree Physiology. 35(4):354-365.

Orwa C, Mutua A, Kindt R, Jamnadass R, Anthony S. 2009. Agroforestree database: a tree reference and selection guide version 4.0

Phillips NG, Ryan MG, Bond BJ, McDowell NG, Hinckley TM, Čermák J. 2003. Reliance on stored water increases with tree size in three species in the Pacific Northwest. Tree Physiology. 23(4):237-245.

Pinho RC, Miller RP, Alfaia SS. 2012. Agroforestry and the Improvement of Soil Fertility: A View from Amazonia. Applied and Environmental Soil Science. 2012.

Priyadarshini KVR, Prins HHT, Bie S, Heitkönig IMA, Woodborne S, Gort G, Kirkman K, Ludwig F, Dawson TE, Kroon H. 2016. Seasonality of hydraulic redistribution by trees to grasses and changes in their water-source use that change tree–grass interactions. Ecohydrology. 9(2):218-228.

Sales E, Rodas O, Valenzuela O, Hillbrand A, Sabogal C. 2016. On the way to restore Guatemala's degraded lands: Creating governance conditions. World Development Perspectives. 4:16-18.

Smith DM, Jackson NA, Roberts JM, Ong CK. 1999. Reverse flow of sap in tree roots and downward siphoning of water by Grevillea robusta. Functional Ecology. 13(2):256-264.

Steppe K, Vandegehuchte MW, Tognetti R, Mencuccini M, Oren R. 2015. Sap flow as a key trait in the understanding of plant hydraulic functioning. Tree Physiology. 35(4):341-345.

Strobl S, Cueva E, Silva B, Knuesting J, Schorsch M, Scheibe R, Bendix J, Beck E. 2017. Water relations and photosynthetic water use efficiency as indicators of slow climate change effects on trees in a tropical mountain forest in South Ecuador. Ecological Indicators. 83:550-558.

Tabuti JRS, Mugula BB. 2007. The ethnobotany and ecological status of Albizia coriaria Welw. ex Oliv. in Budondo Sub-county, eastern Uganda. African Journal of Ecology. 45:126-129.

Tobella AB, Hasselquist NJ, Bazié HR, Nyberg G, Laudon H, Bayala J, Ilstedt U. 2017. Strategies trees use to overcome seasonal water limitation in an agroforestry system in semiarid West Africa. Ecohydrology. 10(3):e1808.

Van de Wal B, Guyot A, Lovelock C, Lockington D, Steppe K. 2015. Influence of temporospatial variation in sap flux density on estimates of whole-tree water use in Avicennia marina. Structure and Function. 29(1):215-222.

Webber H, Gaiser T, Ewert F. 2014. What role can crop models play in supporting climate change adaptation decisions to enhance food security in Sub-Saharan Africa? Agricultural Systems.

Wullschleger SD, King AW. 2000. Radial variation in sap velocity as a function of stem diameter and sapwood thickness in yellow-poplar trees. Tree Physiology. 20(8):511-518.

Yan C, Wang B, Zhang Y, Zhang X, Takeuchi S, Qiu GY. 2018. Responses of sap flow of deciduous and conifer trees to soil drying in a subalpine forest. Forests. 9(1):<xocs:firstpage xmlns:xocs=""/>.

Appendix I: Descriptive Statistics

Dependent Variable: Daily water use							
				Bootstrap[a]			
						BCa 95% Confidence Interval	
Tree species	Season		Statistic	Bias	Std. Error	Lower	Upper
Albizia coriaria	Dry season	Mean	25.3234	-.0104	1.3960	22.6398	27.9688
		Std. Deviation	16.60446	-.04626	.72858	15.07530	17.90494
		N	153	0	10	133	173
	Wet season	Mean	33.4224	-.0467	.8400	31.8153	34.9363
		Std. Deviation	8.92192	-.04636	.44956	8.05889	9.67157
		N	123	0	10	105	141
	Total	Mean	28.9327	-.0282	.8945	27.1517	30.5541
		Std. Deviation	14.28175	-.02743	.66613	12.84056	15.50573
		N	276	0	11	255	296
Cordia africana	Dry season	Mean	16.8879	-.0018	.4480	16.0654	17.7711
		Std. Deviation	5.65363	-.03074	.39018	4.90225	6.33522
		N	153	0	11	133	175
	Wet season	Mean	11.0192	-.0270	.7457	9.5409	12.3913
		Std. Deviation	8.12643	-.07804	.62780	6.92785	9.08661
		N	123	0	10	106	140
	Total	Mean	14.2725	-.0099	.4511	13.3606	15.1786
		Std. Deviation	7.45010	-.02659	.31551	6.83288	8.00058
		N	276	0	11	254	299
Total	Dry season	Mean	21.1057	-.0117	.7716	19.6895	22.5512
		Std. Deviation	13.08354	-.01976	.46088	12.16378	13.94305
		N	306	0	11	284	328
	Wet season	Mean	22.2208	-.0460	.8828	20.6678	23.7463
		Std. Deviation	14.08936	-.04863	.45834	13.22694	14.87480
		N	246	0	11	225	267
	Total	Mean	21.6026	-.0270	.5845	20.4687	22.6853
		Std. Deviation	13.53989	-.01802	.33137	12.95477	14.11390
		N	552	0	0	.	.

a. Unless otherwise noted, bootstrap results are based on 1000 bootstrap samples

Chapter 4: Impact of tree pruning on water relations in tree-coffee systems on smallholder farms in Eastern Uganda

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4.1 Statement of Authorship

Title of Paper	**Impact of tree pruning on water relations in tree-coffee systems on smallholder farms in Uganda**
Publication Status	☐ Published ☐ Accepted for Publication ☐ Submitted for Publication ☑ Unpublished and Unsubmitted work written in manuscript style
Publication Details	

Principal Author

Name of Principal Author (Candidate)	Joel Buyinza		
Contribution to the Paper	Identification of research gap, field experimentation, data collection, analysis and interpretation of findings, acted as first and corresponding author		
Overall percentage (%)	80%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	22/04/2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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4.2 Abstract

Tree pruning is an important tree management option for reducing shading effects and altering whole-tree water use in intensive smallholder farming systems. In this study, sap flow meters (SFM1s) were used to monitor whole tree water use in *Cordia africana* (Cordia), *Albizia coriaria* (Albizia) and *Coffea arabica* (coffee) trees in two farms in Eastern Uganda. Overstory trees were subjected to a 50% pruning regime at a 6-month interval over a period of 20 months (July 2018 - February 2020). Pruning altered the synchrony in the vegetative phenology of Albizia trees, as leaf cover changes occurred earlier in pruned trees than in unpruned trees following pruning. Pruned Cordia and Albizia trees respectively used 22.8% and 50.1% less water than unpruned trees whose average daily water use was 76.5L day^{-1} and 133.7L day^{-1} respectively. Episodes of reverse flows were observed in Albizia trees (pruned and unpruned) and the pruned Cordia during certain periods of the year. There was a statistically significant main effect of tree species, pruning, season and their interaction on daily tree water use ($P<0.05$). Coffee used 0.1 to 4.3 litres of water per day over the 20-month study period. While unshaded coffee used more water than shaded coffee, coffee growing under pruned trees used more water than coffee growing under unpruned trees. This could have resulted from more transpiration pull in coffee resulting from increased radiation with reduced shading. Canopy pruning reduced the water demand of the tree component and resulted in recharge in the crop-rooting zone, although this seemed to appear later following consistent pruning. The study findings demonstrate that agroforestry tree canopy pruning can regulate water use in smallholder agroforestry systems, the benefits of other tree products notwithstanding. Studies on quantifying these benefits are recommended.

Key words: *Sap flow, Canopy pruning, Cordia africana, Albizia coriaria, coffee*

4.3 Introduction

Soil water is often the main resource limiting productivity in smallholder agroforestry systems because most farmers select tree-crop combinations without consideration of avoidance of competition for moisture (Nyaga et al., 2019; Namirembe et al., 2008). Farmer selection of on-farm crop and tree combinations primarily depends on specific products and services required for their livelihoods, rather than their differentiated temporal and spatial niches of exploitation. For instance, although differences in leafing phenology influence the extent of competition or complementarity between trees and crops in agroforestry systems, and hence crop yield, farmers may deliberately plant fast-growing, competitive tree species if they provide attractive economic returns or carbon credit subsidies (Muthuri et al., 2009). Therefore, while agroforestry offers promising options for sustainable use of land and water, competition for resources in such intensive farming systems is inevitable particularly when tree and crop roots, and canopies occupy the same space and have overlapping growth cycles. With global food demands projected to increase because of scarcity and overuse of water resources (Descheemaeker et al., 2013; FAO, 2011), it is important that the capacity of farmers is enhanced to manage the quantity and timing of tree water uptake and shade in agroforestry systems where trees and crops compete for resources in the same space. Given the huge amounts of water used in agroforestry systems (Siriri et al., 2013), even minute improvements in agricultural water productivity could have large implications for local water budgets.

Although tree canopy pruning of live branches is usually done to enhance production of high-value knot-free timber in plantation trees (Alcorn et al., 2013), it is also a practical measure to control competition for resources in an intensive farming system (Luedeling et al., 2016; Jackson et al., 2000) such as coffee agroforestry reported in this study. Tree canopy pruning could also alter whole-tree water use, but little is known about the impact and duration of changes in transpiration. Trees can still maintain growth rates following pruning through changes in leaf physiology, canopy architecture and by modifying biomass allocation to facilitate leaf area development (Forrester et al., 2010). While there have been commendable efforts to promote shaded coffee in the Mt. Elgon region of Uganda (Bukomeko et al., 2017; Gram et al., 2018; UCDA, 2017, 2018), minimal effort has been put into the management of shade trees. Farmers are reluctant to deliberately prune tree canopies of shade trees (Buyinza. et al., 2020a, 2020b), which is usually done when there is need for fuelwood and building materials. However, canopy pruning can increase light availability at the crop level, and directly affect tree demand for water and nutrients (Bayala et al., 2004; Bazié. et al., 2012). A recent study in Mt. Elgon region on coffee water use also highlighted the need to explore how farm management activities such as pruning can be used to match the systems water requirements with expected soil water availability (Sarmiento-Soler et al., 2019).

Understanding the interactions in tree and coffee water use in managed *Cordia africana* Lam (Cordia) and *Albizia coriaria* Welw. ex Oliv (Albizia) agroforestry systems is crucial to developing long-term tree monitoring and management programmes in such intensive farming systems. These target semi-deciduous tree species are commonly integrated in coffee plantations occurring in more than 25% of the agroforestry systems in the Mt. Elgon region of Uganda (Rahn et al., 2018). While unpruned Cordia and Albizia trees have contrasting tree water use patterns (Buyinza et al., 2019), the water use interactions in managed coffee agroforestry systems have not been explored in similar systems. The impact of the semi-deciduous nature of Cordia and Albizia trees has also been overlooked, yet tree leafing phenology can directly impact agroforestry tree growth and water use (Taugourdeau et al., 2014; Muthuri et al., 2004) and how species respond to increasing drought stress (Aitken et al., 2008). Understanding the relationship between tree leafing phenology and tree water use can also inform appropriate management options for agroforestry trees in smallholder farms. The aim of this study was therefore to assess the impact of tree canopy pruning on water use of smallholder coffee agroforestry systems. It was hypothesized that tree canopy pruning would minimize competition for water in coffee agroforestry systems by reducing the water requirement of the tree component in such farming systems.

4.4 Materials and methods

4.4.1 Study area

The study was conducted in Manafwa district located in Eastern Uganda, bordering the Republic of Kenya in the East, Bududa district to the North, Mbale district to the West and Tororo to the Southwest. In terms of climate, the average annual rainfall is 1500 mm, with two peak rainy seasons that occur in the months of April-May and September-November. A pronounced dry period occurs from December to February, with a mean annual temperature of 23^{o}C. The topography of the slope is characterized by two escarpments that naturally separate three altitude classes of <1400 m.a.s.l, 1400–1700 m.a.s.l, and >1700 m.a.s.l within the inhabited area of the mountain (Rahn et al., 2018). Local farming communities live between 1000 m.a.s.l. at the foothill and 2200 m.a.s.l. close to the protected Mt. Elgon National Park. Coffee (*Coffea arabica* L.) is the main cash crop and is traditionally grown in combination with bananas, common beans, maize and multi-purpose shade-trees.

The field experiment was conducted in two separate farms, approximately 2 km apart; each having either Cordia or Albizia mature trees integrated in Coffee agroforestry systems. The Albizia experimental site was located at N00^{0}56.007' and E034^{0}16.605' at 1196 metres above sea level (m.a.s.l) while the Cordia site was at N00^{0}55.582' and E034^{0}15.244' at 1233m.a.s.l in Butta Sub County, Manafwa district in Eastern Uganda. The study sites fall within the lower altitude class (<1400 m.a.s.l) on the foothills of Mt. Elgon, following a recent altitudinal classification of the region by Rhan et al., (2018).

4.4.2 Soil characterization of study sites at project baseline and end line

Soil sampling was done in the study sites using a soil auger at the beginning of the experiment in July 2018 (to obtain baseline scenario) and at the end of the experiment in February 2020. This was done to establish the status of the study sites and any differences in soil physical and chemical properties that may have resulted from the tree management interventions of the study. The soil sampling protocol was such that soil was collected from six sites: under pruned Albizia, unpruned Albizia, pruned Cordia, unpruned Cordia (Albizia and Cordia trees were in coffee agroforestry systems), unshaded coffee and in the open field with neither coffee nor trees within the same farms. At each sampling point (in quadrats), soil samples were collected at 3 soil depths, *i.e.*, 0 to 15 cm, >15 to 30 cm and >30 to 45 cm. Soil collected from the quadrats at each depth was mixed well and a sample (about 500 g) collected and kept in a labelled plastic bag. The samples were taken to the laboratory for analysis.

Unshaded coffee sites generally had the least organic matter content (Figure 1). Initially, both Cordia and Albizia sites had relatively the same organic matter content ranging from 2.3-2.6%. However, there was a relative increase in organic matter content following pruning of Cordia and Albizia, more predominantly under pruned Albizia trees.

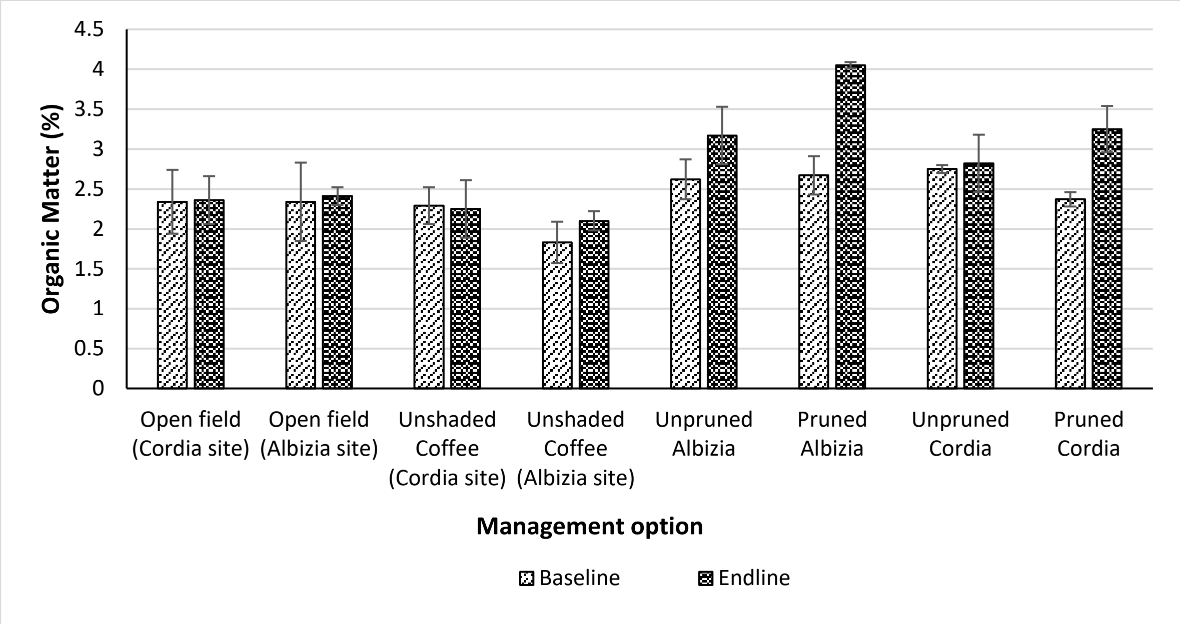


Fig. 1 Organic matter content of the soil before and after the biophysical experiment (*Double standard errors of the mean are shown)*

The Cordia site generally had a high composition of sand, exhibiting a sandy loam textural class (Table 1). However, unlike the open field in the Albizia site which had sandy clay soils, the rest of the Albizia sites had clay loam soil texture. Total phosphorus was highest in the Cordia site ranging between 32-46 ppm and least in Albizia sites (Supplementary Table 1). However, the Cordia site had the least potassium (k), magnesium (M) and sodium (Na). The highest base saturation (BS) was found in the Cordia site (28-52%). Other soil characteristics are summarised in Supplementary Table 1. Available phosphorus (Total P) and total nitrogen (N) have been reported to be below the optimum required level, while potassium (K) is optimally available in the Mt. Elgon region (UCDA, 2017).

Table 1: Soil texture range and textural class of the experimental sites in Manafwa District

Experimental site	**Soil texture ranges**			**Soil textural class***
	Sand (%)	**Clay (%)**	**Silt (%)**	
Open field (Albizia site)	45 – 46	30 - 31	23 - 25	Sandy clay
Open field (Cordia site)	59 – 60	18 - 19	22 - 23	Sandy loam
Unshaded Coffee (Albizia site)	33 – 35	45 - 48	19 - 20	Clay loam
Unshaded Coffee (Cordia site)	61 – 63	14 - 16	22 - 23	Sandy loam
Unpruned Albizia site (with coffee)	30 – 41	32 - 47	23 - 27	Clay loam
Pruned Albizia site (with coffee)	39 – 45	28 - 48	19 - 27	Clay loam
Unpruned Cordia site (with coffee)	61 – 64	12 - 20	19 - 24	Sandy loam
Pruned Cordia site (with coffee)	62 – 63	11 - 18	19 - 27	Sandy loam

** The USDA textural triangle (https://esdac.jrc.ec.europa.eu/public_path/shared_folder/projects/DIS4ME/indicator_descriptions/soil_texture.htm)*

4.4.3 Research design, instrumentation and installation

Sap flow metres (SFM1s)

Sap Flow Meters (SFM1s) were installed on 4 Cordia and 4 Albizia trees existing in the two farmers' fields. The 4 trees of each species were spaced at a distance of 10 -12 m, with coffee integrated at a spacing of 3 x 3 m. Following installation of the SFM1 Sap Flow Meters on Cordia and Albizia trees, 3 coffee plants were selected from each site and one SFM1 Sap Flow Meter was installed on each of them. The 3 SFM1 Sap Flow Meters were distributed such that 2 were installed on coffee plants closest (approximately 1 m) to any two of the trees (one close to the pruned and another close to the unpruned tree). The third SFM1 Sap Flow Meter was installed on a coffee plant far from any effect of shade (approximately 50 m from the tree crown). To avoid the need to install the SFM1 on multiple stems on coffee, the installation was made below the branching point (approximately 30 cm above ground). The average diameter of the coffee plant stems (measured 30cm above ground) was 3.9±0.3 cm.

Installation of the SFM1s on trees and coffee was done following the procedure described by Buyinza et al., (2019). Sap flow in coffee and the trees was assessed simultaneously at 30 minutes temporal resolution. Because radial profile information was lacking for our site, sap flow was assumed to be constant over the radial sapwood profile for Albizia, Cordia and coffee trees (Bovard et al., 2005; N. Phillips et al., 1996). Sap flow instrumentation used in this study is based on the Heat Ratio Method (HRM) as it is non-destructive and has the ability to detect low and reverse flow rates over extended periods (Burgess et al., 2001).

Estimating wood properties/ tree metadata

The tree metadata included stem diameter and stem circumference (cm) at 1.3 m, sapwood depth and bark thickness (cm) of each tree. These were used as input values into the sap flow tool analysis software to allow for scaling sap flow and sap velocity to the whole-tree scale. Sapwood depth was determined on samples that were collected using a 6 mm diameter increment corer. Two perpendicular wood cores were taken from each tree and sapwood was distinguished from heartwood by visual inspection of a distinct colour change. When the boundary between sapwood and heartwood was not clear (especially in Cordia), sapwood was stained with methyl orange. Bark thickness was determined using a bark-depth gauge.

Pruning of selected trees

At each site, 2 trees were pruned while the other 2 remained unpruned. This study adopted the 50% pruning regime. To attain the 50% canopy pruning regime, all secondary branches on the tree under investigation were counted and divided by two. Thereafter, branches to be pruned were randomly selected, labelled by making slit cuts and later pruned using a three-cut procedure (Bedker et al., 2012). The three-cut procedure was preferred because it minimizes splitting of the branch, and damage during pruning. The three-cut procedure was conducted as follows; first, at 30 cm from the trunk, cut halfway through the branch from the underside. Second, about 3 cm past the first cut, cut through the branch from the top side until the branch falls away. The weight of the branch would cause it to break between the two cuts. Lastly, the resulting stub was then cut back to the collar of the branch. Tree canopy pruning was done 3 times at an approximate interval of 6 months from July 2018 to January 2020. However, the first pruning was done in the fourth month following installation of the experiment to allow time for the experiment to run before subjecting the trees to canopy pruning. The first pruning was done on October 5th 2018, followed by the second pruning on April 30th 2019 and the third on November 1st 2019. The small branches from pruning were left to decompose below the trees while the large branches were used as firewood by the host farmers.

Tree leafing phenology data collection

Leaf cover changes were assessed in all the Cordia and Albizia trees in the experimental sites at approximately 14 days intervals of every month between July 2018 and February 2020. Leaf cover was scored on an arbitrary four-point scale denoting the proportion of the canopy bearing leaves; where 0 indicated that no leaves were present and 1, 2 and 3 denote low, intermediate, and full leaf cover respectively (Broadhead et al., 2003).

Soil moisture measurement

Soil moisture was assessed using an MPKit (ICT International, Australia), a portable soil moisture sensor for rapid sampling of Volumetric Soil Water Content (VSW%). To allow routine measurement of soil moisture at the same location and depth over a period of time, a series of holes were randomly augured to depths of 20 cm, 40 cm, 60 cm, 80 cm and 100 cm under each experimental tree (4 Cordia and 4 Albizia trees), in the unshaded coffee and in the open field. A set of 50 mm PVC tubes (representing the 5 depths) were installed in each of the holes augured at a distance from tree stem corresponding to half the radius of its crown as suggested by (Bazié et al., 2017). The MP406 was then inserted into each PVC tube to the required depth of measurement and the corresponding soil moisture content read out on the display of the MPM160 meter. The readings were taken every two weeks and automatically saved for later recall and download to a computer.

Meteorology station installation

A mini-weather station was setup close to each of the study sites to collect local weather data on daily incident rainfall, atmospheric (daily minimum and maximum) temperature and humidity. The data were manually collected and recorded daily.

4.4.4 Data analysis

Downloaded data was analysed using the Sap Flow Tool (SFT) software and the Combined Instrument Software (CIS) to obtain Daily Flows (L day^{-1}). A linear transformation on the heat pulse velocity to obtain corrected zero flow baselines for asymmetry of installation was performed (Buyinza et al., 2019; Ren et al., 2017). The daily flows were analysed and compared with rainfall patterns using line graphs (for daily flows) and bar graphs (for rainfall data). Daily flow data was exported from the SFT software as a .csv file and used for further analysis. To obtain standard comparable daily sap flow in the two tree species, the daily flows were computed per cross sectional area of the tree at 1.3 m height (L day^{-1} cm^{-2}). Analysis of variance General Linear Model (ANOVA-GLM) was performed in SPSS statistical software 25 to assess the influence of tree species, management option, season and their interaction on mean daily sap flow. The analysis considered 'tree species' (Cordia and Albizia), 'management' (either pruned or unpruned) and 'season' (dry and wet season) as the main effects at $P \leq 0.05$ significance level. The ANOVA would establish whether the main effects or their interaction had an influence on the mean daily sap flow.

Data on tree leafing phenology was presented in line graphs to show seasonal trends in leaf cover changes during the study period. Pairwise Pearson correlation coefficients between daily sap flow (as sample 1) and leaf phenology (as sample 2) in Cordia and Albizia trees were obtained using Minitab 19 (Minitab Inc., Pennsylvania, USA).

4.5 Results

4.5.1 Leaf cover in Cordia and Albizia trees

Leaf cover changes of Cordia and Albizia trees were recorded during the same period of assessing tree water use. Cordia trees were observed to achieve full canopy closure twice a year in the months of December - January and June - July (Figure 2). However, periods of canopy closure between the pruned and unpruned Cordia trees were asynchronous (before and after pruning), with leaf cover changes in pruned trees generally occurring later than the unpruned trees. However, there was a faster and more pronounced leaf fall in pruned Cordia than that in unpruned Cordia from June – July 2019. This may be attributed to the fact that scheduled tree pruning coincided with leaf fall during this period, thus the leaf cover of pruned Cordia was further reduced following pruning at the end of May 2019.

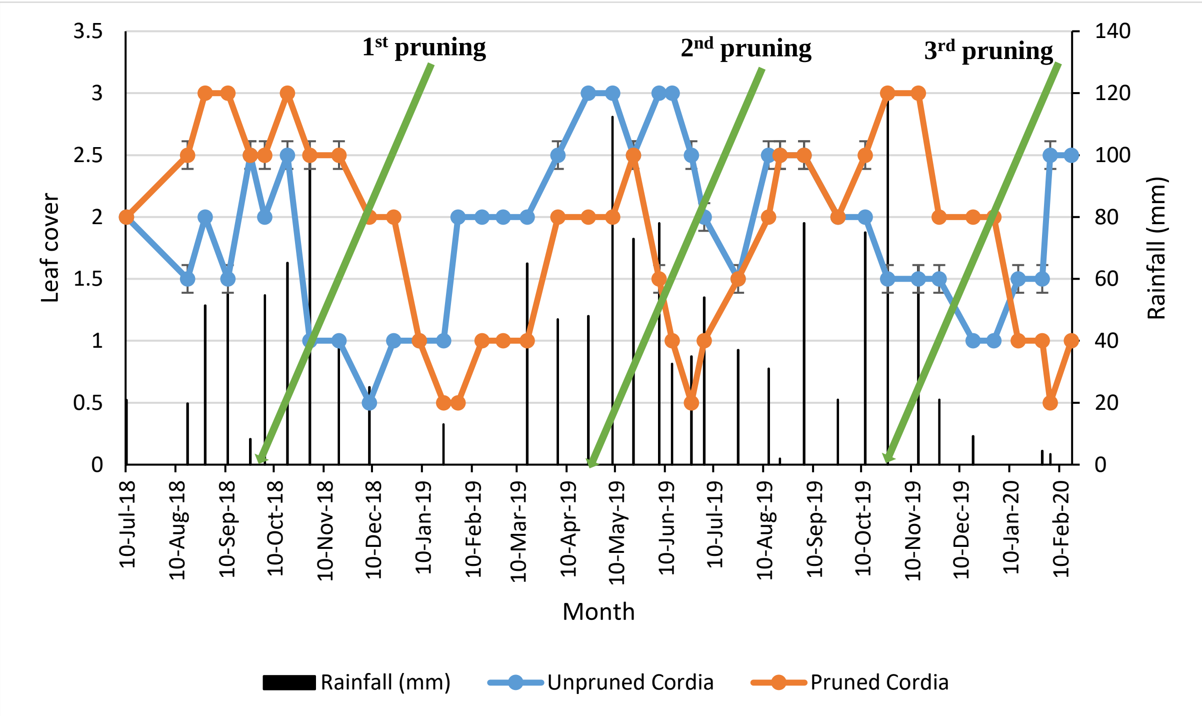


Fig. 2 Seasonal trends of leaf cover for Cordia between July 2018 and February 2020 in Manafwa district. *Leaf cover was scored on an arbitrary scale where 0 indicates that no leaves were present and 1, 2 and 3 denote low, intermediate and full leaf cover. Double standard errors of the mean are shown and daily rainfall histograms*

In Albizia trees, leaf cover changes in all trees were synchronous prior to the commencement of canopy pruning (before October 2018) (Figure 3). However, canopy pruning altered the synchrony of leaf phenology in Albizia, and the leaf cover changes were observed to consistently occur much earlier in pruned trees than in unpruned trees following pruning. This trend appears to exist consistently thereafter (after the 1st pruning in October 2018) through the entire period of the experiment. This implied that canopy pruning triggered faster leaf cover changes in Albizia trees. This was also observed during period of 'no leaves present' in January-February 2019 and 2020, where the pruned Albizia lost all their leaves earlier than the unpruned trees (Figure 3).

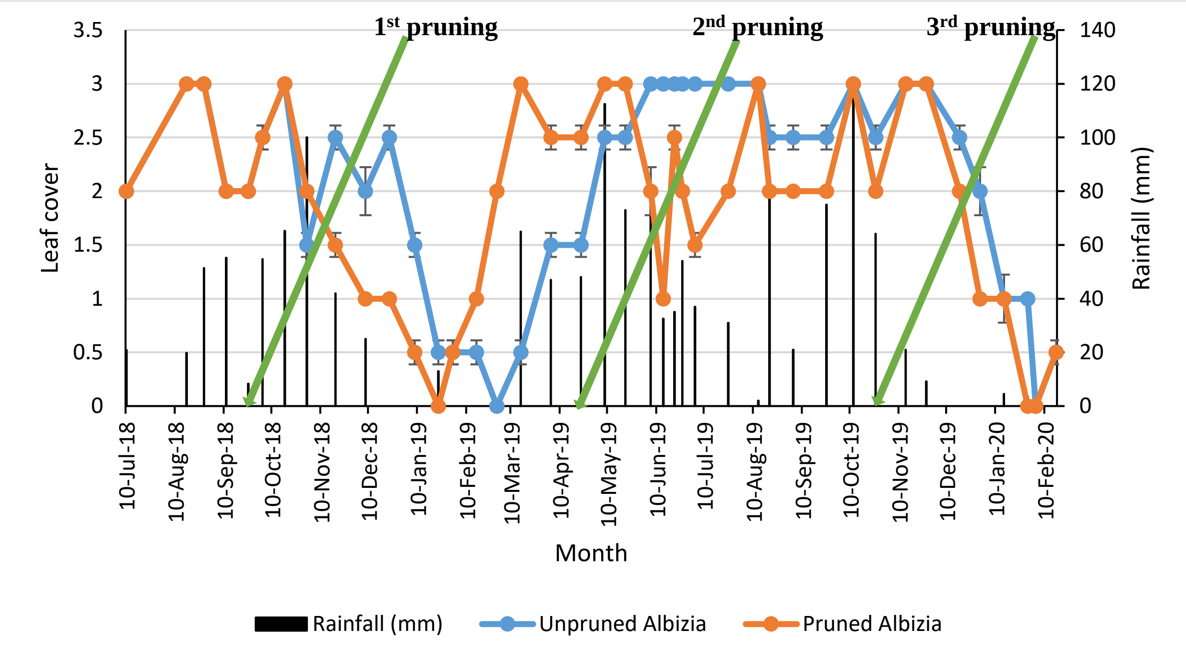


Fig. 3 Seasonal time courses of leaf cover for Albizia trees between July 2018 and February 2020 in Manafwa district. *Leaf cover was scored on an arbitrary scale where 0 indicates that no leaves were present and 1, 2 and 3 denote low, intermediate and full leaf cover. Double standard errors of the mean are shown and daily rainfall histograms*

4.5.2 Time courses in tree water use

Time courses in daily sap flow in pruned and unpruned Cordia trees

Prior to the first pruning (before October 5, 2018), the Cordia trees exhibited a uniform trend in daily sap flow (Figure 4). However, the trend changed following pruning. The unpruned trees showed a drastic decline in daily sap flow in December 2018 (beginning of the dry season), while the pruned trees maintain a consistent daily sap flow. The consistent daily sap flow in the pruned trees from mid-October to late December may have resulted from development of new shoots following pruning in early October (see Figure 2). Daily sap flow in the unpruned trees then started increasing exponentially from late December through January 2019. The pruned trees were then observed to have old leaves while the unpruned trees had started new leaf production, which may explain the increasing water use in unpruned Cordia trees between March and April 2019.

Following the second pruning, which coincided with heavy rains in April –May 2019, the pruned Cordia trees used less water than the unpruned trees, which continued until October 2019 (Figure 4). There were episodes of reverse flows in the pruned Cordia trees during the heavy rains in October 2019. The third pruning in November 2019 resulted into no observable changes in tree water use in the pruned trees. However, there was a drastic decline in tree water use of the unpruned trees towards the start of the dry season, between December 2019 and January 2020 that was not mimicked by the pruned trees.

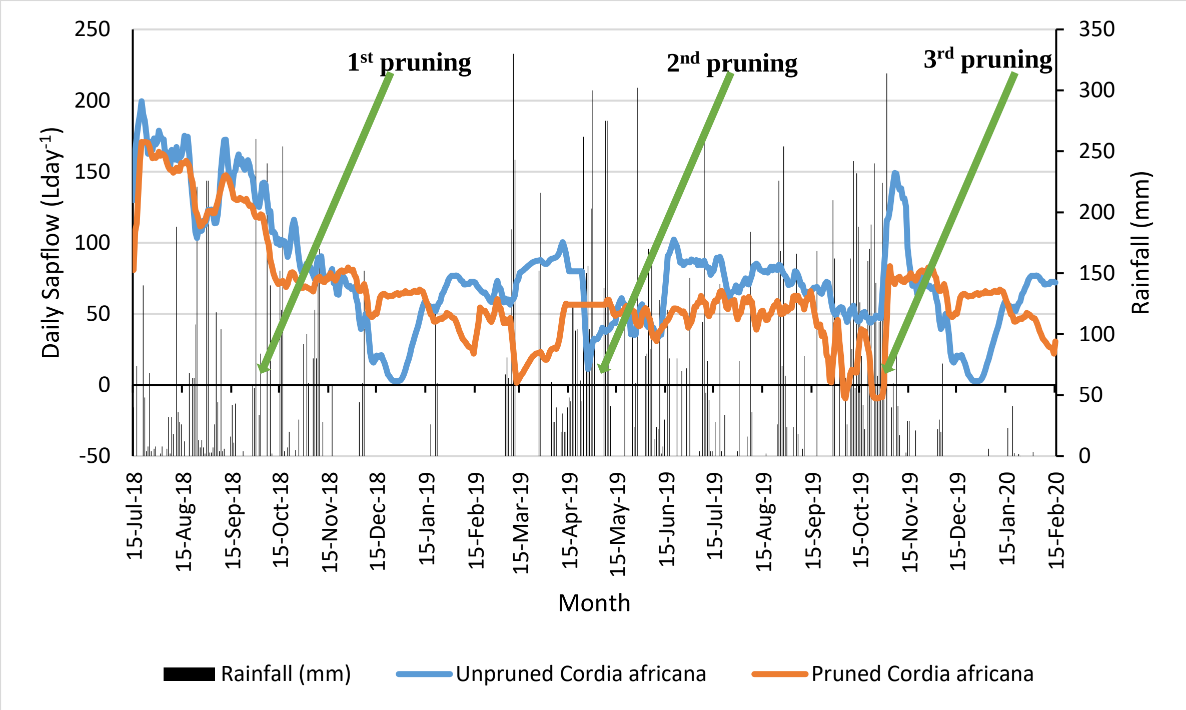


Fig. 4 Time courses in daily sap flow in pruned and unpruned Cordia trees over a 20- month period

Tree water use in pruned and unpruned Albizia trees

While there were no observable changes in tree water use trends following pruning of Albizia trees, mean daily sap flow was generally lower in pruned Albizia than in the unpruned trees (Figure 5). Daily sap flow generally declined during high rainfall events (for example August to September and mid-October to early November) and increased during the dry seasons (January to February) in 2018 and 2019. From December, Albizia trees begin shedding their leaves through January. During this period, daily sap flow declined and the trees eventually experienced episodes of reverse flows in January 2019 and 2020. However, pruned trees experienced reverse flows much earlier than the unpruned trees, probably due to reduction in the photosynthetic component of the tree through pruning, coupled with total leaf fall during the dry season. Albizia trees increased their water use about a month prior to the start of the wet season, which may result from the growth of new leaves at that time of the year in preparation of a very predictable start to the wet season.

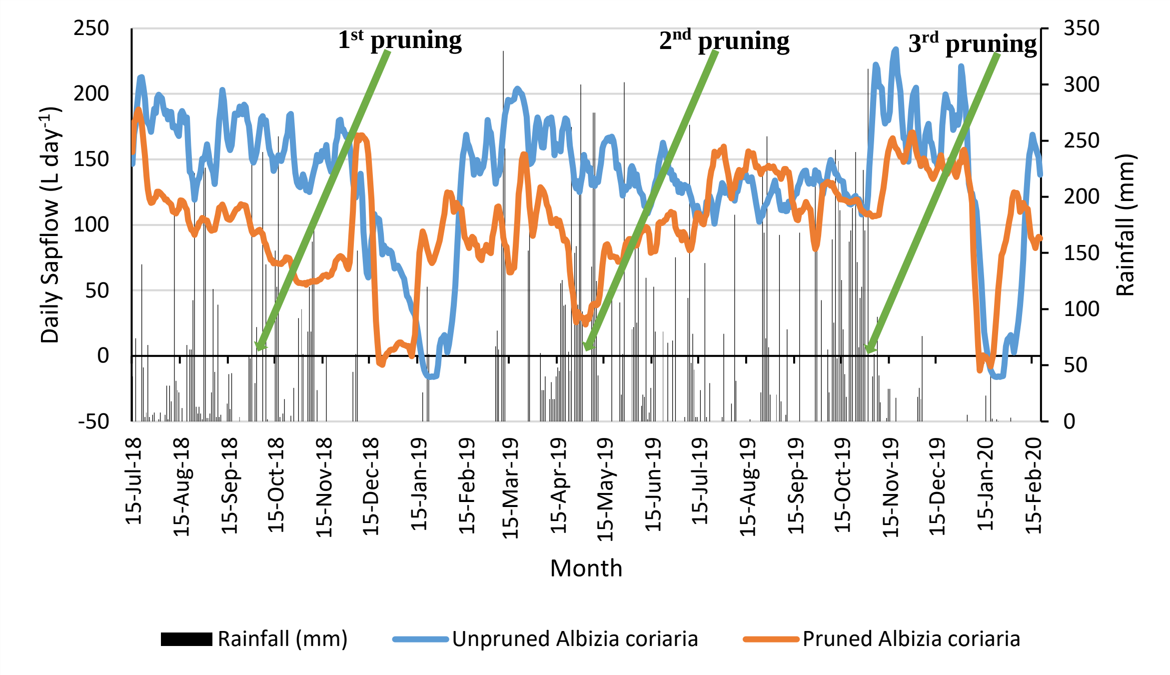


Fig. 5 Time courses in daily sap flow in pruned and unpruned Albizia trees over a 20-month period

Average daily sap flow in Cordia and Albizia trees over a 20 month period

Table 2 below gives a summary of the daily tree water use (minimum, maximum and average) for pruned and unpruned Cordia and Albizia trees integrated in coffee-bean systems. Prior to standardisation of tree water use (based on the study trees), the results show that unpruned trees generally used more water than the pruned trees, with Albizia trees exhibiting more water than Cordia trees. Apart from the unpruned Cordia trees, the rest of the trees registered reverse flows during certain periods of the study, as revealed by the negative minimum daily flows (Table 2). While reverse flows can be common in Albizia, canopy pruning might have triggered reverse flows in Cordia trees.

Table 2: Average daily flow for each tree management option over a period of 20 months

Tree species	**Management option**	**Average DBH (cm)**	**Daily sap flow (L day^{-1})**			**Daily sap flow (L day^{-1} cm^{-2})**
			Min	**Max**	**Average**	
Cordia africana	Unpruned	40.2	2.7	199.5	76.5	0.060
C. africana	Pruned	41.9	-9.4	170.8	64.2	0.047
Albizia coriaria	Unpruned	49.6	-16.0	234.0	133.7	0.069
A. coriaria	Pruned	60.4	-11.2	188.1	99.0	0.035

Following computation of tree water use per cross sectional area of the tree at 1.3 m height (standardisation), the results show that unpruned Albizia trees used more water than unpruned Cordia trees (Table 2). On this standardised basis, the pruned Cordia and Albizia trees respectively used 23% and 50% less water than unpruned trees, presumably resulting from reduced leaf area.

4.5.3 Effect of tree species, management option, season and their interaction on tree water use

In Table 3, the ANOVA performed revealed a statistically significant main effect of tree species, management and season on daily tree water use (P<0.05). The interaction of the three main effects (tree species x management', 'tree species x season', and 'management x season') also had a significant influence on the mean daily sap flow (P<0.05), implying that all the main effects and their interaction had a significant influence on the daily water use of the study trees.

Table 3: Results of Analysis of Variance (ANOVA) to assess the effect of tree species, tree management, season and their interaction on mean daily sap flow

Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F- value**	***P*-value**
Tree species	1132642.7	1	1132642.7	648.9	.000
Tree management	277775.6	1	277775.6	159.1	.000
Season	10076.2	1	10076.2	5.8	.016
Tree species x Tree management	46702.9	1	46702.9	26.8	.000
Tree species x Season	93952.7	1	93952.7	53.8	.000
Tree management x Season	26488.9	1	26488.9	15.2	.000
Error	4060303.3	2326	1745.6		
Total	26383516.9	2334			

The impact of the main effects on daily sap flow was further demonstrated through standardised mean daily sap flow values of managed and unmanaged trees in the dry and wet seasons (Figure 6). Unpruned trees had the greatest variation in tree daily water use during the wet and dry seasons. However, pruned trees show comparable daily sap flow per unit cross section area across seasons. This may have resulted from the low water demand of pruned trees following canopy pruning.

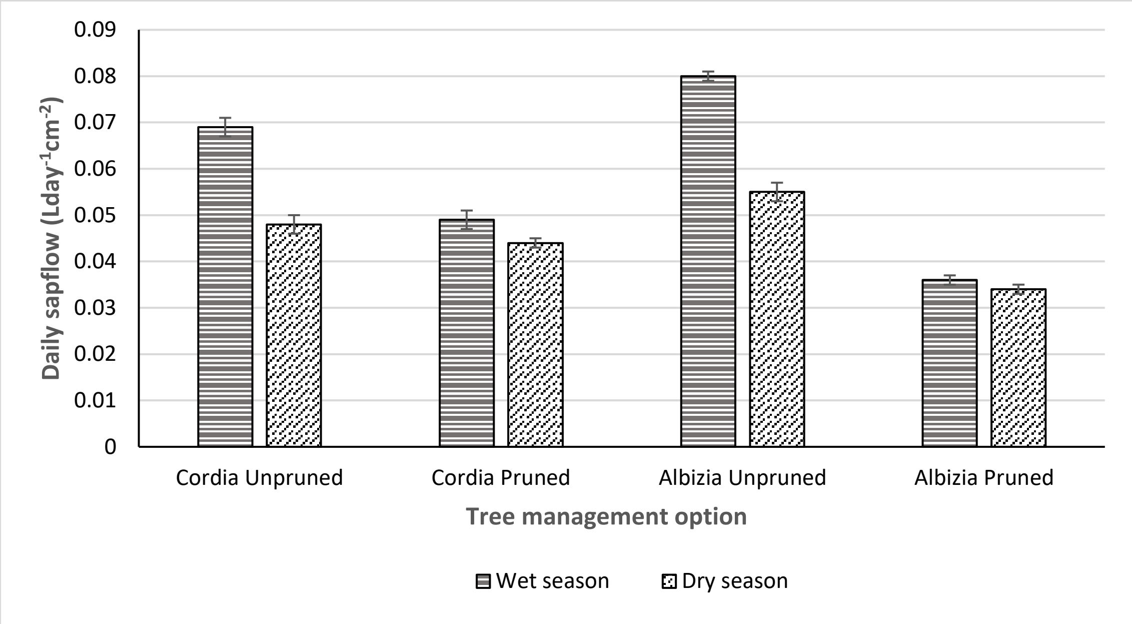


Fig. 6 Standardised daily tree water use of pruned and unpruned Cordia and Albizia trees across seasons (*Double standard errors of the mean are shown)*

The pairwise Pearson correlation revealed that overall, tree leafing phenology was highly correlated (P<0.05) with daily sap flow of Cordia and Albizia trees (Table 4). When correlations were run between specific trees (pruned and unpruned) and their corresponding leafing phenology, the result showed significant correlation between phenology and daily sap flow in unpruned Albizia and pruned Cordia trees. The correlation between phenology and daily sap flow was positive but insignificant in pruned Albizia and unpruned Cordia trees. While positive correlations may be an indication that tree leafing phenology plays a key role in the overall tree water use, other factors may contribute to the observed trends in the overall tree water use. Such factors may include rainfall, available soil moisture, atmospheric temperature and rooting structure/ depth.

Table 4: Pairwise Pearson correlations between daily sap flow and leafing phenology in managed and unmanaged Cordia and Albizia trees

Sample 1	Sample 2	Correlation	95% CI for ρ	P-Value
Unpruned Albizia daily flow	Unpruned Albizia phenology	0.342*	(0.035, 0.591)	0.031
Pruned Albizia daily flow	Pruned Albizia phenology	0.290^{ns}	(-0.023, 0.552)	0.069
Unpruned Cordia daily flow	Unpruned Cordia phenology	0.199^{ns}	(-0.120, 0.481)	0.218
Pruned Cordia daily flow	Pruned Cordia phenology	0.394*	(0.094, 0.628)	0.012
Overall daily flow	Overall leaf phenology	0.299*	(0.151, 0.434)	0.000

*Correlations significant at the level of P < 0.05 are indicate by *; the non-significant are labelled as ns.*

4.5.4 Time courses in coffee water use

Time courses in daily sap flow in coffee growing under pruned and unpruned trees over a 20 month period

The pruning intervals indicated in Figure 7 represent the days when Cordia trees were pruned. No pruning was done on coffee, as is the general practice among coffee farmers in the region. There were no observable changes in coffee water use following the first pruning of Cordia trees through the rainfall events between October and December 2018. Thereafter, water use of coffee growing under pruned Cordia was greater than that of coffee under unpruned Cordia in the dry season from late December 2018 to February 2019. Through the rainy season until July 2019, coffee under pruned Cordia used less water than coffee under unpruned Cordia, and thereafter used more water through the rain season (August – November 2019) and the dry season until early February 2020. Unlike the first pruning, coffee water use appears to increase in coffee growing under pruned Cordia following the second and third prunings, which may be attributed to increased exposure to sunlight and reduced competition for soil water resulting from pruning. This may imply that continued pruning of Cordia may have created a water reserve in the soil.

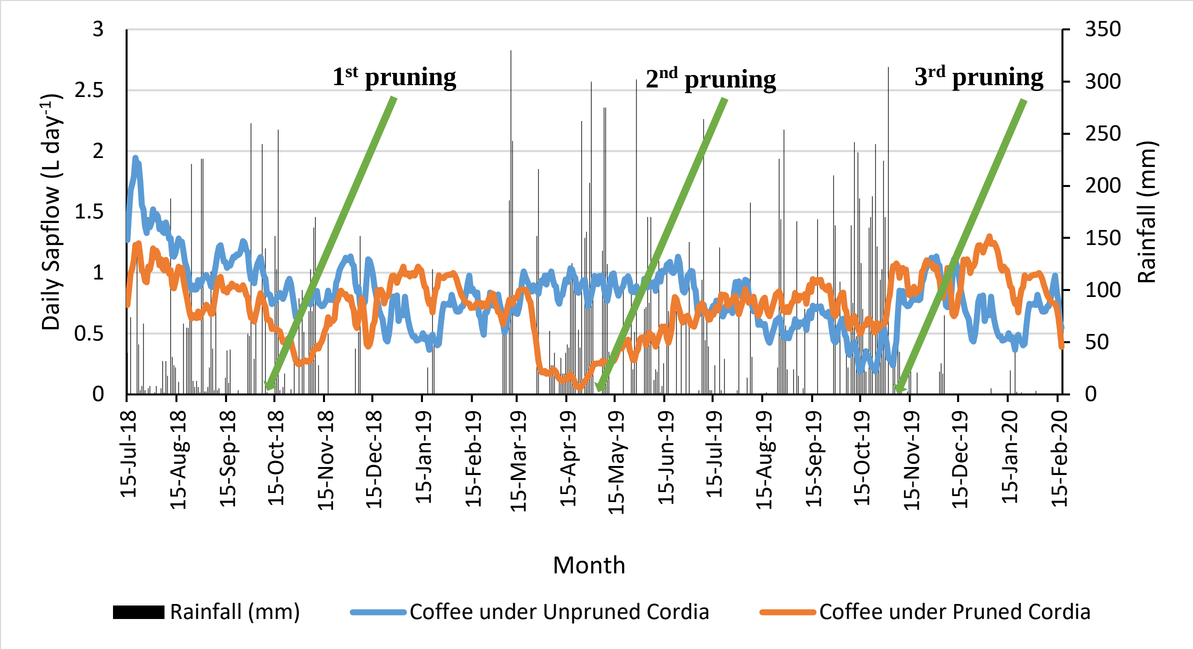


Fig. 7 Time courses in daily sap flow in coffee growing under Cordia trees over a 20-month period

Coffee growing under pruned Albizia increased its water use compared to that under unpruned Albizia trees following the first and second pruning in October 2018 and April 2019 (Figure 8). There was no observable difference in water use trends in coffee under pruned and unpruned Albizia following the third pruning, though daily flow appears slightly higher in coffee under pruned Albizia. However, water use in coffee kept declining during key rainfall events and increased during the dry periods throughout the study period.

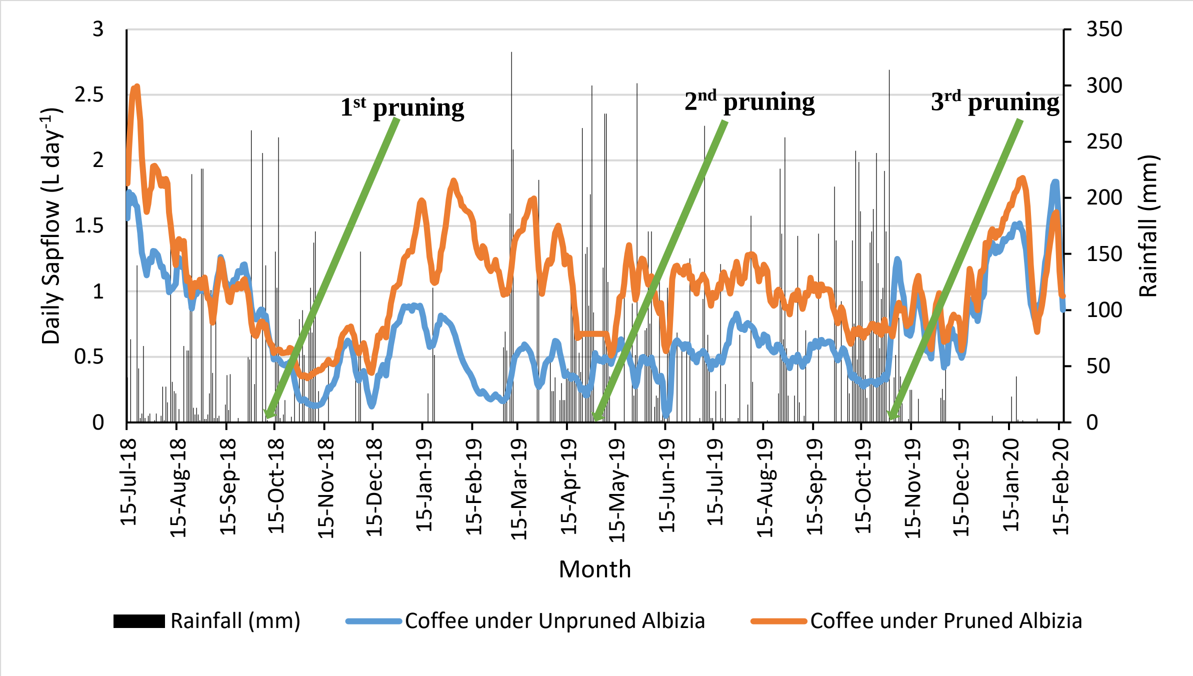


Fig. 8 Time courses in daily sap flow in coffee growing under Albizia trees over a 20-month period

Unshaded coffee, grown in the absence of overstory trees, generally used more water than shaded coffee throughout the field experiment duration, using a maximum 4.3 L/day and a minimum of 0.2 L/day (Figure 9). There was a general decline in water use during rainfall events through the 20-month study period.

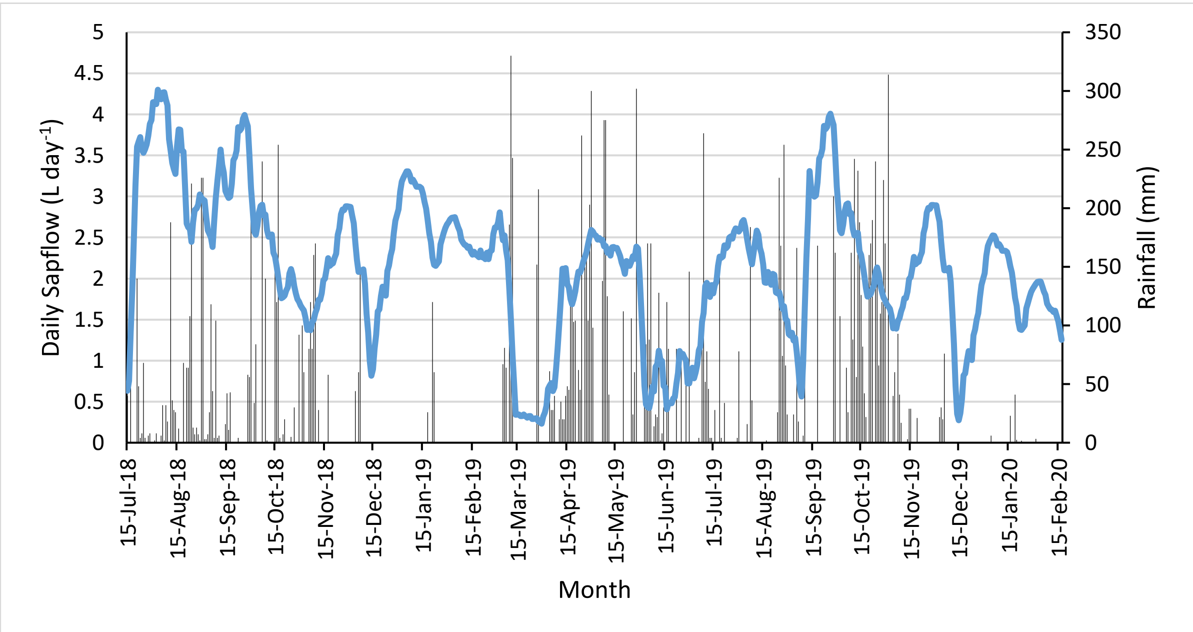


Fig. 9 Time courses in daily sap flow in unshaded coffee over a 20-month period

Average daily sap flow in coffee growing over a 20-month period

Coffee generally used 0.1 to 4.3 litres of water per plant daily over a 20-month study period (Table 5). Unshaded coffee used much more water compared to coffee growing under pruned and unpruned Cordia and Albizia trees, which may be attributed to lack of competition for soil water and the high respiration demand due to direct sunlight in the unshaded coffee. On the other hand, unlike Cordia, coffee growing under pruned Albizia used more water than coffee growing under unpruned Albizia trees, an indication that pruning might have increased the amount of water available to coffee growing under pruned trees Albizia.

Table 5: Average daily sap flow for coffee growing under different management options

Management option	**Daily sap flow (L day^{-1})**		
	Min	**Max**	**Average**
Coffee under unpruned *Cordia africana*	0.2	1.9	0.8
Coffee under pruned *C. africana*	0.1	1.3	0.7
Coffee under unpruned *Albizia coriaria*	0.1	1.8	0.7
Coffee under pruned *A. coriaria*	0.3	2.6	1.1
Unshaded coffee	0.2	4.3	2.2

4.6 Discussion

4.6.1 Leaf phenology of managed Cordia and Albizia trees

Vegetative phenological changes in Cordia and Albizia trees were recorded during the 20-month period of the experiment. In this study, Cordia trees were observed to shade their leaves twice a year in the months of December - January and June – July, while Albizia trees consistently shade their leaves between January and February. Although phenological events of most tree species in the tropics are generally bimodal and follow the rainfall patterns (Omondi et al., 2016), Albizia trees tend to have one pronounced period of leaf fall. Inter-annual and individual variations in vegetative phenology have also been reported in *Ficus obtusifolia* in tropical Venezuela (Ballestrini et al., 2011).

Vegetative phenology of tropical trees has been reported to frequently occur synchronously at the end of the dry season (Ballestrini et al., 2011; Omondi et al., 2016) and also to be strongly influenced by daily insolation (Borchert et al., 2015). In this study, canopy pruning appeared to alter the leafing phenology of Albizia trees. While leaf cover changes in Cordia trees were unsynchronised (before and after pruning), canopy pruning altered the synchrony of vegetative phenology in Albizia trees, as leaf canopy changes were observed to consistently occur much earlier in pruned trees than in unpruned trees. This was also observed during a period of 'no leaves present' in January-February 2019 and 2020, where the pruned Albizia lost all their leaves earlier than the unpruned trees (see Figure 3). A similar trend was observed in tree water use in pruned Albizia (see Figure 4).

The positive correlation coefficients between leaf phenology and daily tree water use further emphasise the role of vegetative phenology in the overall tree water use. The differences in phenological responses may regulate competition between tree species (Linares et al., 2012) and other agroforestry components. Therefore, the contrasting phenological responses of Cordia and Albizia tree water use following pruning may be beneficial for facilitating temporal complementarities of agroforestry systems, by regulating the amount of water available to the agroforestry components.

4.6.2 Impact of pruning Cordia and Albizia on tree water use

Cordia and Albizia trees exhibit contrasting tree water use patterns (Buyinza et al., 2019). In the current study, canopy pruning of Cordia and Albizia trees generally reduced their average daily total water use by 23% and 50% respectively, when compared with the unpruned trees. This may be attributed to reduced tree leaf area following pruning, as reported in a related study of whole tree water use of pruned Eucalyptus trees in New South Wales (Alcorn et al., 2013). Unlike the current study, the reduction in Eucalyptus tree water use lasted only 8 days after pruning. Although the overall water requirement of the pruned trees in the current study was reduced, this was only observed after the third pruning in November 2019, when the soil profile water storage was able to recharge following rainfall (see supplementary figures 1 & 2). This may be due to the intensive level of canopy removal which subsequently reduced the leaf area at the third 50% pruning regime adopted by the study. This is further supported by a study where more intense leaf area removal from *Eucalyptus nitens* reduced transpiration by 16%, 2-3 years after pruning (Forrester et al., 2012). Another related study on *Grevillea robusta* in Kenya revealed that moderate pruning of the tree canopy only slightly modified water demand of the tree (Jackson et al., 2000). However, when *G. robusta* canopy was more heavily pruned, the water requirement of the tree component reduced, and the soil profile water storage was able to recharge following rainfall. This implies that deliberate phased tree canopy pruning can potentially reduce the volume of water transpired, subsequently reducing competition for water with other agroforestry components in the farming system.

Prior to the first pruning (before October 5th 2018), all the Cordia trees exhibited a uniform trend in daily sap flow (see Figure 4). However, the trend changed following pruning as the unpruned trees showed a drastic decline in daily sap flow in December 2018 (beginning of the dry season), while the pruned trees maintained a consistent daily sap flow. It is anticipated that the consistent daily sap flow in the pruned Cordia trees could have resulted from development of multiple new re-growths following pruning, consistent with what was observed in two Eucalyptus species in Australia (Alcorn et al., 2013). Conserved soil moisture conditions soon after pruning Cordia may have allowed rapid leaf production following pruning. Unlike for Albizia trees, pruning induced rapid development of new multiple shoots around the cut sections of pruned Cordia branches. A similar characteristic was reported in *Senna spectabilis* in Kenya, where shoot pruning induced multiple stems and narrow xylem vessels with low hydraulic conductivity (Namirembe et al., 2008). Conversely, pruned Cordia trees were later observed to have old leaves, while the unpruned trees had started flushing, which may explain the increasing water use in unpruned Cordia trees between March and April 2019. Differences in stomatal conductance have also been reported in *G. robusta*, *Eucalyptus* clones and *Cordia africana* in Kenya (Kuyah et al., 2009) which may also play a part, especially as the soil moisture declines.

4.6.3 Reverse flows in Albizia and pruned Cordia

Apart from the unpruned Cordia trees, the rest of the tree treatments (pruned Cordia, and pruned and unpruned Albizia) registered reverse flows during certain periods of the study (see Figure 4 and Table 2). While reverse flows are common in agroforestry trees such as Albizia (Buyinza et al., 2019) and *G. robusta* (Burgess et al., 1998), canopy pruning might have triggered reverse flows in Cordia trees. Reverse flows have been reported to occur through hydraulic redistribution when the soils are drier than the atmosphere (Hafner et al., 2017), and are common in deciduous tree species during the dry season (Scholz et al., 2008). This is consistent with Albizia trees that exhibit reverse flow during the December – January dry season. However, this study revealed that reverse flows appeared earlier in pruned than unpruned Albizia trees, probably due to reduction in the photosynthetic component of the tree through pruning, coupled with a total leaf fall during the dry season (see Figure 3).

The episodes of reverse flow occurred in pruned Cordia trees during the heavy rains in October 2019, just before the third pruning. Reverse flow phenomena have been reported to enable plants to store water for later use, especially when transpiration demand cannot be met by the sparse root network in the subsoil (Smith et al., 1999). The HRM (Sap flow) gauges (Burgess et al., 2001) used in this study provide an important tool for investigating the role of reverse flow phenomena in resource acquisition strategies used by trees and crops in agroforestry systems. This can, in turn, inform the design and management of agroforestry systems. For example, in the current study, pruning Cordia trees minimized competition for water in this coffee agroforestry system by reducing the water requirement of the tree component and triggering reverse flows in the water conducting xylem tissue.

4.6.4 Water use of coffee trees under different management regimes

In this study, average daily coffee tree water use was 0.7-2.2 $Lday^{-1}$ over the 20-month study period (see Table 5). The results are comparable to a related study in the region where the average daily arabica coffee water use was 0.9 -1.6 $Lday^{-1}$ (Sarmiento-Soler et al., 2019). The larger stem diameter coffee trees in the current study (3.9±0.3 cm) than coffee in the previous study (2.3cm) may explain the slightly higher water use in the current study, as tree water use is proportional to tree size (Meinzer et al., 2004; Phillips et al., 2003). That study also observed that water use in coffee continued declining during key rainfall events and increased in the dry periods throughout the study period. This is attributed to higher transpiration rates during the dry season than during the wet season, largely because of increased evaporative demand and the exploitation of ground water reserves by the coffee trees (O'Grady et al., 1999). In the present study, unshaded coffee used more average daily water (>2 $Lday^{-1}$) than shaded coffee which used 0.7-1.1 $Lday^{-1}$ (see Table 5), a similar scenario reported by Sarmiento-Soler et al., (2019). The high coffee water use by the unshaded coffee can be due to lack of competition for soil water.

Overall, coffee growing under pruned trees used more water than coffee growing under unpruned trees. This may be attributed to more transpiration pull due to increased radiation with reduced shading. Low shade coffee agroforestry systems have been reported to increase the overall evaporative demand from soil evaporation and coffee transpiration in Southern Mexico (Lin, 2010). Pruning Cordia and Albizia trees in this study might also have contributed to the increased amount of water availability to coffee growing under pruned trees as well as their evapotranspiration rates due to increasing radiation. However, this was particularly observed in coffee under pruned Cordia following the second pruning (see Figure 7), implying that the tree pruning impact of conserving water occurred later in the experiment. The consistent trend in water use reported earlier in Cordia trees following pruning and the growth of multiple shoots around the pruned sections of the tree may explain the delayed increase in water use of coffee under pruned Cordia.

Relatedly, the increased water use in coffee under pruned Albizia may be attributed to the 50% water use deficit observed in pruned Albizia trees following pruning (see Table 2). Adequate shade management has been reported to improve both the water status of the soil and coffee production after prolonged droughts (DaMatta & Ramalho, 2006). Therefore, phased pruning of Cordia and Albizia trees appeared to create a water reserve in the soil (see supplementary figure 1 & 2) that was subsequently accessed by the coffee growing below the trees. In addition, shade trees lower the radiation input at canopy level, reducing the extent of photo oxidative damage (DaMatta et al., 2018), a phenomenon frequently observed in unshaded coffee.

4.7 Conclusion

Tree pruning was shown to be a powerful means of controlling water use of agroforestry systems, the benefits of other tree products notwithstanding. Canopy pruning reduced the water demand of trees, triggered reverse flows in the water conducting xylem tissue of Cordia trees and altered the leafing phenology of Albizia trees to recharge the coffee rooting zone. Carefully phased tree canopy pruning can therefore provide an opportunity to reduce the volume of water transpired, and reduce competition for water in coexisting species. Tree pruning and the deciduous nature of Cordia and Albizia trees offer opportunities for regulating water competition in agroforestry systems. The knowledge generated can be used to match smallholder farming systems' water requirements with expected soil water availability, to manage competition for water. However, we propose further studies analysing the impact of shoot pruning on root behaviour and growth and accompanying isotope studies in these and other agroforestry tree species to gain a holistic understanding of these processes. In addition, studies quantifying additional benefits resulting from canopy pruning, especially in provision of fuelwood as an important tree product in this region, the mulch and soil nutrient enrichment components are recommended.

4.8 References

Aitken, S. N., Yeaman, S., Holliday, J. A., Wang, T., & Curtis-Mclane, S. (2008). Adaptation, migration or extirpation: climate change outcomes for tree populations. *Evolutionary Applications, 1*(1), 95-111. doi: 10.1111/j.1752-4571.2007.00013.x

Alcorn, P. J., Forrester, D. I., Thomas, D. S., James, R., Smith, R. G. B., Nicotra, A. B., & Bauhus, J. (2013). Changes in Whole-Tree Water Use Following Live-Crown Pruning in Young Plantation-Grown Eucalyptus pilularis and Eucalyptus cloeziana. *Forests, 4*(1), 106-121.

Ballestrini, C., Tezara, W., & Herrera, A. (2011). Environmental drivers of leaf phenology in trees of the tropical species Ficus obtusifolia. *Brazilian Journal of Plant Physiology, 23*, 113-122.

Bayala, J., Teklehaimanot, Z., & Ouedraogo, S. J. (2004). Fine root distribution of pruned trees and associated crops in a parkland system in Burkina Faso. *Agroforestry Systems, 60*(1), 13-26. doi: 10.1023/B:AGFO.0000009401.96309.12

Bazié, H. R., Sanou, J., Bayala, J., Bargués-Tobella, A., Zombré, G., & Ilstedt, U. (2017). Temporal variations in transpiration of Vitellaria paradoxa in West African agroforestry parklands. *Agroforestry Systems*. doi: 10.1007/s10457-017-0115-4

Bazié., H., Bayala, J., Zombré, G., Sanou, J., & Ilstedt, U. (2012). Separating competition-related factors limiting crop performance in an agroforestry parkland system in Burkina Faso. *Agroforestry Systems, 84*(3), 377-388. doi: 10.1007/s10457-012-9483-y

Bedker, P. J., O'Brien, J. G., & Mielke, M. M. (2012). *How to prune trees.* . Newtown Square, USA: USDA Agriculture Dept., Forest Service, Northeastern Area State and private forestry.

Borchert, R., Calle, Z., Strahler, H. A., Baertschi, A., Magill, E. R., Broadhead, S. J., . . . Muthuri, C. (2015). Insolation and photoperiodic control of tree development near the equator. *The New phytologist, 205*(1), 7-13. doi: 10.1111/nph.12981

Bovard, B. D., Curtis, P. S., Vogel, C. S., Su, H. B., & Schmid, H. P. (2005). Environmental controls on sap flow in a northern hardwood forest. *Tree Physiology, 25*(1), 31-38. doi: 10.1093/treephys/25.1.31

Broadhead, J. S., Black, C. R., & Ong, C. K. (2003). Tree leafing phenology and crop productivity in semi-arid agroforestry systems in Kenya. *Agroforestry Systems, 58*(2), 137-148. doi: 10.1023/a:1026091921043

Bukomeko, H., Jassogne, L., Tumwebaze, S. B., Eilu, G., & Vaast, P. (2017). Integrating local knowledge with tree diversity analyses to optimize on-farm tree species composition for ecosystem service delivery in coffee agroforestry systems of Uganda. *Agroforestry Systems*. doi: 10.1007/s10457-017-0172-8

Burgess, S. S. O., Adams, M. A., Turner, N. C., Beverly, C. R., Ong, C. K., Khan, A. A. H., & Bleby, T. M. (2001). An improved heat pulse method to measure low and reverse rates of sap flow in woody plants †. *Tree Physiology, 21*(9), 589-598. doi: 10.1093/treephys/21.9.589

Burgess, S. S. O., Adams, M. A., Turner, N. C., & Ong, C. K. (1998). The redistribution of soil water by tree root systems. *Oecologia, 115*(3), 306-311. doi: 10.1007/s004420050521

Buyinza, J., Muthuri, C. W., Downey, A., Njoroge, J., Denton, M. D., & Nuberg, I. K. (2019). Contrasting water use patterns of two important agroforestry tree species in the Mt Elgon region of Uganda. *Australian Forestry*, 1-9. doi: 10.1080/00049158.2018.1547944

Buyinza., J., Nuberg, I. K., Muthuri, C. W., & Denton, M. D. (2020a). Assessing smallholder farmers' motivation to adopt agroforestry using a multi-group structural equation modeling approach. *Agroforestry Systems*. doi: 10.1007/s10457-020-00541-2

Buyinza., J., Nuberg, I. K., Muthuri, C. W., & Denton, M. D. (2020b). Psychological Factors Influencing Farmers' Intention to Adopt Agroforestry: A Structural Equation Modeling Approach. *Journal of Sustainable Forestry, 39*(8), 854-865. doi: 10.1080/10549811.2020.1738948

DaMatta, F. M., Avila, R. T., Cardoso, A. A., Martins, S. C. V., & Ramalho, J. C. (2018). Physiological and Agronomic Performance of the Coffee Crop in the Context of Climate Change and Global Warming: A Review. *Journal of agricultural and food chemistry, 66*(21), 5264. doi: 10.1021/acs.jafc.7b04537

DaMatta, F. M., & Ramalho, J. D. C. (2006). Impacts of drought and temperature stress on coffee physiology and production: a review. *Brazilian Journal of Plant Physiology, 18*, 55-81.

Descheemaeker, K., Bunting, S. W., Bindraban, P., Muthuri, C., Molden, D., Beveridge, M., . . . Jarvis, D. I. (2013). *Increasing water productivity in Agriculture*.

FAO. (2011). *The state of the world's land and water resources for food and agriculture : managing systems at risk* (1st ed. ed.). Milton Park, Abingdon. New York, NY: Earthscan.

Forrester, D. I., Collopy, J. J., Beadle, C. L., Warren, C. R., & Baker, T. G. (2012). Effect of thinning, pruning and nitrogen fertiliser application on transpiration, photosynthesis and water-use efficiency in a young Eucalyptus nitens plantation. *Forest Ecology and Management*, *266*, 286-300. doi: https://doi.org/10.1016/j.foreco.2011.11.019

Forrester, D. I., Medhurst, J. L., Wood, M., Beadle, C. L., & Valencia, J. C. (2010). Growth and physiological responses to silviculture for producing solid-wood products from Eucalyptus plantations: An Australian perspective. *Forest Ecology and Management, 259*(9), 1819-1835. doi: https://doi.org/10.1016/j.foreco.2009.08.029

Gram, G., Vaast, P., Wolf, J., & Jassogne, L. (2018). Local tree knowledge can fast-track agroforestry recommendations for coffee smallholders along a climate gradient in Mount Elgon, Uganda. *An International Journal incorporating Agroforestry Forum, 92*(6), 1625-1638. doi: 10.1007/s10457-017-0111-8

Hafner, B. D., Tomasella, M., Häberle, K.-H., Goebel, M., Matyssek, R., Grams, T. E. E., & Mencuccini, M. (2017). Hydraulic redistribution under moderate drought among English oak, European beech and Norway spruce determined by deuterium isotope labeling in a split-root experiment. *Tree Physiology, 37*(7), 950-960. doi: 10.1093/treephys/tpx050

Jackson, N. A., Wallace, J. S., & Ong, C. K. (2000). Tree pruning as a means of controlling water use in an agroforestry system in Kenya. *Forest Ecology and Management, 126*(2), 133-148. doi: 10.1016/S0378-1127(99)00096-1

Kuyah, S., Muthuri, C., & Chin, O. (2009). Gas exchange responses of Eucalyptus, C. africana and G. robusta to varying soil moisture content in semi-arid (Thika) Kenya. *Agroforestry Systems*, *75*(3), 239-249. doi: 10.1007/s10457-008-9176-8

Lin, B. B. (2010). The role of agroforestry in reducing water loss through soil evaporation and crop transpiration in coffee agroecosystems. *Agricultural and Forest Meteorology, 150*(4), 510-518. doi: 10.1016/j.agrformet.2009.11.010

Linares, J., Covelo, F., Carreira, J., & José, M. (2012). Phenological and water-use patterns underlying maximum growing season length at the highest elevations: Implications under climate change. *Tree Physiology, 32*, 161-170. doi: 10.1093/treephys/tps003

Luedeling, E., Smethurst, P. J., Baudron, F., Bayala, J., Huth, N. I., van Noordwijk, M., . . . Sinclair, F. L. (2016). Field-scale modeling of tree–crop interactions: Challenges and development needs. *Agricultural Systems*, *142*, 51-69. doi: https://doi.org/10.1016/j.agsy.2015.11.005

Meinzer, F. C., James, S. A., & Goldstein, G. (2004). Dynamics of transpiration, sap flow and use of stored water in tropical forest canopy trees. *Tree Physiology, 24*(8), 901-909. doi: 10.1093/treephys/24.8.901

Muthuri, C. W., Ong, C. K., Black, C. R., Mati, B. M., Ngumi, V. W., & van Noordwijk, M. (2004). Modelling the effects of leafing phenology on growth and water use by selected agroforestry tree species in semi-arid Kenya. *Land Use and Water Resources Research, 4*, 11. doi: 10.22004/ag.econ.47874

Muthuri, C. W., Ong, C. K., Craigon, J., Mati, B. M., Ngumi, V. W., & Black, C. R. (2009). Gas exchange and water use efficiency of trees and maize in agroforestry systems in semi-arid Kenya. *Agriculture, Ecosystems & Environment, 129*(4), 497-507. doi: 10.1016/j.agee.2008.11.001

Namirembe, S., Brook, R. M., & Ong, C. K. (2008). Manipulating phenology and water relations in Senna spectabilis in a water limited environment in Kenya. *Agroforestry Systems, 75*(3), 197. doi: 10.1007/s10457-008-9169-7

Nyaga, J., Muthuri, C. W., Barrios, E., Öborn, I., & Sinclair, F. L. (2019). Enhancing maize productivity in agroforestry systems through managing competition: lessons from smallholders’ farms, Rift valley, Kenya. *Agroforestry Systems, 93*(2), 715-730. doi: 10.1007/s10457-017-0169-3

O'Grady, A. P., Eamus, D., & Hutley, L. B. (1999). Transpiration increases during the dry season: patterns of tree water use in eucalypt open-forests of northern Australia. *Tree Physiology, 19*(9), 591-597. doi: 10.1093/treephys/19.9.591

Omondi, S. F., Odee, D. W., Ongamo, G. O., Kanya, J. I., & Khasa, D. P. (2016). Synchrony in Leafing, Flowering, and Fruiting Phenology of<i> Senegalia senegal</i> within Lake Baringo Woodland, Kenya: Implication for Conservation and Tree Improvement. *International Journal of Forestry Research, 2016*, 6904834. doi: 10.1155/2016/6904834

Phillips, N. G., Ryan, M. G., Bond, B. J., McDowell, N. G., Hinckley, T. M., & Čermák, J. (2003). Reliance on stored water increases with tree size in three species in the Pacific Northwest. *Tree Physiology, 23*(4), 237-245. doi: 10.1093/treephys/23.4.237

Rahn, E., Liebig, T., Ghazoul, J., van Asten, P., Läderach, P., Vaast, P., . . . Jassogne, L. (2018). Opportunities for sustainable intensification of coffee agro-ecosystems along an altitudinal gradient on Mt. Elgon, Uganda. *Agriculture, Ecosystems and Environment, 263*, 31-40. doi: 10.1016/j.agee.2018.04.019

Ren, R., Liu, G., Wen, M., Horton, R., Li, B., & Si, B. (2017). The effects of probe misalignment on sap flux density measurements and in situ probe spacing correction methods. *Agricultural and Forest Meteorology, 232*, 176-185. doi: https://doi.org/10.1016/j.agrformet.2016.08.009

Sarmiento-Soler, A., Vaast, P., Hoffmann, M. P., Rötter, R. P., Jassogne, L., van Asten, P. J. A., & Graefe, S. (2019). Water use of Coffea arabica in open versus shaded systems under smallholder’s farm conditions in Eastern Uganda. *Agricultural and Forest Meteorology, 266-267*, 231-242. doi: 10.1016/j.agrformet.2018.12.006

Scholz, F. G., Bucci, S. J., Goldstein, G., Moreira, M. Z., Meinzer, F. C., Domec, J. C., . . . Miralles-Wilhelm, F. (2008). Biophysical and Life-History Determinants of Hydraulic Lift in Neotropical Savanna Trees. *Functional Ecology, 22*(5), 773-786. doi: 10.1111/j.1365-2435.2008.01452.x

Siriri, D., Wilson, J., Coe, R., Tenywa, M., Bekunda, M., Ong, C., & Black, C. (2013). Trees improve water storage and reduce soil evaporation in agroforestry systems on bench terraces in SW Uganda. *Agroforestry Systems, 87*(1), 45-58. doi: 10.1007/s10457-012-9520-x

Smith, D. M., Jackson, N. A., Roberts, J. M., & Ong, C. K. (1999). Reverse flow of sap in tree roots and downward siphoning of water by Grevillea robusta. *Functional Ecology, 13*(2), 256-264. doi: 10.1046/j.1365-2435.1999.00315.x

Taugourdeau, S., le Maire, G., Avelino, J., Jones, J. R., Ramirez, L. G., Jara Quesada, M., . . . Roupsard, O. (2014). Leaf area index as an indicator of ecosystem services and management practices: An application for coffee agroforestry. Agriculture, Ecosystems & Environment, 192, 19-37. doi: https://doi.org/10.1016/j.agee.2014.03.042

UCDA. (2017). Annual report (2016-2017) (Vol. 26, pp. 92). Kampala, Uganda: Uganda Coffee Development Authority.

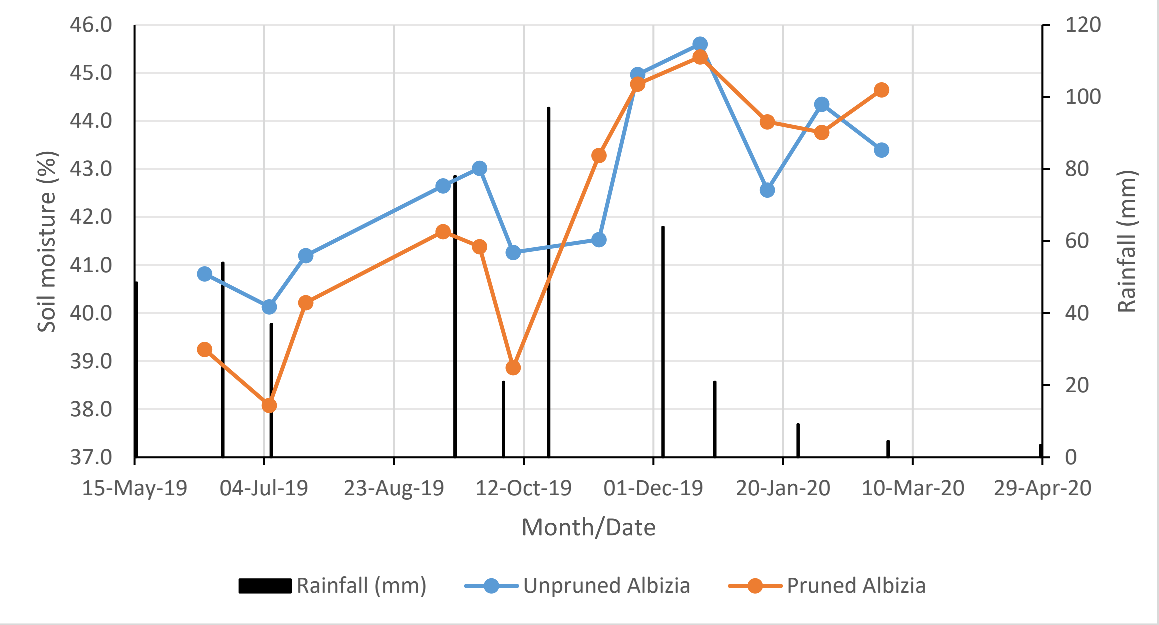
UCDA. (2018). Annual report (2017-2018) (Vol. 27, pp. 74). Kampala, Uganda: Uganda Coffee Development Authority.

Supplementary Table 1 Initial and final scenarios of the different soil nutrients.

Management option	PH	Total N (%)	Total P (ppm)	CEC (cmoles/kg)	Major elements (cmoles/kg)				Trace elements - ppm (mg/kg)				BS (%)
					K	Ca	Mg	Na	Cu	Zn	Fe	Mn	
Initial scenario													
Open field (Albizia site)	5.8	0.1	5.6	49.2	0.9	5.3	3.0	0.1	4.3	7.8	102.8	27.0	19.0
Open field (Cordia site)	6.1	0.1	35.6	30.2	0.9	5.3	3.0	0.1	3.3	7.8	123.6	32.0	29.0
Unshaded coffee (Albizia site)	5.8	0.1	9.2	65.2	0.9	5.2	2.1	0.1	2.1	7.2	126.9	26.7	13.3
Unshaded coffee (Cordia site)	6.2	0.1	32.4	25.2	0.6	5.6	2.1	0.1	2.2	7.0	117.9	36.7	23.3
Unpruned Albizia	6.0	0.2	9.1	52.1	1.3	5.6	1.9	0.1	3.6	6.9	110.0	26.2	17.3
Pruned Albizia	6.1	0.2	9.4	47.7	1.1	6.0	2.5	0.1	2.6	8.1	159.9	63.3	20.7
Unpruned Cordia	6.2	0.2	46.0	29.5	0.7	5.6	1.9	0.1	1.6	7.0	117.8	32.2	28.0
Pruned Cordia	6.0	0.1	46.4	27.3	0.6	5.6	1.7	0.1	2.2	8.5	133.0	35.5	29.3
Final scenario													
Open field (Albizia site)	6.2	0.1	5.3	46.4	0.6	8.8	1.9	0.1	2.2	19.7	124.9	21.5	47.3
Open field (Cordia site)	6.2	0.2	32.6	30.2	0.9	5.3	3.0	0.1	3.3	7.8	123.6	32.0	29.0
Unshaded coffee (Albizia site)	6.1	0.1	5.7	43.1	0.6	3.1	2.6	0.2	2.1	18.4	101.1	29.1	39.1
Unshaded coffee (Cordia site)	6.3	0.1	33.4	23.2	0.8	5.6	2.1	0.1	2.2	17.0	107.9	26.7	23.3
Unpruned Albizia	6.4	0.2	7.0	39.7	0.7	8.4	2.2	0.2	1.1	22.0	112.6	36.7	44.6
Pruned Albizia	6.4	0.2	7.4	39.1	1.0	6.4	2.8	0.2	0.9	15.5	105.1	39.4	43.2
Unpruned Cordia	6.3	0.2	35.2	27.2	0.9	9.8	2.1	0.2	1.5	14.3	185.3	33.6	49.2
Pruned Cordia	6.2	0.2	33.8	21.7	0.7	8.7	1.3	0.2	0.7	15.5	168.9	25.1	52.2

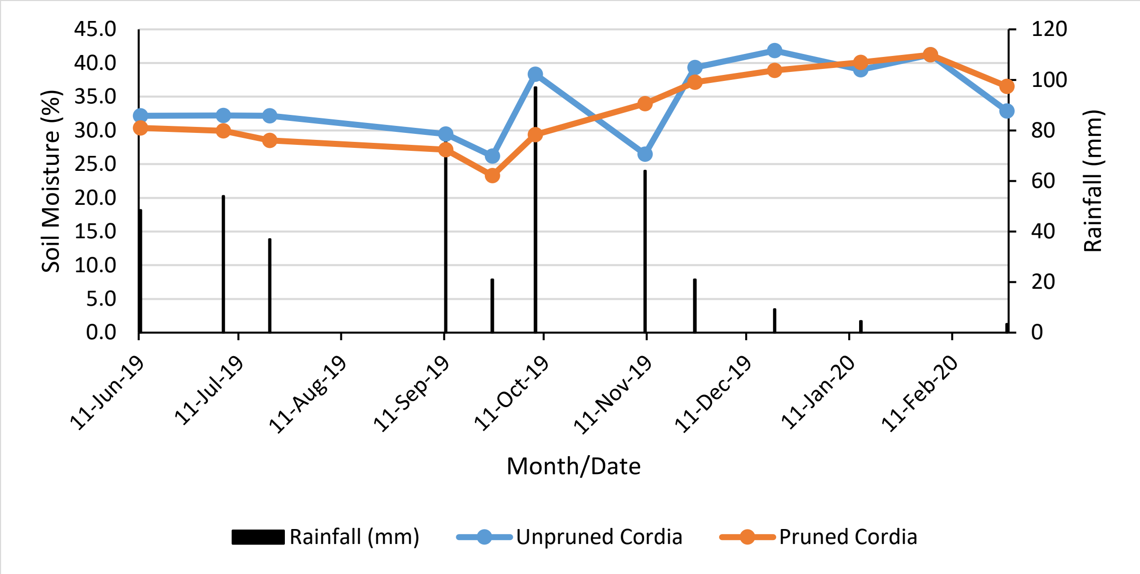
Soil moisture

The initial soil moisture data is missing due to lack of equipment, which were later procured and installed after 11 months of the experiment. We therefore have soil moisture data covering the last 9 months of the experiment. The supplementary figures 1 and 2 show that pruning may have been responsible for the higher soil moisture content in sites with pruned trees after October 2019. This is an indication that canopy pruning led to a recharge in the soil, though this does not occur until after the third pruning regime.



Supplementary Fig. 1: Average soil moisture under pruned and unpruned Albizia sites

The impact of pruning on soil moisture appears to occur with consistent canopy pruning of trees, a practice that farmers need to embrace to enable associated crops to benefit from the soil water reserves resulting from canopy pruning of agroforestry trees.



Supplementary Fig. 2: Average soil moisture under pruned and unpruned Cordia sites

Chapter 5: Impact of tree management on coffee and common bean productivity in smallholder agroforestry systems of Uganda

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5.1 Statement of Authorship

Title of Paper	**Impact of tree management on coffee and common bean productivity in smallholder agroforestry systems of Uganda**
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Principal Author

Name of Principal Author (Candidate)	Joel Buyinza		
Contribution to the Paper	Field experimental design and set up, data collection and analysis, interpretation of findngs, writing manuscript, acted as the first and corresponding author		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	26/05/2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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5.2 Abstract

Agroforestry tree management is essential for minimizing negative tree shading effects in intensive smallholder farming systems. In this study, it was hypothesize that tree canopy pruning would positively influence the relative growth performance and productivity of coffee (*Coffea arabica* L.) and common beans (*Phaseolus vulgaris* L.) growing under *Cordia africana* and *Albizia coriaria* trees. The trees were subjected to a 50% pruning regime at a 6-month interval over a period of 20 months (July 2018 - February 2020), and common beans were introduced following local planting seasons. Yields of parchment coffee were highest under pruned Albizia (949 kg/ha), followed by coffee under unpruned Albizia (792kg/ha*)*. Unshaded coffee produced the least yield at 402 kg/ha and 422 kg/ha in the Albizia and Cordia sites respectively. The highest common beans yields (708 and 688 kg/ha) were obtained when planted in open field sites, followed by those grown under unshaded coffee sites. Beans that were planted under unpruned Cordia gave the least yield of 420 kg/ha. Unlike coffee, there was a significant variation in yield of common beans across the different management options ($P<0.05$). The low yields from coffee and common beans under unpruned trees may have resulted from below-ground and above-ground competition consistently outweighing the benefits of shade. Assessment of the different coffee and common beans yield components and their interactions provided practical information on management interventions that could potentially improve coffee and common beans yields. The results of this study show that agroforestry tree canopy pruning is an important on-farm management decision for controlling competition in coffee-bean agroforestry systems and subsequently increasing crop yields, while prolonging the period of intercropping in such intensive farming systems.

Key words: *pruning, common beans, coffee, agroforestry, yield components*

5.3 Introduction

Millions of farmers in developing countries are struggling to feed their families because of land degradation and land use pressures (Winterbottom et al., 2013). Eighty percent of the chronically hungry in Africa are smallholder farmers and their hunger is related to low crop yields and degradation of water resources (Descheemaeker et al., 2013). Land use pressures arising from increasing human population in sub-Saharan Africa dictate a shift to intensive agricultural farming systems (Sebatta et al., 2019), such as agroforestry, to optimize benefits from the biological interactions created when trees are deliberately combined with agricultural crops (Brown et al., 2018; Pinho et al., 2012). While agroforestry is one promising option for sustainable use of land (Das et al., 2020; Laudares et al., 2017; Ong & Swallow, 2003), competition for growth resources in such intensive farming systems is inevitable, as tree and crop roots and canopies occupy the same space and overlapping growth cycles.

There is a growing societal desire for attaining agricultural sustainability (Nair & Toth, 2016; Santiago-Freijanes et al., 2018) rather than simply increased production. For agroforestry, sustainability refers to the concept that production can occur on a given land management unit on an indefinite basis. For example, while use of inorganic fertilizers can increase production over a short period of time, it is regarded as unsustainable given the short period of fertilizer efficiency, and the negative land and environmental effects associated with use of inorganic fertilizers. To achieve agricultural sustainability, researchers need to develop innovative technologies aimed at adaptive management of farming systems. Sustainable intensification of farming systems through agroforestry has been suggested to improve farmers' livelihoods and facilitate adaptation of coffee production to climate change (Rahn et al., 2018). Use of fertilizer or leguminous trees in farming systems has been reported to enhance agricultural sustainability (Nair & Toth, 2016; Nyong & Martin, 2019). Global food production has, to some extent, been dependent upon biological nitrogen (N) fixation (about 100 million tons per year globally) in agroecosystem (Jhariya et al., 2018; Herridge et al., 2008). While trees provide a cheap alternative for sustaining agricultural production, most of the smallholder farmers in the Mt. Elgon region of Uganda with trees on their farms have failed to realize the co-benefits due to poor management of the tree component.

Tree canopy pruning of live branches is usually done to enhance production of high-value knot-free timber in plantation trees (Alcorn et al., 2013). However, it is also one practical way of controlling competition for growth resources in an intensive farming system (Jackson et al., 2000) such as coffee agro-ecosystems reported in this study. The Mt. Elgon region of Uganda has three coffee agro-ecosystems practiced by smallholder farmers: open canopy coffee systems, coffee-banana intercropping, and coffee-shade tree systems (Rahn et al., 2018; Sarmiento-Soler et al., 2020). The focus of this study was the coffee-tree system, where farmers usually introduce the common bean (*Phaseolus vulgaris* L.) crop under the same land management unit. Failure of farmers to adopt shade tree canopy pruning as a deliberate agricultural land management practice has negatively affected crop productivity and hindered development of appropriate pruning regimes for agroforestry trees. While there have been commendable efforts in promoting shaded coffee in the region (Bukomeko et al., 2017; Gram et al., 2018; UCDA, 2017, 2018), minimal effort has been put into the management of shade trees that would maximize benefits and minimize the associated trade-offs.

The aim of this study was therefore to assess the impact of tree canopy pruning of *Cordia africana* Lam. and *Albizia coriaria* Welw. ex Oliv (hereafter simply referred to as Cordia and Albizia, respectively) on the relative performance of coffee - common bean agroforestry systems. These semi-deciduous tree species are commonly integrated in coffee plantations occurring in more than 25% of the agroforestry systems in this region (Rahn et al., 2018). We contend that tree canopy pruning would minimize the competitive effects of Cordia and Albizia trees on coffee and common beans, and hypothesized that tree canopy pruning would positively influence the relative growth performance and productivity of agricultural crops growing under such systems.

5.4 Materials and methods

5.4.1 Study area

The study was conducted in Manafwa district located in Eastern Uganda, bordering the Republic of Kenya in the East, Bududa district to the North, Mbale district to the West and Tororo to the Southwest. In terms of climate, the average annual rainfall is 1500 mm, with two peak rainy seasons that occur in the months of April-May and September-November. A pronounced dry period occurs from December to February, with a mean annual temperature of 23 ^{o}C. The topography of the slope is characterized by two escarpments that naturally separate three altitude classes of <1400 m.a.s.l, 1400–1700 m.a.s.l, and >1700 m.a.s.l within the inhabited area of the mountain (Rahn et al., 2018; Sarmiento-Soler et al., 2020). Local farming communities live between 1000 m.a.s.l. at the foothill and 2200 m.a.s.l., close to the protected Mt. Elgon National Park. Coffee (*Coffea arabica* L.) is the main cash crop and is traditionally grown in combination with bananas, common beans, maize and multi-purpose shade-trees.

The field experiment was conducted in two separate farms, approximately 2 km apart; each having either Cordia or Albizia mature trees integrated in Coffee agroforestry systems. The Albizia experimental site was located at N00^{0}56.007' and E034^{0}16.605' at 1196 metres above sea level (m.a.s.l) while the Cordia site was at N00^{0}55.582' and E034^{0}15.244' at 1233m.a.s.l in Butta Sub County, Manafwa district. The study sites fall within the lower altitude class (<1400 m.a.s.l) on the foothills of Mt. Elgon, following a recent altitudinal classification of the region by Rhan et al., 2018.

5.4.2 Components under study

Arabica coffee

Uganda's smallholder farmers contribute about 90% of the country's coffee (Gram et al., 2018). While Uganda grows both arabica (accounting for 10-15%) and robusta coffee, the prices received for arabica coffee on the international market are greater than for robusta (Van Asten et al., 2011). Coffee is shade tolerant and traditionally grown under shade trees in complex agroforestry systems (Gram et al., 2018). While competition for water and nutrients, and pest/disease incidence are central issues in shaded coffee (Ayalew, 2018), unshaded plantations generally require higher levels of external inputs to maximize yield. Many smallholder farmers have intensified coffee management by eliminating shade trees and increasing their agrochemical input to increase coffee productivity. Arabica coffee was selected for this study because it is the predominant coffee variety grown in the Mt. Elgon region.

Common beans

Common bean (*Phaseolus vulgaris* L.) is an important rotation crop and intercrop, important for food security, especially in Sub-Saharan Africa (Lupwayi et al., 2011; Namugwanya et al., 2018). In Uganda, per capita consumption of common beans averages about 9.8 kg annually contributing, on average, 12% of total protein, about 4% calorie intake, selected minerals and vitamins consumed per person (Ronner et al., 2018). The crop is ranked fifth behind banana, cassava, cattle meat, and milk in terms of value of output (Sibiko et al., 2013). The majority of Ugandan farming households grow beans twice a year, during March to June and September to December cropping seasons. However, the crop has registered low productivity with a yield gap of about 75% below its potential in Uganda (Goettsch et al., 2016), with the lowest yields (200 - 250 kg/ha) reported in Eastern Uganda (FAO et al., 2019). The low yields have been attributed to poor agronomic practices, low soil infertility, lack of improved cultivars, moisture stress, weed competition, and damage caused by pests and diseases (Sinclair & Vadez, 2012). Therefore, there is need for farmers to reverse soil nutrient depletion through better management of their soils and cropping systems (Bekunda et al., 2004). This is because cultivable land continues to be scarce in the Mt. Elgon region of Uganda (Vedeld et al., 2016), as the country's forest cover continues to decline at an annual rate of 200,000 ha (FLROA-Uganda, 2016).

Albizia coriaria and *Cordia africana* agroforestry trees

Albizia coriaria Welw. ex Oliv. (locally called mugavu in Luganda and Swahili, and kumoluko in Lugisu) is a deciduous nitrogen fixing tree that belongs to the family Fabaceae (Katende et al., 1995). It is commonly found in homesteads and protected in fields. The absence of Albizia in closed canopy rainforests is largely the result of its high light requirements (Janani et al., 2014). The tree can be established through direct sowing the seeds, planting seedlings and from wildings. A related study in Uganda identified the species as being multipurpose and attributed to it fourteen different products and services (Tabuti & Mugula, 2007). Albizia is one of the most common tree species used in permanent indigenous agroforestry systems of Uganda. It was chosen for this project because it is a popular tree already widely grown by farmers in Mt. Elgon region and for its ability to fix nitrogen.

Cordia africana Lam. (commonly known as large-leaved cordia, locally called mukebu in Luganda and Chichikiri in Lugishu) belongs to the *Boraginaceae* family. In Uganda, it has been reported to grow well in moist forests, especially forest edges, riverine gallery forest, wooded grassland in Elgon, Ankole and Kigezi at altitudes ranging between 1200-2000 m above sea level (Katende et al., 1995). The mature fruits of Cordia have a sweet edible pulp and the flowers have been reported to yield plenty of nectar (Mbere et al., 2020). Cordia is planted as a shade tree in coffee plantations, as it provides shade for crops and leaf fall in the dry season, making good mulch (Alemayehu et al., 2016). A recent study by Gram *et al.* (2017), based on local knowledge, reported that Cordia was exceptionally well ranked by farmers as an important agroforestry tree species in coffee plantations in Eastern Uganda, irrespective of altitude. This tree species was selected for this study because of its unique unsynchronized deciduous leafing phenology and it has also been widely integrated in coffee systems in Mt. Elgon region.

5.4.3 Soil characterization of study sites

Soil sampling was done in the study sites using a soil auger at the beginning of the experiment in July 2018 (to obtain baseline scenario) and at the end of the experiment in January 2020. This was done to establish the status of the study sites and any differences in soil physical and chemical properties that may have resulted from the tree management interventions of the study. The soil sampling protocol was such that soil was collected from six sites: under coffee growing below pruned Albizia, coffee below unpruned Albizia, coffee below pruned Cordia, coffee below unpruned Cordia, unshaded coffee and in the open field with neither coffee nor trees. At each sampling spot (in quadrants), soil samples were collected at 3 depths, i.e., 0-15 cm, 15-30 cm and 30-45 cm. Soil collected from the quadrants at each depth was mixed well and a sample (about 500 g) collected and kept in a well-labelled plastic bag. The samples were taken to the Makerere University soil analytical laboratory for analysis. Composite soil samples obtained from the field were analysed for organic matter content, soil texture, and major and trace elements following procedures by (Okalebo et al., 2002).

Unshaded coffee sites generally had the least organic matter content (Table 1). At baseline, both Cordia and Albizia sites had relatively the same organic matter content ranging from 1.8-2.8%. However, there was a relative increase in organic matter content following pruning of

Cordia and Albizia, more predominantly under pruned Albizia trees, where organic matter above 4% was recorded.

Table 1: Organic matter content, soil texture range and textural class of the experimental sites

Experimental site	Organic matter		Soil texture ranges (%)			Soil textural class*
	Baseline	Endline	Sand	Clay	Silt	
Open field (Albizia site)	2.3±0.5	2.4±0.1	45 - 46	30 - 31	23 - 25	Sandy clay
Open field (Cordia site)	2.3±0.4	2.4±0.3	59 - 60	18 - 19	22 - 23	Sandy loam
Unshaded Coffee (Albizia site)	1.8±0.3	2.1±0.1	33 - 35	45 - 48	19 - 20	Clay loam
Unshaded Coffee (Cordia site)	2.3±0.2	2.3±0.4	61 - 63	14 - 16	22 - 23	Sandy loam
Unpruned Albizia site (with coffee)	2.6±0.3	3.2±0.4	30 - 41	32 - 47	23 - 27	Clay loam
Pruned Albizia site (with coffee)	2.7±0.2	4.1±0.1	39 - 45	28 - 48	19 - 27	Clay loam
Unpruned Cordia site (with coffee)	2.8±0.1	2.8±0.4	61 - 64	12 - 20	19 - 24	Sandy loam
Pruned Cordia site (with coffee)	2.4±0.1	3.3±0.3	62 - 63	11 - 18	19 - 27	Sandy loam

** The USDA textural triangle (https://esdac.jrc.ec.europa.eu/public_path/shared_folder/projects/DIS4ME/indicator_descriptions/soil_texture.htm)*

In terms of soil texture, the Cordia site generally had a high composition of sand, exhibiting a sandy loam textural class (Table 1). However, unlike the open field in the Albizia site which had sandy clay soils, the rest of the Albizia sites had clay loam soil texture. Total phosphorus was highest in the Cordia site ranging between 32-46 ppm and as low as 5-9 ppm in the Albizia sites (Supplementary Table 1). Conversely, the Cordia site had the least potassium (K), magnesium (Mg) and sodium (Na). However, available phosphorus (Total P) and total nitrogen (N) were reported to be below the optimum required level, while K is optimally available in the Mt. Elgon region (UCDA, 2017). The highest base saturation (BS) was found in the Cordia site (28-52%). Other soil characteristics are summarised in Supplementary Table 1.

5.4.4 Research design, instrumentation and installation

Pruning of selected trees

In each site, 2 trees were pruned while the other 2 remained unpruned. This study adopted the 50% pruning regime. To attain a 50% canopy-pruning regime, all secondary branches on the tree under investigation were counted and divided by two. Thereafter, branches to be pruned were randomly selected, labelled by making slit cuts and later pruned using a three-cut procedure (Bedker et al., 2012). The three-cut procedure is preferred because it minimizes splitting of the branch, and damage during pruning. The three-cut procedure was conducted as follows: first, at 30 cm from the trunk, cut halfway through the branch from the underside. Second, about 3 cm past the first cut, cut through the branch from the top side until the branch falls away. The weight of the branch would then cause it to break between the two cuts. Lastly, the resulting stub was then cut back to the collar of the branch. Tree canopy pruning was done 3 times at an approximate interval of 6 months. The first pruning was done in October 2018, followed by the second and third pruning in April and November 2019 respectively.

Coffee yield and yield components assessment

Coffee yields were assessed from 20 randomly selected and tagged coffee trees growing under five treatments including (i) coffee growing under pruned Cordia, (ii) coffee under unpruned Cordia, (iii) coffee under pruned Albizia, (iv) coffee under unpruned Albizia and (v) unshaded or open sun coffee. Yield assessments were done for three consecutive coffee harvesting seasons (August - October 2018, February-April 2019 and August-October 2019) by handpicking ripe coffee cherries (when bright red in colour) and processing them using the wet process described by (Joët et al., 2010). Ripe cherries were handpicked 3 to 5 times from each coffee tree in a season until all the cherries had been completely harvested, over a period of 2 to 3 months. For each coffee plant yield, the fresh weight of the harvested coffee bean (before pulping), fresh weight after pulping and washing were measured. The dry weight of the parchment was determined at 12% moisture content using a digital weighing scale. Parchment are coffee beans with endocarp, obtained after wet-processing of ripe coffee cherries using a pulping machine. Coffee yield per hectare (kg ha^{-1}) is a product of coffee yield per tree (kg $tree^{-1}$) and density of coffee trees per hectare (number of coffee trees ha^{-1}).

Other parameters assessed were coffee tree diameter, height, age, number of stems per bush, branches per coffee tree, number of berry clusters per branch (assessed from 5 randomly selected branches) and number of berries per cluster (assessed from 5 randomly selected berry clusters) documented from each of the tagged coffee trees.

Common beans variety selection and planting

Selection of the common bean variety was based on abundance and preference of the existing varieties, obtained through a rapid survey of common bean abundance and farmer preference by sampling 15 randomly selected household heads in Butta Sub County (*See Table 2*). While common bean variety abundance was influenced by location, preference was mainly influenced by taste, yield and ease of cooking. The Kanyebwa (NABE 15), a mottled pink variety (Sebuwufu et al., 2015), was subsequently selected and planted due to the high relative abundance and preference among local farmers. It has also been classified as one of the multi-stress tolerant varieties in Uganda (FAO/TECA, 2017). Nonetheless, Kanyebwa has been reported to be highly susceptible to a bean fly (*Ophiomyia spp.*) attack that has threatened bean production in East Africa (Ssekandi et al., 2016). However, in areas where the pest is highly prevalent, farmers have been able control the bean stem maggot damage by planting Kanyebwa together with resistant varieties in a systematic random arrangement.

In this study, common beans were planted in the two study sites at a spacing of 30 x 30 cm at the beginning of each of the annual rainfall seasons in August 2018 (season 1), April 2019 (season 2) and August 2019 (season 3). Beans were also planted in additional sites with unshaded coffee and an open field approximately 50 m from each of the Cordia and Albizia study sites. The seeds were locally sourced and apart from sorting to separate Kanyebwa from other varieties, no pre-treatment was done to the beans prior to planting. After germination, data on bean height, number of leaves, flowers and pods were collected weekly until the day of harvest. A single weeding regime was applied to the bean crop as commonly done by the farming communities.

Table 2: Some of the existing common beans varieties among the Mt. Elgon communities

Bean variety	Local description	Abundance[1]	Preference[2]	Remarks
Nambale	Long	2	5	Easy to cook, with a tasty rich rea stew when cooked
Obweru	White and small	4	3	High yielding but easily affected by too much rain
Kanyebwa	Cream with red stripes	1	1	High yielding, grows at any altitude, tasty, short time to cook and swells on cooking
Yellow beans	Large	5	2	High yielding but yield is easily affected by too much rain
Black beans	Small and long	5	6	Has good taste
Lwakhakha	Faba beans	3	7	High yielding but location specific
Kachuma	Small & round red bean	7	3	Easy to cook, but low yielding

[1]Abundance was generally influenced by area/location, where 1=most abundant variety; [2]Preference was mainly based on taste, yield and ease to cook, where 1=most preferred variety

Common bean yields and yield components assessment

Common bean growth performance parameters including height, number of leaves and flowers per plant were assessed fortnightly until maturity. At the end of each physiological maturity period (approximately 3 months after planting) during the planting season, bean plants were harvested from each site by hand from 5 randomly sampled plots measuring 2 x 2 metres. The number of pods was determined by counting pods on all the harvested plants in each treatment replicate. A pod was counted if it contained at least one mature seed. The pods were threshed in a customary way with sticks after sun drying. Grain yield per treatment was estimated with a digital weighing balance at 13% moisture content, and then extrapolated to yield per hectare.

The moisture content was determined using a moisture meter (Steinlite SL95, Atchison, Kansas, USA).

Soil moisture measurement

Soil moisture was assessed using an MPKit (ICT International, Australia), a portable soil moisture sensor for rapid sampling of Volumetric Soil Water Content (VSW%). To allow routine measurement of soil moisture at the same location and depth over a period of time, a series of holes were augured to depths of 20 cm, 40 cm, 60 cm, 80 cm and 100 cm. A set of 50 mm PVC tubes (representing the 5 depths) were installed 1.5 m from the tree, under each experimental tree (4 Cordia and 4 Albizia trees), in the unshaded coffee and in the open field. The MP406 was then inserted into each PVC tube to the required depth of measurement and the corresponding soil moisture content read out on the display of the MPM160 meter (Tang et al., 2006). The readings were taken fortnightly and automatically saved for later recall and download to a computer (Liu et al., 2014). However, assessment of soil moisture began in May 2019, 10 months into the experiment, due to delays in procuring the MPKit from Australia.

5.4.5 Data analysis

Data on coffee and common bean yield components from the two experimental sites were summarised (descriptive statistics including mean, maximum, minimum values) and an analysis of variance (ANOVA) to assess any differences in yield components across the different management options was conducted. Yield data from coffee and common beans over 3 coffee harvesting seasons and 3 planting seasons for common beans in the two experimental sites. A single factor one-way analysis of variance was conducted to assess any differences in yield across the different treatment options. A correlation test between yield components and management options was performed to obtain Pearson correlation coefficients.

5.5 Results

5.5.1 Impact of pruning Cordia africana and Albizia coriaria trees on coffee yield

The coffee yield results show relatively higher yields from the Albizia site than the Cordia site (Figure 1). In terms of seasons, season 2 coffee yields were generally low across all sites and management options, with the highest yields obtained from unshaded coffee in the Albizia site. This is mainly because season 2 (February-April) is a 'fly crop' season (where coffee yields are usually minimal) while season 1 (August - October 2018) and season 3 (August-October 2019) represent the main annual coffee harvesting season. At both sites the highest coffee yields were obtained in the third season from coffee growing under pruned Albizia (1418 kg/ha) and under pruned Cordia (1091 kg/ha). Deliberate and consistent canopy tree pruning may have contributed to the increase in coffee yields as pruning may have reduced competition for light and other growth resources. However, the lowest coffee yields were obtained from unshaded coffee in both sites across the three seasons.

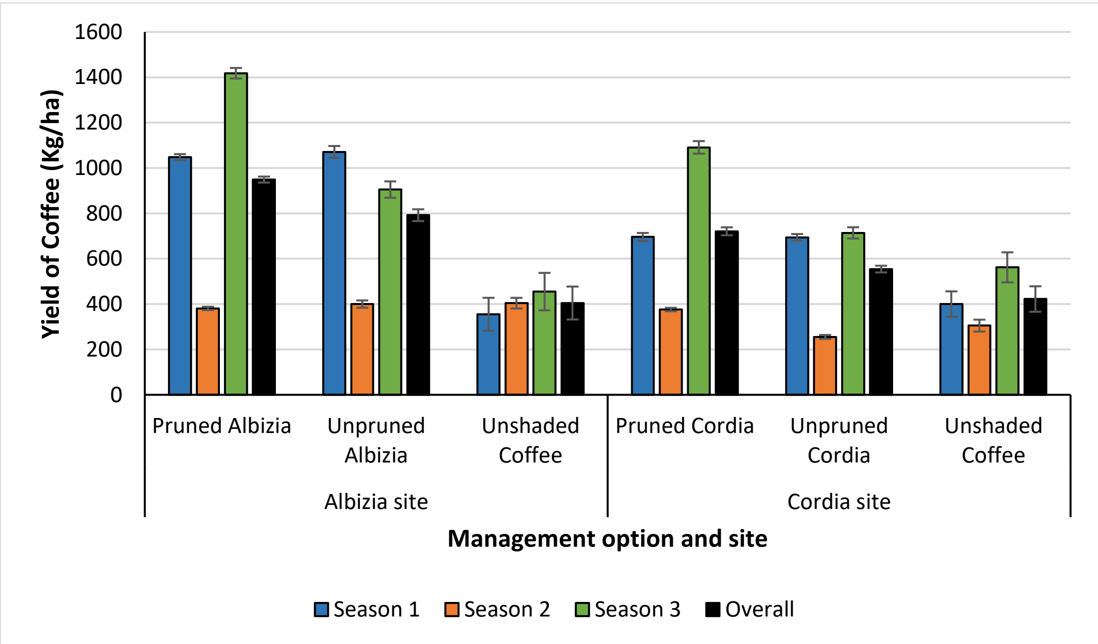


Figure 1: Average coffee yields from garden with pruned and unpruned trees and unshaded coffee across the 3 harvesting seasons

Overall, coffee under pruned Albizia gave the highest yield (949 kg/ha) of parchment coffee, followed by coffee under unpruned Albizia (Figure 1). Unshaded coffee produced the lowest yield at 405 kg/ha and 422 kg/ha in the Albizia and Cordia site, respectively. Although there was a 20 and 30% increase in coffee yield resulting from pruning Albizia and Cordia trees, there was no statistical significant variation in coffee yield across the different tree management options (Supplementary Table 2).

5.5.2 Coffee yield components under different management options

The Cordia site generally had coffee with more stems per bush than coffee in the Albizia site (Table 3). However, coffee growing under Albizia and Cordia trees (both pruned and unpruned) had the same number of stems per bush. The study results also show that unshaded coffee in both sites had the highest number of branches, with a maximum and minimum number of 368 and 44 branches registered respectively. While there was no significant difference in number of berry clusters per branch, the number of berries per cluster differed significantly with management ($p<0.05$). Coffee growing under pruned Albizia registered the highest number of berries per cluster.

Table 3: Coffee tree yield components in the different management options

Variables	Albizia site			Cordia site			Overall		*P* - value
	Coffee under unpruned Albizia	Coffee under pruned Albizia	Unshaded coffee	Coffee under unpruned Cordia	Coffee under pruned Cordia	Unshaded coffee	Max	Min	
Coffee yield components									
No. of stems per bush	1.3	1.3	2.8	2.6	2.6	4.9	7	1	0.000*
No. of branches per coffee tree	89.1	84.6	123.1	101.5	115.2	250.3	368	44	0.001*
No. of berry clusters per branch	9.3	9.2	10.3	7.9	8.7	10.1	13	1	0.208[ns]
No. of berries per cluster	8.4	9.6	8.2	7.0	6.7	8.9	18	0	0.005*
Other coffee tree parameters									
Coffee tree diameter (cm)[a]	4.5	4.5	4.7	3.7	3.7	4.2	4.9	3.2	0.000*
Coffee tree height (m)	2.4	2.4	2.1	2.6	2.6	2.2	2.8	1.9	0.001*
Age of coffee trees (years)	5	5	5	6	6	6	6	5	0.070[ns]

*[a]Diameter measured at 30cm above ground; Anova significant at the level of P < 0.01 are indicate by *; the non-significant are labelled as ns, df=5*

Other coffee tree parameters assessed were coffee diameter (measured at 30 cm above ground), height and age, which are summarised in Table 1. While coffee trees from the Albizia site were generally larger in diameter than those in the Cordia site, they were shorter and younger. There was also a significant difference in coffee tree diameter and height across the treatment options ($p<0.05$) and the largest coffee tree diameters were registered by unshaded coffee.

5.5.3 Correlation between management, coffee yield and yield components

There was a significant negative correlation between management and season 3 coffee yield as well as the overall yield in both the Albizia and Cordia sites (Table 4). Management was positively correlated with number coffee branches in the Albizia site ($p<0.05$). However, season 1 yields negatively correlated with number of coffee stems per bush and number of branches per coffee stem. Conversely, season 1 yields positively correlated with the number of berry clusters per branch and number of berries per cluster in the Albizia site, but negatively correlated with the same in the Cordia site. While the number of berries per cluster were positively correlated with season 1 and the overall yield in the Albizia site (p<0.05), there was no correlation with these yield components in the Cordia site.

Table 4: Correlation between coffee yield components, management option and yield in the study sites

Coffee yield components		Albizia site		Cordia site	
		Estimate	**Sig.**	**Estimate**	**Sig.**
Management option	Season 1 yield	-0.852	ns	-0.869	ns
Management option	Season 2 yield	0.836	ns	-0.584	ns
Management option	Season 3 yield	-0.998	*	-0.971	*
Management option	Overall yield	-0.971	*	-0.998	*
Management option	No. of coffee stems/bush	0.708	ns	0.642	ns
Management option	No. of coffee branches	0.915	*	0.821	ns
Management option	No. of berry clusters/ branch	-0.843	ns	0.629	ns
Management option	No. of berries/ cluster	-0.986	*	0.922	*
No. of coffee stems/bush	Season 1 yield	-0.973	*	-0.937	*
No. of coffee stems/bush	Season 2 yield	0.414	ns	0.247	ns
No. of coffee stems/bush	Season 3 yield	-0.681	ns	-0.441	ns
No. of coffee stems/bush	Overall yield	-0.855	ns	-0.590	ns
No. of coffee branches	Season 1 yield	-0.991	*	-0.997	*
No. of coffee branches	Season 2 yield	0.713	ns	-0.160	ns
No. of coffee branches	Season 3 yield	-0.899	*	-0.662	ns
No. of coffee branches	Overall yield	-0.984	*	-0.781	ns
No. of berry clusters/ branch	Season 1 yield	0.999	*	-0.931	*
No. of berry clusters/ branch	Season 2 yield	-0.599	ns	0.264	ns
No. of berry clusters/ branch	Season 3 yield	0.822	ns	-0.425	ns
No. of berry clusters/ branch	Overall yield	0.947	*	-0.575	ns
No. of berries/ cluster	Season 1 yield	0.927	*	-0.993	*
No. of berries/ cluster	Season 2 yield	-0.864	ns	-0.224	ns
No. of berries/ cluster	Season 3 yield	0.979	*	-0.803	ns
No. of berries/ cluster	Overall yield	0.997	*	-0.894	ns

*Significant correlations (P<0.05) are indicated by * and non-significant correlations (P>0.05) are indicated by ns*

5.5.4 Yield of common beans under different management options

The Albizia site generally had higher common bean yields than the Cordia site in this study, and the highest yield was obtained from the open field (842.3 kg/ha) in the second planting season (Figure 2). While the yield of common beans growing under unpruned Albizia and Cordia trees declined in the subsequent planting seasons, the yields from beans growing under pruned trees gradually increased from the first to the third planting season. Canopy pruning may have played a role as it allowed sufficient light through the pruned canopies, accumulated organic matter from branches and leaves left on ground after pruning and allowed continuous cultivation below the pruned trees.

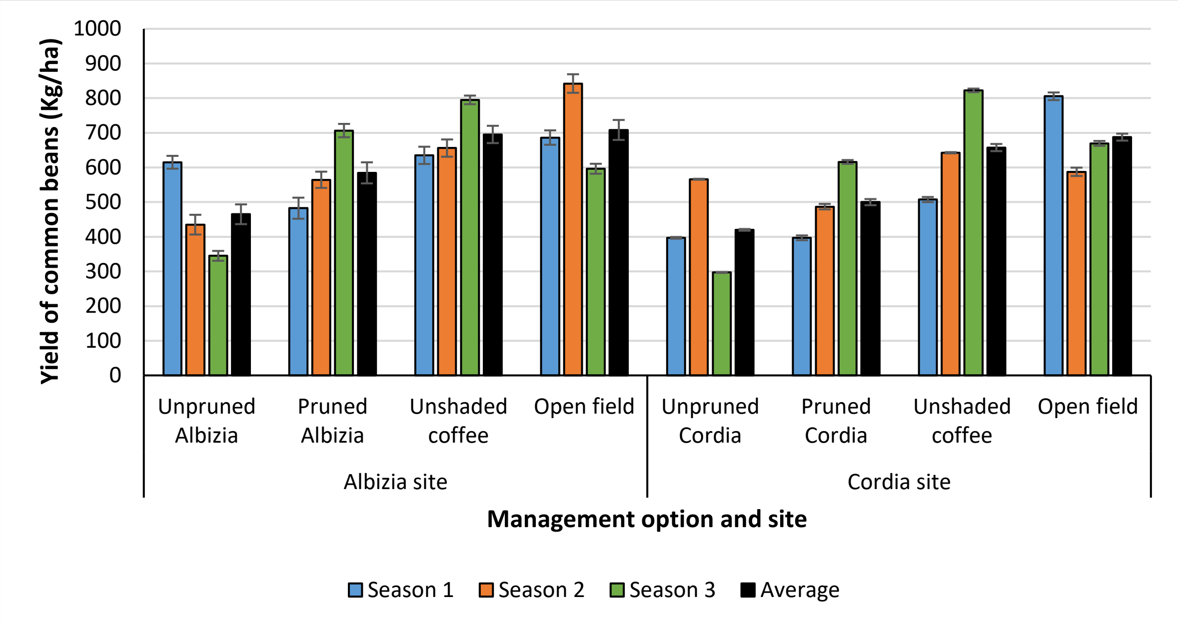


Figure 2: Yield of common beans from different management options and sites across the 3 harvesting seasons

Overall, the highest yield was obtained from common beans planted in the open fields in the Albizia (708.3 kg/ha) and Cordia (687.5 kg/ha) site, followed by those grown under unshaded coffee (Figure 2). Beans that were planted under unpruned Cordia trees gave the lowest yield of 420 kg/ha. An analysis of variance (ANOVA) in of common bean yields identified a statistical significant variation in of common bean yields based on different management options ($p<0.05$), (supplementary Table 3). However, there was a 26% and 19% yield difference that may have resulted from pruning Albizia and Cordia trees, respectively, an indication that canopy pruning might have contributed to the yield differences from beans grown under pruned and unpruned trees.

5.5.5 Common bean yield components under different management options

The tallest common bean plants were registered under unpruned Albizia trees with coffee trees and under unpruned Cordia with coffee at 34.2 cm and 32.4 cm respectively (Table 5). However, there were no significant differences in height of common beans across the management options in the two experimental sites ($p<0.05$). Common beans planted in the open field had the highest number of flowers and pods per plant. The number of flowers and pods per plant differed significantly with management options in the two experimental sites.

Table 5: Growth performance variable of common beans measured during the study

Variable	Albizia site				Cordia site				Overall		P - value
	Beans under unpruned Albizia	**Beans under pruned Albizia**	**Beans under unshaded coffee**	**Beans in open field**	**Beans under unpruned Cordia**	**Beans under pruned Cordia**	**Beans under unshaded coffee**	**Beans in open field**	**Max**	**Min**	
Height (cm)	34.2	31.3	26.3	26.0	32.4	31.5	29.4	25.7	38.5	12	0.939^{ns}
No. of leaves per plant	6.3	6.8	6.0	7.0	7.0	6.8	7.5	7.7	10	4	0.225^{ns}
No. of flowers per plant	6.5	7.3	8.6	12.0	6.8	6.3	5.8	9.3	20	3	0.003*
No. of pods per plant	5.9	6.7	6.5	10.0	6.0	6.3	5.5	8.1	20	4	0.001*

*Anova significant at the level of P < 0.01 are indicate by *; the non-significant are labelled as ns, df=7; The sites with trees also have coffee trees*

5.5.6 Correlation between management, common beans yield and yield components

Management options positively correlated with the overall yield of common beans in both experimental sites ($p<0.05$) (Table 6). However, the height of beans was negatively correlated with management options and the overall yield in the two experimental sites. Apart from the positive correlation between number of flowers per plant and season 1 yield in the Cordia site, there was no significant correlation between other yield components and yield ($p>0.05$).

Table 6: Correlation between common beans yield components, management option and yield in the study sites

Common beans yield components		**Albizia site**		**Cordia site**	
		Estimate	**Sig.**	**Estimate**	**Sig.**
Management option	Season 1 yield	0.545	ns	0.894	ns
Management option	Season 2 yield	0.990	*	0.441	ns
Management option	Season 3 yield	0.558	ns	0.774	ns
Management option	Overall yield	0.957	*	0.972	*
Management option	Height of bean plant	-0.922	*	-0.987	*
Management option	No. of leaves/plant	-0.800	ns	-0.544	ns
Management option	No. of flowers/plant	0.905	*	0.767	ns
Management option	No. of pods/plant	0.840	ns	0.627	ns
Height of bean plant	Season 1 yield	-0.487	ns	-0.932	ns
Height of bean plant	Season 2 yield	-0.859	ns	-0.329	ns
Height of bean plant	Season 3 yield	-0.748	ns	-0.685	ns
Height of bean plant	Overall yield	-0.985	*	-0.921	*
No. of leaves/plant	Season 1 yield	-0.892	ns	-0.787	ns
No. of leaves/plant	Season 2 yield	-0.828	ns	0.210	ns
No. of leaves/plant	Season 3 yield	0.026	ns	0.038	ns
No. of leaves/plant	Overall yield	-0.630	ns	-0.340	ns
No. of flowers/plant	Season 1 yield	0.802	ns	0.935	*
No. of flowers/plant	Season 2 yield	0.868	ns	0.051	ns
No. of flowers/plant	Season 3 yield	0.406	ns	0.221	ns
No. of flowers/plant	Overall yield	0.874	ns	0.607	ns
No. of pods/plant	Season 1 yield	0.720	ns	0.848	ns
No. of pods/plant	Season 2 yield	0.894	ns	-0.118	ns
No. of pods/plant	Season 3 yield	0.028	ns	0.049	ns
No. of pods/plant	Overall yield	0.649	ns	0.436	ns

*Significant correlations (P<0.05) are indicated by * and non-significant correlations (P>0.05) are indicated by ns*

5.6 Discussion

5.6.1 Yield performance of coffee under different management options

Coffee is an important cash crop that secures both smallholder farming rural livelihoods and national economies in the East African region (UCDA, 2018; Wang et al., 2015). Therefore, any interventions aimed at sustaining coffee production are valued by smallholder farmers. Integration of shade trees has been widely documented for sustainable coffee yield (Gram et al., 2017; Jezeer et al., 2018; UCDA, 2018), improved coffee quality and increased carbon storage (Jezeer & Verweij, 2015). In this current study, unshaded coffee generally produced the lowest overall coffee yield at 405 kg/ha when compared to coffee under either pruned or unpruned Cordia and Albizia trees (see Figure 1). The low yields may be attributed to soil nutrient deficiencies, high disease burdens and temperature extremes associated with open sun coffee (Ayalew, 2018). However, shade trees have been reported to address corresponding soil nutrient deficiencies in coffee soils by contributing organic matter content from decomposition of tree litter (Alemu, 2015) and control the incidence and severity of coffee leaf rust disease in arabica coffee (UCDA, 2018). Shade trees can also buffer high and low temperature extremes by as much as 5 ^{0} C (Wang et al., 2015). Production of arabica coffee has been reported to reduce at temperatures higher than the optimum range (18–23 ^{o} C), while development and ripening of berry pulp are accelerated (Vaast et al., 2006), often leading to incomplete bean filling (Davis et al., 2012). However, when trees are incorporated in coffee, they buffer changes in temperature and precipitation that can enhance the sustainability and resilience of agricultural systems (Souza et al., 2012).

A related study in the Mt. Elgon region of Uganda reported that coffee yields benefited from shade trees at low altitudes, with no yield differences among systems at mid and high altitudes (Rahn et al., 2018). This relates to the findings of this study which was conducted within the low altitude range (<1400 m.a.s.l). However, another related coffee yield study in the region reported an 11% reduction in coffee yield from coffee under Cordia shading (UCDA, 2017). Similarly, coffee- shade tree systems produced the lowest yields when compared with coffee-banana and coffee-open systems in another recent study in the Mt. Elgon region (Sarmiento-Soler et al., 2020). The low coffee yields from coffee-shade tree systems in the above studies may be attributed to poor/lack of shade management of the trees integrated with the coffee. Trees integrated in coffee compete for growth resources including soil water, nutrients and light, thus requiring deliberate management to optimise shade levels (Schnabel et al., 2018). In the current study, there was a 30% yield difference between coffee yield from coffee trees under pruned and unpruned Cordia. In contrast, coffee under pruned Cordia trees produced 721 kg/ha, above the average 600 kg/ha yield reported by the UCDA (2017). Therefore, deliberate shade management may have contributed to the yield increase from coffee growing under pruned Cordia, resulting from reduced competition for growth resources and regulation of incoming radiation.

Additionally, coffee under pruned Albizia trees gave the highest yield (949 kg/ha) of parchment coffee (see Figure 1). Although still below the potential yield of 1701 kg/ha (Wang et al., 2015), the relatively high coffee yields when growing under pruned shade trees may be attributed to controlled competition for growth resources and added organic matter from dead leaves and branches following pruning. A related study in Hawaii reported that tree pruning mulch increased soil carbon and nitrogen in a shaded agroecosystem (Youkhana & Idol, 2009). Indeed, our baseline and end line soil analyses also show an increase in organic matter following pruning (see Table 1) and less N in the unshaded coffee gardens (see supplementary table 1). Although studies have recommended unshaded coffee plantations where agrochemical inputs, mechanization, irrigation and modern, high-yielding varieties are available (Schnabel et al., 2018), the costs involved are unbearable for the majority of smallholder farmers in the Mt. Elgon region. The small land holdings and the mountainous landscape also limit mechanization in the region.

5.6.2 Coffee yield components under different management options

The coffee yield components assessed included number of stems per bush, number of branches per coffee tree, number of berry clusters per branch and number of berries per cluster. In the current study, unshaded coffee generally had more stems per bush than shaded coffee under Albizia and Cordia trees (pruned and unpruned) (Table 3). A recent study in the Mt. Elgon region found that too many coffee stems (> 4 stems) per bush may contribute to a reduction of coffee yields (Sarmiento-Soler et al., 2020), an argument that relates to the current study where the lowest yields were generally obtained from unshaded coffee which had the highest number of stems per bush. Similarly, there was a significant negative correlation between number of stems per bush and season 1 yields. Additionally, unlike season 2 yields, number of stems per bush negatively correlated with season 3 and the overall yield, though the correlation was insignificant. Studies have reported that more stems per bush relate to more leaves, which consequently increases self-shading and probably negatively affect coffee yield (Njoroge et al., 1992; Sarmiento-Soler et al., 2020). This could be attributed to a potential trade-off between fruit load per branch and number of stems per bush. It is therefore likely that coffee yield improvements could be achieved through reducing the number of stems per bush (Dufour et al., 2019).

The study results show that unshaded coffee had the highest number of branches and yet the shortest in height in both experimental sites (Table 3). Our results correspond with the findings of a related study in Brazil where fewer coffee branches were observed in high shading levels (Baliza et al., 2012). Coffee plants grown under open field conditions have also been reported to score the minimum plant height (Bote et al., 2018). The tendency of increasing height by shaded coffee is for better exploitation of light penetrating from tree canopies. Therefore, the increase in coffee tree height under shade was due to a possible adaptation mechanism of the coffee plant for maximizing light interception.

The study results show that unshaded coffee had the highest number of berry clusters when compared with coffee under Albizia and Cordia trees (Table 3). However, this did not translate into higher yields as the lowest yields were obtained from unshaded coffee. This may be attributed to faster maturation of coffee berries resulting in poor bean filling and smaller coffee bean size from unshaded coffee (Bote & Struik, 2011). Dense shading has been reported to reduce flower bud formation and whole tree carbon assimilation, which may result in reduced yield due to death of heavily shaded productive branches (Kufa & Burkhardt, 2013). Dense shading also results in reduced coffee fruit load through its effects on coffee morphology and physiological changes, such as longer internodes, fewer nodes formed per branch (where berry clusters are formed) and less flower buds at existing nodes (DaMatta et al., 2007). Since the number of nodes is a key component of coffee production, the resultant coffee yields should then decline with increased shading. However, reduction of shade by 50% in the current study may have contributed to the increased number of berry clusters and the ultimate overall yield from coffee under pruned Albizia trees. It is therefore important that farmers deliberately prune agroforestry shade trees in coffee plantations to minimize the negative effects of dense shading.

5.6.3 Yield assessment of common beans planted below coffee integrated with trees

In the current study, although the overall highest common beans yields were obtained from open fields, tree pruning generally enhanced the yield of common beans planted under Cordia and Albizia trees (see Figure 2) with a 19% and 26% yield increase, respectively. The increase in yield following pruning may be attributed to increased organic matter generated from the pruning residues. Shade trees have been reported to produce up to 14 t ha^{-1} yr^{-1} of litter fall and pruning residues (Beer et al., 1998), which is a good source of organic matter and nitrogen. The yields obtained from common beans planted under pruned Cordia (500 kg/ha) and Albizia (585 kg/ha) trees are comparable to those obtained from a study in Uganda where the same variety (Kanyebwa) was planted in an open field with 10 t/ha manure applied at planting, and yielded 571.4 kg/ha (Sebuwufu et al., 2015). The contribution of aboveground litter to the formation of mineral-associated organic matter has been reported to be more significant within the top 20 cm of soil (Liebmann et al., 2020), where the common bean rooting zone is located (Beebe et al., 2011). In another related study, canopy pruning of the shea nut tree (*Vitellaria paradoxa*) in West Africa was reported to reduce belowground competition through reduction of root density in the crop rooting zone, which consequently increased crop production (Bayala et al., 2004).

Beans that were planted under unpruned Cordia gave the least yield of 420 kg/ha. The low yield may have resulted from belowground competition consistently outweighing the benefits of shade and competition for light. A related study in the agroforestry parklands of Burkina Faso reported that competition for light limited sorghum growth more than competition from other resources in the studied system (Bazié. et al., 2012), suggesting that farmers need to deliberately manage tree shade in their farming systems. While tree canopy development can also be influenced by water and nutrient availability (Pinkard & Beadle, 2000), it is equally important to correctly choose the timing and intensity of canopy pruning (García-Barrios & Ong, 2004). It is similarly important that farmers select the right annual crops, tree species and densities to optimize trade-offs between positive and negative tree effects.

5.6.4 Common beans yield components under different management options

The tallest common bean plants were registered under unpruned Albizia trees with coffee trees and under unpruned Cordia with coffee at 34.2 cm and 32.4 cm respectively (see Table 5). However, the kanyebwa (NABE 15) common bean has been reported to be a relatively short variety with an average height of 23 cm in a related study conducted in central Uganda (Goettsch et al., 2016). This corresponds to the average height recorded in this study from beans planted in the open fields, which ranged between 25 and 26 cm. Therefore, the increase in height of bean plants under unpruned trees was an adaptation mechanism for maximizing light interception.

The pruning response of Cordia and Albizia trees also influenced the height of common beans in this study. While Cordia generated multiple sprouts around the cut branches following pruning, the wounds created on Albizia trees healed without any sprouts. Therefore, the multiple sprouts in Cordia created an additional shading effect to the common beans growing under the pruned Cordia trees. The impact of the shading effect of the sprouts is evident in the small common bean height difference between beans in the pruned and unpruned Cordia (0.9 cm) when compared with the height difference between beans under pruned and unpruned Albizia trees (2.9 cm) (see Table 5). Therefore, the farmer would be required to consistently remove the sprouts from the pruned Cordia trees to minimize shading effect on the common beans.

Similarly, common beans growing in the open field had the highest number of leaves, flowers and pods per plant in both sites. Development of more leaves has been reported to help crops improve photosynthetic efficiency which would later nourish flowering and pod development (Kebede et al., 2015). The number of pods per plant maintained to the final harvest also depends on management practices, such as weeding (Alfonso et al., 2013) and management of shade to regulate irradiance. For example, a study in Ethiopia attributed a decline in number of pods per plant at low irradiance to a source limitation, as the plants later failed to supply sufficient photosynthate for every developing pod (Worku et al., 2004). However, common beans can compensate reduction in radiation by increasing leaf area, thereby limiting seed yield loss under shade stress via increasing grain filling duration and grain weight (Hadi et al., 2006). While this study did not investigate these aspects (such leaf area and grain filling duration), the ability of the bean plants under shade to compensate for reduction in radiation through grain weight is an important finding (that needs to be investigated further) in enhancing crop productivity under shaded systems, such as one under this study. It also identifies the importance of agroforestry tree management such as canopy pruning as an important on-farm management decision to maintain an optimal shade. This is further supported by the positive correlation between management option and the overall yield of common beans in the current study.

5.7 Conclusion

In this study, we investigated the impact of tree canopy pruning of *Cordia africana* Lam. and *Albizia coriaria* Welw. ex Oliv. on the relative performance of coffee - beans agroforestry system and assessed the yield of coffee and common beans under different on-farm tree management practices. Although pruning generally increased the yield of coffee, it is still below the potential yield of 1701 kg/ha expected from such farming systems, an indication that either the impacts would be observed in the longer term or the presence of other coffee yield limiting factors that need to be explored. Similarly, the time lags involved in forming coffee branches on which flower clusters can develop may explain the statistically significant yield effects noticed in the third harvesting season. While the highest yields of common beans were obtained from open fields, there was a gradual increase in yield from beans planted under pruned Cordia and Albizia trees through the three planting seasons during the study. The study has however observed that, unlike Albizia, the multiple sprouts from Cordia pruned sections compromise the purpose of pruning, as they increase the shading effect in pruned Cordia trees, requiring the farmer to continue removing the sprouts. Understanding the different coffee and common beans yield components and their interactions provided useful information on management interventions that can potentially improve coffee and common beans yields. This study has demonstrated that deliberately phased agroforestry tree canopy pruning is an important management decision that can potentially reduce competition for growth resources and prolong the period of intercropping in smallholder farming systems. However, it is likely that more tangible benefits of agroforestry tree canopy pruning will be accrued in the long-term, beyond the 20-months of this study, we therefore recommend studies longer than the current study period.

5.8 References

Alcorn, P. J., Forrester, D. I., Thomas, D. S., James, R., Smith, R. G. B., Nicotra, A. B., & Bauhus, J. (2013). Changes in Whole-Tree Water Use Following Live-Crown Pruning in Young Plantation-Grown Eucalyptus pilularis and Eucalyptus cloeziana. *Forests, 4*(1), 106-121.

Alemayehu, G., Asfaw, Z., & Kelbessa, E. (2016). Cordia africana (Boraginaceae) in Ethiopia: A review on its taxonomy, distribution, ethnobotany and conservation status. *International Journal of Botany Studies, 1*, 38-46.

Alemu, M. M. (2015). Effect of Tree Shade on Coffee Crop Production. *Journal of Sustainable Development*, *8*(9), 66. doi: 10.5539/jsd.v8n9p66

Alfonso, S. F., Paolo, R., Sergio, S., Benedetto, F., Giuseppe Di, M., Gaetano, A., & Dario, G. (2013). The Critical Period of Weed Control in Faba Bean and Chickpea in Mediterranean Areas. *Weed science, 61*(3), 452-459. doi: 10.1614/WS-D-12-00137.1

Ayalew, B. (2018). Impact of shade on morpho-physiological characteristics of coffee plants, their pests and diseases: A review. . *African Journal of Agricultural Research*, *13*(39), 9. doi: 10.5897/ajar2018.13408

Baliza, D. P., Cunha, R. L., Guimarães, R. J., Barbosa, J. P. R. A. D., Ávila, F. W., & Passos, A. M. A. (2012). Physiological characteristics and development of coffee plants under different shading levels. *Revista Brasileirade Ciencias Agrarias, 7*(1), 37-43.

Bayala, J., Teklehaimanot, Z., & Ouedraogo, S. J. (2004). Fine root distribution of pruned trees and associated crops in a parkland system in Burkina Faso. *Agroforestry Systems, 60*(1), 13-26. doi: 10.1023/B:AGFO.0000009401.96309.12

Bazié., H., Bayala, J., Zombré, G., Sanou, J., & Ilstedt, U. (2012). Separating competition-related factors limiting crop performance in an agroforestry parkland system in Burkina Faso. *Agroforestry Systems, 84*(3), 377-388. doi: 10.1007/s10457-012-9483-y

Bedker, P. J., O'Brien, J. G., & Mielke, M. M. (2012). *How to prune trees.* . Newtown Square, USA: USDA Agriculture Dept., Forest Service, Northeastern Area State and private forestry.

Beebe, S., Ramirez, J., Jarvis, A., Rao, I. M., Mosquera, G., Bueno, J. M., & Blair, M. W. (2011). *Genetic Improvement of Common Beans and the Challenges of Climate Change*: Wiley-Blackwell.

Bekunda, M. A., Nkonya, E., Mugendi, D., & Msaky, J. J. (2004). Soil fertility Status, Management, and Research in East Africa. *Eastern Africa Journal of Rural Development, 20*(1), 18. doi: 10.4314/eajrd.v20i1.28362

Bote, & Struik, P. C. (2011). Effects of shade on growth, production and quality of coffee (Coffea arabica) in Ethiopia. *Journal of Horticulture and Forestry, 3*(11), 336-341.

Bote, A. D., Ayalew, B., Ocho, F. L., Anten, N. P. R., & Vos, J. (2018). Analysis of coffee (Coffea arabica L.) performance in relation to radiation levels and rates of nitrogen supply I. Vegetative growth, production and distribution of biomass and radiation use efficiency. *European Journal of Agronomy, 92*, 115-122. doi: 10.1016/j.eja.2017.10.007

Brown, S. E., Miller, D. C., Ordonez, P. J., & Baylis, K. (2018). Evidence for the impacts of agroforestry on agricultural productivity, ecosystem services, and human well-being in high-income countries: a systematic map protocol. *Environmental Evidence, 7*(1), 24. doi: 10.1186/s13750-018-0136-0

Bukomeko, H., Jassogne, L., Tumwebaze, S. B., Eilu, G., & Vaast, P. (2017). Integrating local knowledge with tree diversity analyses to optimize on-farm tree species composition for ecosystem service delivery in coffee agroforestry systems of Uganda. *Agroforestry Systems*. doi: 10.1007/s10457-017-0172-8

Das, A. K., Rahman, M. A., Keya, S. S., Saha, S. R., & Rahman, M. M. (2020). Malta-based agroforestry system: an emerging option for improving productivity, profitability and land use efficiency. *Environmental Sustainability, 3*(4), 521-532. doi: 10.1007/s42398-020-00139-5

Davis, A. P., Gole, T. W., Baena, S., & Moat, J. (2012). The Impact of Climate Change on Indigenous Arabica Coffee (Coffea arabica): Predicting Future Trends and Identifying Priorities. *PLoS ONE, 7*(11), 1-13. doi: 10.1371/journal.pone.0047981

Descheemaeker, K., Bunting, S. W., Bindraban, P., Muthuri, C., Molden, D., Beveridge, M., . . . Jarvis, D. I. (2013). *Increasing water productivity in Agriculture*.

Dufour, B. P., Kerana, I. W., & Ribeyre, F. (2019). Effect of coffee tree pruning on berry production and coffee berry borer infestation in the Toba Highlands (North Sumatra). *Crop protection, 122*, 151-158. doi: 10.1016/j.cropro.2019.05.003

FAO, WFP, & IFAD. (2019). Food loss analysis: causes and solutions – The Republic of Uganda. Beans, maize, and sunflower studies. (pp. 212). Rome, Licence: CC BY-NC-SA 3.0 IGO.

FAO/TECA. (2017). Multi-stress tolerant bean varieties in Uganda *Technologies and Practices for Small Agricultural Producers* (pp. 5): Food and Agriculture Organization of the United Nations.

FLROA-Uganda. (2016). Forest Landscape Restoration Opportunity Assessment Report for Uganda. In M. o. W. a. Environment (Ed.), (pp. 56). Kampala: International Union for Conservation of Nature.

García-Barrios, L., & Ong, C. K. (2004). Ecological interactions, management lessons and design tools in tropical agroforestry systems. *Agroforestry Systems, 61*(1), 221-236. doi: 10.1023/B:AGFO.0000029001.81701.f0

Goettsch, H. L., Lenssen, W. A., Yost, S. R., Luvaga, S. E., Semalulu, O., Tenywa, M., & Mazur, E. R. (2016). Improved production systems for common bean on Phaeozem soil in South-Central Uganda. *African Journal of Agricultural Research, 11*(46), 4796-4809. doi: 10.5897/AJAR2016.11760

Gram, G., Vaast, P., Wolf, J., & Jassogne, L. (2018). Local tree knowledge can fast-track agroforestry recommendations for coffee smallholders along a climate gradient in Mount Elgon, Uganda. *An International Journal incorporating Agroforestry Forum, 92*(6), 1625-1638. doi: 10.1007/s10457-017-0111-8

Hadi, H., Ghassemi-Golezani, K., Khoei, F. R., Valizadeh, M., & Shakiba, M. R. (2006). Response of Common Bean (Phaseolus vulgaris L.) to Different Levels of Shade. *Journal of Agronomy, 5*(4), 595-599. doi: 10.3923/ja.2006.595.599

Herridge, D. F., Peoples, M. B., & Boddey, R. M. (2008). Global inputs of biological nitrogen fixation in agricultural systems. *Plant and soil,* 311(1/2), 1-18. doi: 10.1007/s11104-008-9668-3

Jackson, N. A., Wallace, J. S., & Ong, C. K. (2000). Tree pruning as a means of controlling water use in an agroforestry system in Kenya. *Forest Ecology and Management, 126*(2), 133-148. doi: 10.1016/S0378-1127(99)00096-1

Janani, L., Hillary, L., & Phillips, K. (2014). Mordanting methods for dyeing cotton fabrics with dye from Albizia coriaria plant species. *International Journal of Scientific and Research Publications, 4*(10), 1-6.

Jezeer, R. E., Santos, M. J., Boot, R. G. A., Junginger, M., & Verweij, P. A. (2018). Effects of shade and input management on economic performance of small-scale Peruvian coffee systems. *Agricultural Systems, 162*, 179-190. doi: 10.1016/j.agsy.2018.01.014

Jezeer, R. E., & Verweij, P. A. (2015). *Shade Grown Coffee: Double dividend for biodiversity and small-scale coffee farmers in Peru*. The Hague, the Netherlands: Utrecht University and Hivos.

Jhariya, M. K., Banerjee, A., Yadav, D. K., & Raj, A. (2018). Leguminous Trees an Innovative Tool for Soil Sustainability. In R. S. Meena, A. Das, G. S. Yadav, & R. Lal (Eds.), *Legumes for Soil Health and Sustainable Management* (pp. 315-345). Singapore: Springer Singapore.

Joët, T., Laffargue, A., Descroix, F., Doulbeau, S., Bertrand, B., kochko, A. d., & Dussert, S. (2010). Influence of environmental factors, wet processing and their interactions on the biochemical composition of green Arabica coffee beans. *Food Chemistry, 118*(3), 693-701. doi: https://doi.org/10.1016/j.foodchem.2009.05.048

Katende, A., Birnie, A., & Tengna, S. (1995). *Useful trees and shrubs for Uganda: identification, propagation and management for agricultural and pastoral communities*. Nairobi (Kenya) Regional Soil Conservation Unit. Technical Handbook No. 10.

Kebede, M., Sharma, J. J., Tana, T., & Nigatu, L. (2015). Effect of Plant Spacing and Weeding Frequency on Weed Infestation, Yield Components, and Yield of Common Bean (Phaseolus vulgaris L.) in Eastern Ethiopia. *East African Journal of Sciences, 9*(1), 1-14.

Kufa, T., & Burkhardt, J. (2013). Studies on root growth of Coffea arabica populations and its implication for sustainable management of natural forests. *Journal of Agricultural and Crop Research, 1*(1), 1-10.

Laudares, S. S. d. A., Borges, L. A. C., Ávila, P. A. d., Oliveira, A. L. d., Silva, K. G. d., & Laudares, D. C. d. A. (2017). Agroforestry as a sustainable alternative for environmental regularization of rural consolidated occupations. *CERNE, 23*, 161-174.

Liebmann, P., Wordell-Dietrich, P., Kalbitz, K., Mikutta, R., Kalks, F., Don, A., . . . Guggenberger, G. (2020). Relevance of aboveground litter for soil organic matter formation – a soil profile perspective. *Biogeosciences, 17*, 3099-3113. doi: 10.5194/bg-17-3099-2020

Liu, Y., Liu, S., Wang, J., Zhu, X., Zhang, Y., & Liu, X. (2014). Variation in soil respiration under the tree canopy in a temperate mixed forest, central China, under different soil water conditions. *Ecological Research, 29*(2), 133-142. doi: 10.1007/s11284-013-1110-5

Lupwayi, N. Z., Kennedy, A. C., & Chirwa, R. M. (2011). Grain legume impacts on soil biological processes in sub-Saharan Africa. *African Journal of Plant Science, 5*(1), 7. doi: https://doi.org/10.5897/AJPS.9000131

Mbere, N., Ela, M., Tchobsala, & Fohouo, F. (2020). Floral activity of *Apis mellifera* (Hymenoptera: Apidae) on *Bidens steppia* (Asteraceae), *Cordia africana* (Boraginaceae), *Pittosporum viridiflorum* (Pittosporaceae) and *Psychotria mahonii* (Rubiaceae) in Nyambaka (Adamawa, Cameroon). *African Journal of Agricultural Research, 16*(9), 1278-1288. doi: https://doi.org/10.5897/AJAR2020.14730

Nair, R. P. K & Toth, G. G. (2016). Measuring Agricultural Sustainability in Agroforestry Systems (pp. 365-394). Cham: Springer International Publishing.

Namugwanya, M., Tenywa, J. S., & Otabbong, E. (2018). Response of common bean genotypes grown in soil with normal or limited moisture, with special reference to the nutrient phosphorus. *Agronomy, 8*(8), <xocs:firstpage xmlns:xocs=""/>. doi: 10.3390/agronomy8080132

Njoroge, J. M., Waithaka, K., & Chweya, J. A. (1992). The influence of tree training and plant density on growth, yield components and yield of Arabica coffee cv. Ruiru 11. *The Journal of horticultural science, 67*(5), 695-702. doi: 10.1080/00221589.1992.11516300

Nyong, P. A., & Martin, N. T. (2019). Enhancing agricultural sustainability and productivity under changing climate conditions through improved agroforestry practices in smallholder farming systems in Sub-Saharan Africa. *African Journal of Agricultural Research, 14*(7), 379-388. doi: 10.5897/AJAR2018.12972

Okalebo, J. R., Gathua, K. W., & Woomer, P. L. (2002). *Laboratory methods of soil and plant analysis : a working manual* (Second Edition ed.). Nairobi: Tropical Soil Biology and Fertility Programme, TSBF-CIAT and SACRED Africa, Kenya.

Ong, C. K., & Swallow, B. M. (2003). Water productivity in forestry and agroforestry. St. Louis: Federal Reserve Bank of St Louis.

Pinho, R. C., Miller, R. P., & Alfaia, S. S. (2012). Agroforestry and the Improvement of Soil Fertility: A View from Amazonia. *Applied and Environmental Soil Science, 2012*. doi: 10.1155/2012/616383

Pinkard, E. A., & Beadle, C. L. (2000). A physiological approach to pruning. *The International Forestry Review, 2*(4), 295-305.

Rahn, E., Liebig, T., Ghazoul, J., van Asten, P., Läderach, P., Vaast, P., . . . Jassogne, L. (2018). Opportunities for sustainable intensification of coffee agro-ecosystems along an altitudinal gradient on Mt. Elgon, Uganda. *Agriculture, Ecosystems and Environment, 263*, 31-40. doi: 10.1016/j.agee.2018.04.019

Ronner, E., Descheemaeker, K., Almekinders, C. J. M., Ebanyat, P., & Giller, K. E. (2018). Farmers' use and adaptation of improved climbing bean production practices in the highlands of Uganda. *Agriculture, Ecosystems & Environment, 261*, 186-200. doi: 10.1016/j.agee.2017.09.004

Santiago-Freijanes, J. J., Mosquera-Losada, M. R., Rois-Díaz, M., Ferreiro-Domínguez, N., Pantera, A., Aldrey, J. A., & Rigueiro-Rodríguez, A. (2018). Global and European policies to foster agricultural sustainability: agroforestry. *Agroforestry Systems*. doi: 10.1007/s10457-018-0215-9

Sarmiento-Soler, A., Vaast, P., Hoffmann, M. P., Jassogne, L., van Asten, P., Graefe, S., & Rötter, R. P. (2020). Effect of cropping system, shade cover and altitudinal gradient on coffee yield components at Mt. Elgon, Uganda. *Agriculture, Ecosystems & Environment, 295*. doi: 10.1016/j.agee.2020.106887

Sebatta, C., Mugisha, J., Bagamba, F., Nuppenau, E.-A., Domptail, S. E., & Karungi-Tumutegyereize, J. (2019). Barriers and opportunities for intensification of the coffee-banana agroecosystem of the Mt. Elgon in Uganda. *African Journal of Rural Development, 3*(4), 1005-1011.

Sebuwufu, G., Mazur, R., Ugen, M., & Westgate, M. (2015). Using improved varieties and fertility enhancements for increasing yield of common beans (Phaseolus vulgaris L.) grown by small-landholder farmers in Uganda. *African Journal of Agricultural Research, 10*(52), 4795-4805. doi: 10.5897/AJAR2015.9638

Sibiko, K., Mwangi, J., Gido, E., & Mutai, B. K. (2013). Allocative efficiency of smallholder common bean producers in Uganda: A stochastic frontier and Tobit model approach. *International Journal of Development and Sustainability, 2*(2), 12.

Sinclair, T. R., & Vadez, V. (2012). The future of grain legumes in cropping systems. *Crop and Pasture Science, 63*(6), 501-512, 512.

Souza, H. N. d., de Goede, R. G. M., Brussaard, L., Cardoso, I. M., Duarte, E. M. G., Fernandes, R. B. A., . . . Pulleman, M. M. (2012). Protective shade, tree diversity and soil properties in coffee agroforestry systems in the Atlantic Rainforest biome. *Agriculture, Ecosystems & Environment, 146*(1), 179-196. doi: https://doi.org/10.1016/j.agee.2011.11.007

Ssekandi, W., Mulumba, J., Colangelo, P., Nankya, R., Fadda, C., Karungi, J., . . . Jarvis, D. (2016). The use of common bean (Phaseolus vulgaris) traditional varieties and their mixtures with commercial varieties to manage bean fly (Ophiomyia spp .) infestations in Uganda. *Journal of Pest Science, 89*(1), 45-57. doi: 10.1007/s10340-015-0678-7

Schnabel, F., de Melo Virginio Filho, E., Xu, S., Fisk, I. D., Roupsard, O., & Haggar, J. (2018). Shade trees: a determinant to the relative success of organic versus conventional coffee production. *Agroforestry Systems, 92*(6), 1535-1549. doi: 10.1007/s10457-017-0100-y

Tabuti, J. R. S., & Mugula, B. B. (2007). The ethnobotany and ecological status of Albizia coriaria Welw. ex Oliv. in Budondo Sub-county, eastern Uganda. *African Journal of Ecology, 45*(s3), 126-129. doi: https://doi.org/10.1111/j.1365-2028.2007.00869.x

Tang, X.-L., Zhou, G.-Y., Liu, S.-G., Zhang, D.-Q., Liu, S.-Z., Li, J. and Zhou, C.-Y. (2006), Dependence of Soil Respiration on Soil Temperature and Soil Moisture in Successional Forests in Southern China. Journal of Integrative Plant Biology, 48: 654-663. https://doi.org/10.1111/j.1744-7909.2006.00263.x

UCDA. (2017). Annual report (2016-2017) (Vol. 26, pp. 92). Kampala, Uganda: Uganda Coffee Development Authority.

UCDA. (2018). Annual report (2017-2018) (Vol. 27, pp. 74). Kampala, Uganda: Uganda Coffee Development Authority.

Vaast, P., Bertrand, B., Perriot, J.-J., Guyot, B., & Génard, M. (2006). Fruit thinning and shade improve bean characteristics and beverage quality of coffee (Coffea arabica L.) under optimal conditions. *Journal of the Science of Food and Agriculture, 86*(2), 197-204. doi: 10.1002/jsfa.2338

Van Asten, P. J. A., Wairegi, L. W. I., Mukasa, D., & Uringi, N. O. (2011). Agronomic and economic benefits of coffee-banana intercropping in Uganda's smallholder farming systems.(Report). *Agricultural Systems, 104*(4), 326. doi: 10.1016/j.agsy.2010.12.004

Vedeld, P., Cavanagh, C., Petursson, J., Nakakaawa, C., Moll, R., & Sjaastad, E. (2016). The Political Economy of Conservation at Mount Elgon, Uganda: Between Local Deprivation, Regional Sustainability, and Global Public Goods. *Conservation and Society, 14*(3), 183-194. doi: 10.4103/0972-4923.191155

Wang, N., Jassogne, L., van Asten, P. J. A., Mukasa, D., Wanyama, I., Kagezi, G., & Giller, K. E. (2015). Evaluating coffee yield gaps and important biotic, abiotic, and management factors limiting coffee production in Uganda. *European Journal of Agronomy, 63*(40), 1-11. doi: 10.1016/j.eja.2014.11.003

Winterbottom, R., Reij C, Garrity D, Glover J, Hellums D, Mcgahuey M, & Scherr S. (2013). Improving land and water management. WRI Working Paper *Installment 4 of Creating a Sustainable Food Future* (pp. 44). Washington, DC: World Resources Institute. http://www.worldresourcesreport.org.

Worku, W., Skjelvåg, A., & Gislerød, H. (2004). Responses of common bean (Phaseolus vulgaris L.) to photosynthetic irradiance levels during three phenological phases. *Agronomie, 24*(5), 267-274. doi: 10.1051/agro:2004024

Youkhana, A., & Idol, T. (2009). Tree pruning mulch increases soil C and N in a shaded coffee agroecosystem in Hawaii. *Soil biology &amp, 41*, 2527-2534.

Supplementary Table 1 Baseline and end line scenarios of the different

Management option	PH	Total N (%)	Total P (ppm)	CEC (cmoles/kg)	Major elements (cmoles/kg) K	Ca	Mg	Na	Trace elements - ppm (mg/kg) Cu	Zn	Fe	Mn	BS (%)
Initial scenario													
Open field (Albizia site)	5.8	0.1	5.6	49.2	0.9	5.3	3.0	0.1	4.3	7.8	102.8	27.0	19.0
Open field (Cordia site)	6.1	0.1	35.6	30.2	0.9	5.3	3.0	0.1	3.3	7.8	123.6	32.0	29.0
Unshaded coffee (Albizia site)	5.8	0.1	9.2	65.2	0.9	5.2	2.1	0.1	2.1	7.2	126.9	26.7	13.3
Unshaded coffee (Cordia site)	6.2	0.1	32.4	25.2	0.6	5.6	2.1	0.1	2.2	7.0	117.9	36.7	23.3
Unpruned Albizia	6.0	0.2	9.1	52.1	1.3	5.6	1.9	0.1	3.6	6.9	110.0	26.2	17.3
Pruned Albizia	6.1	0.2	9.4	47.7	1.1	6.0	2.5	0.1	2.6	8.1	159.9	63.3	20.7
Unpruned Cordia	6.2	0.2	46.0	29.5	0.7	5.6	1.9	0.1	1.6	7.0	117.8	32.2	28.0
Pruned Cordia	6.0	0.1	46.4	27.3	0.6	5.6	1.7	0.1	2.2	8.5	133.0	35.5	29.3
Final scenario													
Open field (Albizia site)	6.2	0.1	5.3	46.4	0.6	8.8	1.9	0.1	2.2	19.7	124.9	21.5	47.3
Open field (Cordia site)	6.2	0.2	32.6	30.2	0.9	5.3	3.0	0.1	3.3	7.8	123.6	32.0	29.0
Unshaded coffee (Albizia site)	6.1	0.1	5.7	43.1	0.6	3.1	2.6	0.2	2.1	18.4	101.1	29.1	39.1
Unshaded coffee (Cordia site)	6.3	0.1	33.4	23.2	0.8	5.6	2.1	0.1	2.2	17.0	107.9	26.7	23.3
Unpruned Albizia	6.4	0.2	7.0	39.7	0.7	8.4	2.2	0.2	1.1	22.0	112.6	36.7	44.6
Pruned Albizia	6.4	0.2	7.4	39.1	1.0	6.4	2.8	0.2	0.9	15.5	105.1	39.4	43.2
Unpruned Cordia	6.3	0.2	35.2	27.2	0.9	9.8	2.1	0.2	1.5	14.3	185.3	33.6	49.2
Pruned Cordia	6.2	0.2	33.8	21.7	0.7	8.7	1.3	0.2	0.7	15.5	168.9	25.1	52.2

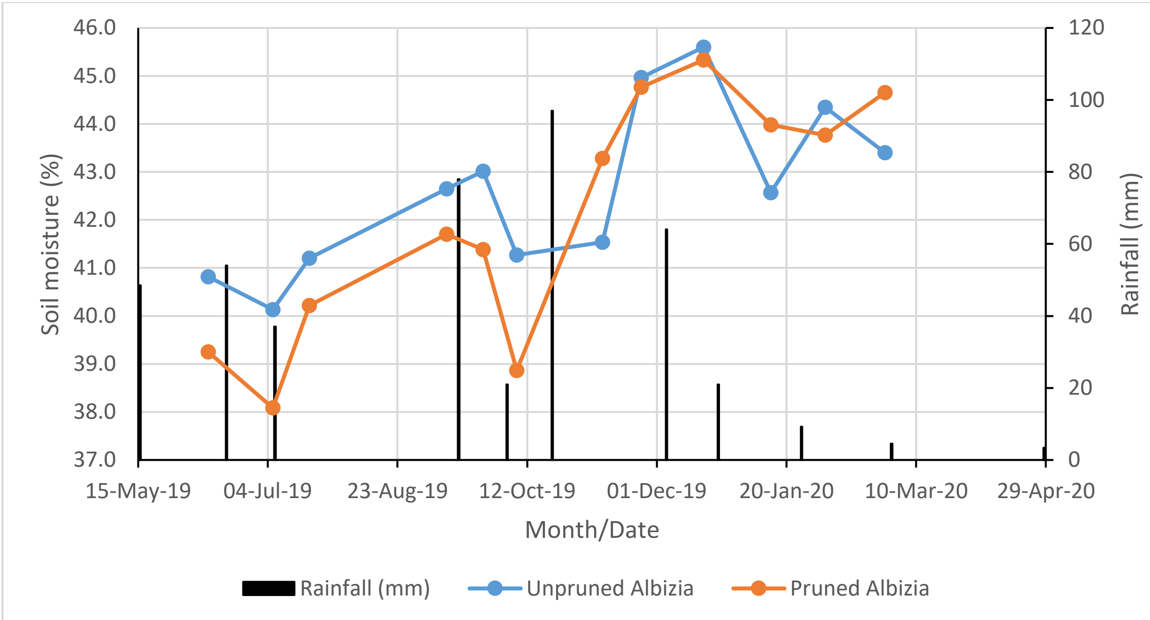
Supplementary Table 2: ANOVA in coffee yield in the 3 treatments in each of the experimental sites

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Albizia site						
Between Groups	627966.5	2	313983.3	3.524994	0.074038	4.256495
Within Groups	801660.7	9	89073.41			
Total	1429627	11				
Cordia site						
Between Groups	179204.7407	2	89602.37	1.897804	0.205266	4.25649
Within Groups	424923.3333	9	47213.7			
Total	604128.0741	11				
Overall						
Between Groups	940973.9	5	188194.8	2.76174	0.050655	2.772853
Within Groups	1226584	18	68143.56			
Total	2167558	23				

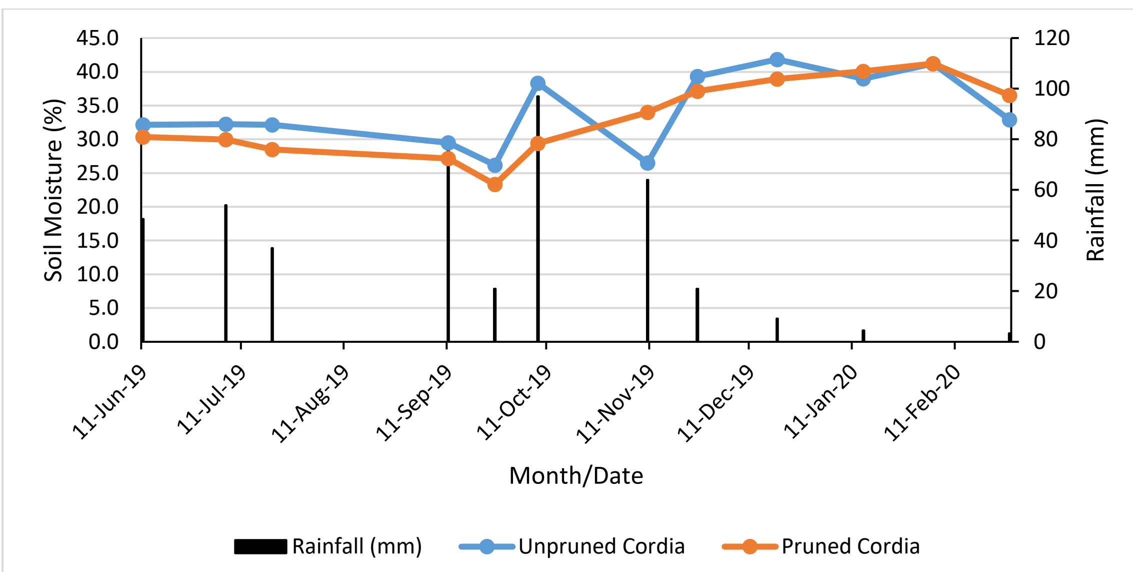
Supplementary Table 3: ANOVA in yield of common beans across the four treatments in each experimental site

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Albizia site						
Between Groups	154307.2	3	51435.73	5.632026	0.012062	3.490295
Within Groups	109592.7	12	9132.722			
Total	263899.9	15				
Cordia site						
Between Groups	195225	3	65075	5.7671	0.011138	3.490295
Within Groups	135406	12	11283.83			
Total	330631	15				
Overall						
Between Groups	367229.3	7	52461.32	5.139096	0.001125	2.422629
Within Groups	244998.7	24	10208.28			
Total	612227.9	31				

Volumetric Soil Water Content (VSW%) summary results



Supplementary Fig. 1: Average soil moisture under pruned and unpruned *A. coriaria* sites



Supplementary Fig. 2: Average soil moisture under pruned and unpruned *C. africana* sites

Chapter 6: Psychological factors influencing farmers' intention to adopt agroforestry in Uganda: A structural equation modeling approach

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Name of Principal Author (Candidate)	Joel Buyinza		
Contribution to the Paper	Identification of research gap, theoretical foundation, data collection and analysis, interpretation of finding, writing manuscript and acted as the first and corresponding author		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
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By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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Psychological Factors Influencing Farmers' Intention to Adopt Agroforestry: A Structural Equation Modeling Approach

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ABSTRACT

The biophysical characteristics of the farm and farmers' socioeconomic factors have been used to explain adoption of technologies in Africa. However, agricultural technology adoption requires that we also understand the psychological factors that can encourage or discourage farmer adoption of technologies. The aim of this article is to assess the psychological drivers of farmers' intentions to adopt agroforestry technologies on their farms. We obtained data from 400 smallholder farmers in the Mt. Elgon region of Uganda. The Theory of Planned Behavior was used as the main framework. Quantitative data were analyzed using structural equation modeling to assess the impact of a set of psychological factors on farmers' intention to integrate trees in coffee. The intention of farmers to integrate trees in coffee plantations was mainly driven by their evaluation of the benefits of shaded coffee (attitude) followed by beliefs about their own capability (perceived behavioral control). However, social pressure (subjective norm) was insignificant, implying that smallholder farmers tend to deny the influence of other people's behavior on their actions. Therefore, farmers' positive evaluation of shading coffee and the perceived capability to overcome tree planting barriers reinforced their intention to integrate trees in coffee. This renders attitude and perceived behavioral control as reliable predictors of farmer tree planting behavior, especially in the context of developing countries.

KEYWORDS

Shaded coffee; adoption; attitude; perceived behavioral control; subjective norm; Uganda

6.2 Introduction

Millions of farmers in developing countries struggle to feed their families as they contend with land degradation and land use pressures (Winterbottom et al., 2013). These challenges are particularly acute in Sub-Saharan Africa, where land degradation, water stress, depleted soil fertility and high costs for fertilizers contribute to low agricultural production. Uganda's agriculture is sustained by smallholder farmers with majority having landholdings of less than 2 ha (Kaweesa et al., 2018). While agricultural production is a sector that contributes over 20% of the country's Gross Domestic Product (UBoS, 2017), and has a transformative role in poverty reduction among farmers (World Bank, 2016), it is continually impeded by land degradation. Improving agricultural productivity typically involves the use of expensive inputs that inherently increases the risks, which most smallholder farmers are often unable or unwilling to bear. Agroforestry is one solution to these complex challenges, as it serves to mitigate climate change by sequestering carbon in trees, while helping to control soil erosion, improve soil fertility and the microclimate.

A number of research and development efforts in the Mt. Elgon region continue to demonstrate the importance of trees in fields and farming landscapes for enhancing and sustaining crop yield and food security (Buyinza et al., 2019; Gram et al., 2018; MENA Report, 2018; Oyana et al., 2015; Rahn et al., 2018; UGANDA, 2010). As an example, planting of trees in existing coffee systems (shaded coffee) has been promoted to control soil erosion and boost coffee production (Rahn et al., 2018). However, a number of smallholder farmers are still reluctant to incorporate trees in their coffee despite demonstrations and participatory trials that have shown positive results in sustaining agricultural production. The majority of those who have taken up the practice have failed to deliberately manage the tree component. The trees are often left to grow without canopy pruning and thinning, which creates a dense shade that negatively affects the subsequent coffee yields and that of other accompanying food crops. A lack of tree management has created mixed perceptions towards shaded coffee among smallholder farmers who look at the tree component as a competitor in the coffee production system.

The decision-making process to adopt new agricultural innovations depends on both intrinsic and extrinsic factors of the farmer (Meijer et al., 2015; Reimer et al., 2012). However, most agroforestry adoption studies have acknowledged resource constraints and socio-economic factors (Cedamon et al., 2018; Etshekape et al., 2018; Meijer et al., 2015; Nahayo et al., 2016; Nyaga et al., 2015; Pattanayak et al., 2003; Thangata & Alavalapati, 2003), with limited focus on the cognitive and psychological constraints to adoption. Nonetheless, a few studies have recommended investigations into the influence of psychological variables in agroforestry adoption (Caveness & Kurtz, 1993; Cullen, 2009; Martínez-García et al., 2013; Sood & Mitchell, 2006). Some farmers may fail to take up agricultural innovations simply because the new technologies are not aligned to the social norms and customs of the community. The behavioural intentions are mainly shaped by attitude, subjective norms and perceived behavioural control, as suggested by the Theory of Planned Behaviour (Ajzen, 1991).

6.2.1 Theoretical background

The Theory of Planned Behaviour (TPB) offers a theoretical foundation for studying psychological factors that influence people’s behaviours. Behavioural intentions are determined by attitudes, subjective norms (social pressures) and perception of control on implementation of behavioural tasks (Ajzen, 2011). Several studies based on TPB (Figure 1) have been used in the context of agriculture to understand farmers' decisions on the adoption of improved grassland (Borges et al., 2014; Martínez-García et al., 2013), and soil conservation practices (Wauters et al., 2010). These studies have demonstrated that the TPB can adequately model people’s behavioural intentions.

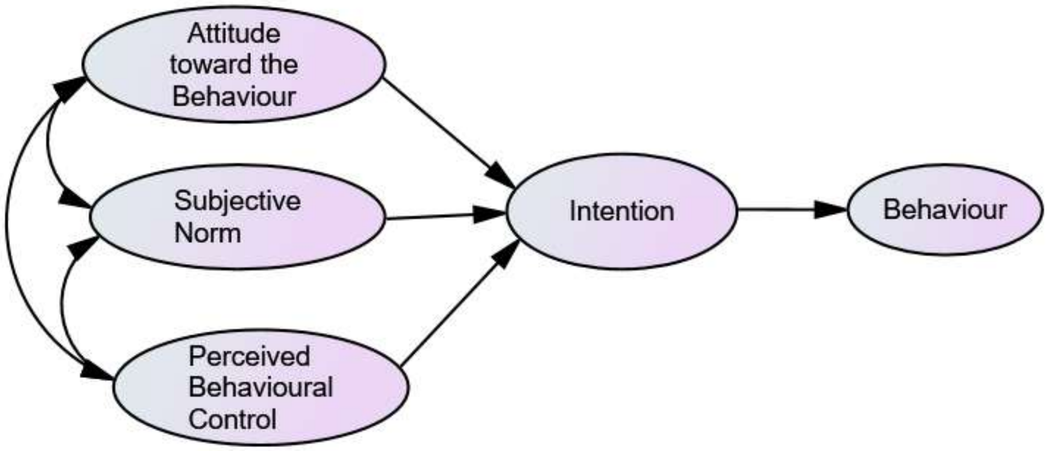


Figure 1: Theory of Planned Behaviour (Adapted from Ajzen, 2005)

Attitude is the degree to which execution of the behaviour is positively or negatively evaluated by an individual (Ajzen, 1991). Subjective norm refers to a person's perception of the social pressure upon them to perform or not perform the behaviour, and perceived behavioural control is the individual's perceived capability to successfully perform the behaviour (Borges & Lansink, 2016; Wauters et al., 2010). In the context of this study, farmers would have a higher intention to plant trees in their coffee gardens when they evaluate integration of trees in coffee as more favourable (attitude), when they perceive social pressure to use this agroforestry practice to be higher (subjective norm), and when they have more positive beliefs about their own capability to implement this practice on their farms (perceived behavioural control).

This study thus, sought to understand the decision making process of farmers regarding integration of trees in coffee on their farms using the Theory of Planned Behaviour. This is because farmers' decisions regarding tree integration on-farm may be influenced by their attitudes, opinions and behaviour of the people around them, as well as their perceived capability. Therefore, the study tested three hypotheses that were derived from the conceptual model:

H_1: Attitude has a positive influence on smallholder farmers' intention to integrate trees in their coffee gardens

H_2: Subjective norm (social pressure) has a positive influence on farmers' intention to integrate trees in coffee gardens

H_3: Perceived behavioural control has a positive influence on farmers' intention to integrate trees in coffee gardens

6.3 Methods

The study was conducted in three districts of Manafwa, Bududa and Sironko, located in Mt. Elgon region of Uganda. These study sites form part of the Trees for Food Security (T4FS) project sites. The T4FS is an Australian Centre for International Agricultural Research (ACIAR) funded project aimed at improving household food security and smallholder livelihoods through widespread adoption of appropriate locally adapted agroforestry practices in key agricultural landscapes in Ethiopia, Rwanda and Uganda. The project has been reaching out to smallholder farmers in rural regions where an estimated 10 million people are facing acute food security problems since 2012. In Uganda, the T4FS project started in 2014 and is currently in its second phase of implementation in the Mt. Elgon region of Uganda.

Prior to the main survey, a pre-test was conducted with 15 farmers to ensure that the questions could be clearly understood. The final version of the survey tool consisted of three groups of questions: socio-demographic characteristics, farmers' opinion and assessment of existing agroforestry practices, and questions based on TPB. This paper only addresses socio-demographic characteristics and TPB questions. The measurement scale used for the TPB questions (Table 1) was based on a seven-point Likert scale ranging from one (most negative answer) to seven (most positive answer).

Table 1. Statements and scales used for the measurable variables representing the four TPB constructs

Item	Statement	Scale (1-7)
INT_1	Do you intend to plant trees for shade in at least part of your farm in the next 5 years?	definitely no – definitely yes
INT_2	How likely is it that you will plant trees for shade in at least part of your farm in the next 5 years?	very unlikely – very likely
INT_3	How strong is your intention to plant trees for shade in coffee in at least part of your farm in the next 5 years?	extremely weak – extremely strong
ATT_1	Planting trees in my coffee garden reduces the amount of inputs (e.g fertilizers) into the farm	strongly disagree – strongly agree
ATT_2	Planting trees in my coffee garden provides more economic benefits (e.g income from yields & other products) compared to unshaded gardens	strongly disagree – strongly agree
ATT_3	Given the location of my farm and crop mix, planting trees for shade is possible	strongly disagree – strongly agree
ATT_4	I need to use shade trees on my coffee farm to maximize production from my farm	strongly disagree – strongly agree
SN_1	Most people who are important to me think I should plant shade trees on my coffee farm	strongly disagree – strongly agree
SN_2	Extension workers think I should plant shade trees on my coffee farm	strongly disagree – strongly agree
SN_3	Other farmers whom I regularly interact with would approve that I should plant shade trees on my coffee farm	strongly disagree – strongly agree
SN_4	I feel under social pressure from fellow farmers to plant shade trees on my coffee farm	strongly disagree – strongly agree
PBC_1	My decision to plant shade trees or not on my coffee farm in the next 5 years only depends on my needs	strongly disagree – strongly agree
PBC_2	I feel that I have sufficient knowledge on planting shade trees in my coffee farm	strongly disagree – strongly agree
PBC_3	I have all the resources (e.g seedlings, labour, land) I need to plant shade trees in my coffee farm.	strongly disagree – strongly agree
PBC_4	If I want to plant shade trees in my coffee farm, I have enough technical skills on managing trees in coffee	strongly disagree – strongly agree
PBC_5	How confident are you that you could overcome barriers that prevent you to use scattered trees in at least part of your farm within the next 5 years?	completely unconfident – completely confident

Data were collected from two sub counties in each of the three study districts. Using local council household lists, a simple random sampling technique was used to select survey respondents. During the survey, three households declined to be interviewed and were subsequently replaced by others on the list. A total of four hundred (400) respondents were interviewed for this study, 57% of whom were male and 64.3% had attained only primary school education. Respondents that had attained secondary and tertiary education were only 23.8% and 6.8% respectively. Other socio-demographic characteristics of the respondents are presented in supplementary Table 1. Data collection took place from May to July 2018.

6.4 Data analysis

Quantitative data from questionnaire interviews were analyzed using Partial Least Squares (PLS) regression - Structural Equation Modeling (SEM) to provide a quantitative assessment of farmers' behaviour in terms of their intentions (Tobi & Kampen, 2017). SEM combines analytical properties of both factor analysis and ordinal least squares regression. SEM can also test complex relationships of observed and unobserved (latent) variables. IBM SPSS statistical software 25 was used to generate descriptive statistics. Data screening was done to test for multiple collinearity assumptions of the TPB construct variables. This was done to eliminate any form of redundancy in the measurement model (Borges & Lansink 2016).

Construct validity was tested by undertaking convergent validity and discriminant validity tests. The convergent validity of the measurement model was tested by assessing standard factor loadings, *average variance extracted (AVE)* and composite reliability (CR) (Dang et al., 2014). Average variance extracted is a measure of the amount of variance that is captured by a construct in relation to the amount of variance due to measurement error. For a measurement model to be valid, *composite reliability* should be equal to or greater than 0.7 and AVE should be greater than 50% (Hair et al., 2010). Discriminant validity of the measurement model tested conformity of the constructs to the criteria where all construct should had AVEs greater than the squared inter-construct correlations (Borges & Lansink, 2016).

IBM AMOS SPSS statistical software 25 was used to run the measurement model and the structural model (regression). The two-step approach was followed to test the TPB model (Anderson & Gerbing, 1988). In the first step, confirmatory factor analysis (CFA) was used to obtain a satisfactory measurement model (MM). The second step was to develop and test the structural model, and obtain the Goodness-of-fit (GOF) indices with the same assessment criteria as in CFA.

6.4.1 Data screening

Multivariate collinearity was assessed by conducting multiple regressions, each with a different item as the dependent variable and all other items as independent variables, followed by checking the tolerance values and variance inflation factor (VIF) for each regression (Hildreth, 2012). The test for multiple collinearity assumptions of the TPB construct variables showed that no construct variable violated the assumption (Supplementary table 2). All the items had tolerance values greater than 0.10 and VIF values less than 3. Therefore, we do not expect any form of redundancy in the model.

6.5 Results

6.5.1 Summary statistics of the measured items

The mean and standard deviation of all the measured variables and the correlations between all variables are presented in Supplementary Table 3. In general, farmers showed a positive intention to incorporate trees in their coffee gardens in the next five years, as the three variables used to measure intention all had a mean of at least 6. The intra-construct correlations for the intention variables varied from 0.382 to 0.493. Farmers showed a predominantly positive attitude towards planting of trees in their coffee gardens. All variables used to measure attitude had means above 6, with correlations from 0.339 to 0.358. The social pressure perceived by farmers towards tree planting in coffee gardens was moderately low. The variables used to measure subjective norm presented means of at least 4 and correlations from 0.363 to 0.602. Farmers perceived a moderately high capability to plant and manage trees in their coffee gardens and the variables used to measure PBC presented a mean of at least 4.66 and correlations varied from 0.449 to 0.582. There were generally low inter-construct correlations between intention and subjective norm measured variables ranging from -0.16 to 0.114.

6.5.2 Confirmatory Factor Analysis (CFA)

Construct validity of the measurement model (MM)

In our measurement model, all standardized factor loadings were above 0.5 (Table 2). Loadings of this size not only contribute to construct validity, but also indicate that observed indicators were strongly related to their associated constructs. In this model, all average variance extracted (AVE) for each construct were above 50% and their respective composite reliability above 0.7, implying acceptable convergent validity. In addition, the AVE values for any two constructs were higher than the squared inter-construct correlations (see supplementary Table 3), confirming satisfactory discriminant validity. Since the data meet the construct validity criteria, no modifications were made as the measurement model required no further improvement. The overall path diagram is shown in Appendix 1 with the standardized factor loadings, observed, unobserved and unique variables selected for the structural model.

Table 2. Standardized factor loadings for each item with standard errors (in brackets), and the average variance extracted (AVE) and composite reliability (CR) for each construct in the measurement model.

	INT		**ATT**		**SN**		**PBC**	
	INT1	0.58 (0.04)	ATT1	0.61 (0.04)	SN1	0.81 (0.07)	PBC2	0.71 (0.05)
	INT2	0.69 (0.04)	ATT2	0.61 (0.03)	SN2	0.58 (0.06)	PBC3	0.81 (0.06)
	INT3	0.70 (0.04)	ATT4	0.56 (0.03)	SN3	0.76 (0.07)	PBC5	0.63 (0.05)
					SN4	0.67 (0.07)		
AVE (%)	60.1		54.9		50.5		66.5	
CR	0.818		0.785		0.801		0.855	

6.5.3 Validation of the measurement and structural models

The Goodness of Fit (GOF) indices of the structural model are the same as those in the measurement model (Table 3). This is because the structural model has the same number of structural relationships as construct correlations in the measurement model. All GOF indices are within the acceptable range for an appropriate model fit.

Table 3. Overall model fit indices for the measurement and structural models

Statistic	**Threshold**	**Measurement model**	**Structural model**	**Meaning of statistic**
CMIN/DF	1-3	2.401	2.401	Ratio of Confirmatory Fit Index to degrees of freedom
IFI	≥ 0.900	0.933	0.933	Incremental Fit Index
TLI	≥ 0.900	0.910	0.910	Tucker-Lewis Index
CFI	≥ 0.900	0.932	0.932	Comparative Fit Index
RMSEA	≤ 0.06	0.059	0.059	Root Mean Square Error of Approximation
PCLOSE	≥ 0.05	0.107	0.107	Probability of getting a sample RMSEA as large as its calculated value in the given model

6.5.4 Structural model

After obtaining a satisfactory measurement model, a structural model was estimated to test the hypotheses underlying the Theory of Planned Behaviour. Table 4 shows the results of the structural model. The regression coefficient of attitude on intention was significant and positive, suggesting that the hypothesis H_1 (Attitude has a positive influence on smallholder farmers' intention to integrate trees in their coffee gardens) was not rejected. However, a non-significant regression coefficient of subjective norm on intention suggests that hypothesis H_2 (Subjective norm has a positive influence on farmers' intention to integrate trees in coffee gardens) is rejected. Finally, the regression coefficient of Perceived behavioural control on intention was significant and positive, indicating that hypothesis H_3 (Perceived behavioural control has a positive influence on farmers' intention to integrate trees in coffee gardens) was not rejected. The relative sizes of the regression coefficients indicated that attitude was the main determinant of intention, followed by perceived behavioural control.

Table 4. Structural relations of Attitude, Subjective Norms, and Perceived Behavioural Control on farmers' Intention to use shade trees

Structural relation	Standardized parameter	p (value)	Sig.
ATT ---> INT	0.275	0.000	***
SN ---> INT	0.022	0.389	ns
PBC ---> INT	0.131	0.005	***

****significant at p≤ 0.01; ns- not significant*

6.6 Discussion

6.6.1 Influence of attitude, perceived behavioural control and subjective norm on farmers' intention

Studies that used the theory of planned behaviour in agricultural contexts had mixed results of the relative influence of attitude, subjective norm, and perceived behavioural control on intention

(Borges et al., 2014; Lalani et al., 2016; Senger et al., 2017b). The mixed results are expected because the prediction of intention varies, for instance, across behaviours, situations and cultures (Ajzen, 1991). In the present study, the regression coefficients generated from the structural model indicated that attitude and perceived behavioural control had a positive significant influence on behavioural intention. This is in contrast with a related study identifying psychological factors that determined farmers' intention to use improved natural grasslands in Brazil, which found that all the three constructs were positive and significant (Borges & Lansink, 2016).

In our study, attitude had a larger influence than perceived behavioural control and subjective norm on farmers' intention to integrate trees in coffee plantations. The high influence of attitude showed that the positive evaluation of shading coffee on-farm was the main determinant of farmers' intention to plant trees in coffee plantations. This implies that smallholder farmers evaluated integration of trees in coffee as more favourable compared with unshaded coffee. Indeed, studies have demonstrated that shaded coffee has more ecological, agronomic and economic benefits than unshaded coffee (Borkhataria et al., 2012; Rahn et al., 2018; Van Asten et al., 2011). Therefore, a policy intervention to emphasize the benefits of shaded coffee to farmers could focus on increasing farmers' intention to incorporate trees in their coffee gardens. For instance, government programmes could capitalize upon the emerging international markets for sustainably produced shade-grown coffee (Borkhataria et al., 2012), specialty coffee (Linton, 2008), voluntary and non-voluntary carbon credit schemes (McAfee & Shapiro, 2010; Pandey, 2002; Tumwebaze & Byakagaba, 2016) and provision of other incentives for the production of shaded coffee. Such interventions will reinforce the positive attitudes of the farmers already embracing shaded coffee and may change the attitudes of those who view shaded coffee negatively.

Although attitude was the main determinant, perceived behavioural control also influenced farmers' intention to plant trees in their coffee gardens. However, mixed results have been reported on the ability of perceived behavioural control construct to predict behaviour. A related study in Brazil reported that perceived behavioural control positively influenced farmers' intention to diversify agricultural production (Senger et al., 2017b), although the study did not use a confirmatory factor analysis to check for construct reliability. Another study on consumer attitudes relating to the use of gene technology in tomato production indicated a negative influence of perceived behavioural control on intention of eating the tomatoes (Saba & Vassallo, 2002). The positive influence of perceived behavioural control on intention in the current study implies that the positive beliefs that smallholder farmers have the capability to plant and manage trees in their coffee plantations reinforced their intention. The positive beliefs were based on farmers' confidence to overcome social and economic barriers to tree planting, as well as having the resources (such as land, labour and seedlings) and sufficient knowledge on tree planting and management.

However, in the context of this study, a positive and significant influence of perceived behavioural control on farmers' intention to integrate trees in coffee would consider these farmers to be self-reliant, in a sense. One interpretation of this could be that rural people rely more on tacit and indigenous knowledge when engaging in tree planting and less on explicit/formal knowledge (Ofoegbu & Speranza, 2017). This renders perceived behavioural control to be a reliable predictor of behaviour that should be put into consideration when implementing research and development programmes among smallholder farmers.

In this study, subjective norm had no significant influence on farmers' intention to integrate trees in their coffee plantations. This is in contrast with other studies that have reported subjective norm as the main predictor of behavioural intention. For example, a study in South Africa reported that subjective norm had the strongest influence on intention to adopt sustainable forest use and management practices (Ofoegbu & Speranza, 2017). The intention of farmers to use improved natural grassland in Brazil was also mainly influenced by their perceptions about the social pressure to use the innovation (Borges & Lansink, 2016). However, in a meta-analyses review of TPB studies, subjective norm was found to typically contribute less to explanations of variance on people's intention and behaviour than attitude or perceived behavioural control (Armitage & Conner, 2001). Subjective norm was also found to be insignificant in predicting people's intention to recycle (Tonglet et al., 2004).

The lack of social pressure among farmers in this study also points to the lack of influence of other people's behaviour on fellow farmers. Previous research identified that family, friends and rural extension agents can increase social pressure and influence farmers' behaviour (Borges & Lansink, 2016; Meijer et al., 2015; Ofoegbu & Speranza, 2017). However, from the present study, farmers tend to deny the influence of other people's behaviour on their actions, which suggests that people are unaware of their influence. It is therefore likely that farmers will deny the influence by important others when asked about it. A related study among smallholder farmers in 6 African countries acknowledged limited co-learning to access and quality of information (Brown et al., 2018). More than one-third of the respondents in the study did not seek information from other farmers because they did not feel the information was reliable. The perceived lack of access to information from fellow farmers is often related to farmers' social connectedness and status within the farming community.

6.6.2 Relevance of study methodology

The results of this study demonstrate the use of the theory of planned behaviour (TPB) framework and structural equation modeling (SEM) analytical techniques to explain the behavioural drivers of smallholder farmers' intention for adoption of shaded coffee on their farms. This approach demonstrates potential for understanding the complex behaviour of smallholder farmers towards agroforestry. The significant influence of perceived behavioural control of farmers' intention to plant trees in coffee plantations emphasises the relevance of using the theory of planned behaviour (with ATT, SN and PBC constructs) in this study over the theory of reasoned action (TRA) which does not recognize the component of perceived behavioural control. A number of studies have preferred TRA to TPB when explaining farmers' intentions and behaviour (Senger et al., 2017a; Yazdanpanah et al., 2014), suggesting that farmers are usually under either attitudinal or normative control.

In other instances, TPB has been ignored due to low internal reliability of the perceived behavioural control construct (Saba & Vassallo, 2002; Senger et al., 2017a). However, within the context of the current study, while farmers may hold positive attitudes towards shading of coffee, this does not necessarily mean that they will engage in planting trees in their coffee gardens. Indeed, the performance of the planting behaviour could be constrained by the lack of appropriate opportunities, technical skills, financial and human resources. There was however a shortcoming in designing the data collection tool where the agronomic and economic benefits from integrating agroforestry trees in coffee should have been listed as behavioural beliefs in the TPB questionnaire.

6.7 Conclusion

Resource constraints and socio-economic factors have been widely acknowledged, but there has been limited focus on the psychological factors that constrain adoption of agricultural technologies. Farmers may fail to take up agricultural innovations simply because the new technologies are not aligned to the social norms and customs of the community during research and or technology transfer. The components of the TPB relate to the key aspects affecting smallholder farmers' decision-making on the integration of trees in their coffee gardens in the Mt. Elgon region of Uganda. This study demonstrated how the various components of TPB (attitude, subjective norm and perceived behavioural control) influence farmers' intentions to adopt shaded coffee. Our findings show that attitude had a larger influence than perceived behavioural control and subjective norm on farmers' intention to integrate trees in their coffee plantations. Smallholder farmers evaluated integration of trees in coffee as more favourable compared with unshaded coffee. However, the influence of social pressure to plant trees in their coffee gardens was insignificant. While this study focused on three psychological constructs – Attitude, Subjective Norms and Perceived Behavioural Control – to understand smallholder farmers' intention toward integration of trees in coffee, other non-psychosocial factors that may influence farmers' behavior were not captured. To this end, future application of the TPB framework should include additional factors such as the role of institutions and environmental concern by farmers.

6.8 References

Ajzen, I., 1991. The theory of planned behaviour. *Organizational Behaviour and Human Decision Processes, 50*(2), 179-211. doi: https://doi.org/10.1016/0749-5978(91)90020-T

Ajzen, I., 2005. *Attitudes, Personality and Behaviour*. Berkshire, UNKNOWN: McGraw-Hill Education.

Ajzen, I., 2011. The theory of planned behaviour: Reactions and reflections. *Psychology & Health, 26*(9), 1113-1127. doi: 10.1080/08870446.2011.613995

Anderson, J. C., Gerbing, D. W., 1988. Structural Equation Modeling in Practice: A Review and Recommended Two-Step Approach. *Psychological Bulletin, 103*(3), 411-423. doi: 10.1037/0033-2909.103.3.411

Armitage, C. J., Conner, M., 2001. Efficacy of the Theory of Planned Behaviour: A meta-analytic review. *British Journal of Social Psychology, 40*(4), 471-499. doi: 10.1348/014466601164939

Borges, J. A. R., Lansink, O. A. G. J. M., 2016. Identifying psychological factors that determine cattle farmers' intention to use improved natural grassland. *Journal of Environmental Psychology*, *45*(C), 89-96. doi: 10.1016/j.jenvp.2015.12.001

Borges, J. A. R., Oude Lansink, A. G. J. M., Marques Ribeiro, C., Lutke, V., 2014. Understanding farmers' intention to adopt improved natural grassland using the theory of planned behaviour. *Livestock Science, 169*, 163-174. doi: https://doi.org/10.1016/j.livsci.2014.09.014

Borkhataria, R., Collazo, J. A., Groom, M. J., Jordan-Garcia, A., 2012. Shade-grown coffee in Puerto Rico: Opportunities to preserve biodiversity while reinvigorating a struggling agricultural commodity. *Agriculture, Ecosystems and Environment, 149*(C), 164-170. doi: 10.1016/j.agee.2010.12.023

Brown, B., Llewellyn, R., Nuberg, I., 2018. Why do information gaps persist in African smallholder agriculture? Perspectives from farmers lacking exposure to conservation agriculture. *The Journal of Agricultural Education and Extension, 24*(2), 191-208. doi: 10.1080/1389224X.2018.1429283

Buyinza, J., Muthuri, C., Downey, A., Njoroge, J., Denton, M., Nuberg, I., 2019. Contrasting water use patterns of two important agroforestry tree species in the Mt. Elgon region of Uganda. *Australian Forestry, In press*. doi: https://doi.org/10.1080/00049158.2018.1547944

Caveness, F., Kurtz, W., 1993. Agroforestry adoption and risk perception by farmers in Sénégal. *An International Journal incorporating Agroforestry Forum, 21*(1), 11-25. doi: 10.1007/BF00704923

Cedamon, E., Nuberg, I., Pandit, B., Shrestha, K., 2018. Adaptation factors and futures of agroforestry systems in Nepal. *An International Journal incorporating Agroforestry Forum, 92*(5), 1437-1453. doi: 10.1007/s10457-017-0090-9

Cullen, R., 2009. Factors influencing adoption of agroforestry among smallholder farmers in Zambia (Vol. 97135): New Zealand Agricultural and Resource Economics Society.

Dang, H., Li, E., Nuberg, I., Bruwer, J., 2014. Understanding farmers' adaptation intention to climate change: A structural equation modelling study in the Mekong Delta, Vietnam. *Environmental Science and Policy*. doi: 10.1016/j.envsci.2014.04.002

Etshekape, P. G., Atangana, A. R., & Khasa, D. P. (2018). Tree planting in urban and peri-urban of Kinshasa: Survey of factors facilitating agroforestry adoption. *Urban Forestry & Urban Greening, 30*, 12-23. doi: 10.1016/j.ufug.2017.12.015

Gram, G., Vaast, P., Wolf, J., Jassogne, L., 2018. Local tree knowledge can fast-track agroforestry recommendations for coffee smallholders along a climate gradient in Mount Elgon, Uganda. *An International Journal incorporating Agroforestry Forum, 92*(6), 1625-1638. doi: 10.1007/s10457-017-0111-8

Hair, J. F., Black, W. C., Babin, B. J., Anderson, R. E., 2010. *Multivariate data analysis* (7th ed. ed.). Upper Saddle River, NJ: Prentice Hall.

Hildreth, L. A., 2012. Principles and Practice of Structural Equation Modeling (3rd Edition): Rex B. Kline. New York, NY: Guilford Press, 2011. ISBN 978-1-60623-876-9. vii+366 pp. *The American Statistician*. doi: 10.1080/00031305.2011.645761

Kaweesa, S., Mkomwa, S., Loiskandl, W., 2018. Adoption of conservation agriculture in Uganda: A case study of the Lango subregion. *Sustainability (Switzerland), 10*(10), <xocs:firstpage xmlns:xocs=""/>. doi: 10.3390/su10103375

Lalani, B., Dorward, P., Holloway, G., Wauters, E., 2016. Smallholder farmers' motivations for using Conservation Agriculture and the roles of yield, labour and soil fertility in decision making. *Agricultural Systems, 146*, 80-90. doi: https://doi.org/10.1016/j.agsy.2016.04.002

Linton, A., 2008. A Niche for Sustainability? Fair Labor and Environmentally Sound Practices in the Specialty Coffee Industry. *Globalizations, 5*(2), 231-245. doi: 10.1080/14747730802057621

Martínez-García, C. G., Dorward, P., Rehman, T., 2013. Factors influencing adoption of improved grassland management by small-scale dairy farmers in central Mexico and the implications for future research on smallholder adoption in developing countries. *Livestock Science, 152*(2-3), 228-238. doi: 10.1016/j.livsci.2012.10.007

McAfee, K., Shapiro, E. N., 2010. Payments for Ecosystem Services in Mexico: Nature, Neoliberalism, Social Movements, and the State. *Annals of the Association of American Geographers, 100*(3), 579-599. doi: 10.1080/00045601003794833

Meijer, S. S., Catacutan, D., Sileshi, G. W., Nieuwenhuis, M., 2015. Tree planting by smallholder farmers in Malawi: Using the theory of planned behaviour to examine the relationship between attitudes and behaviour. *Journal of Environmental Psychology, 43*, 1-12. doi: 10.1016/j.jenvp.2015.05.008

MENA Report., 2018. Trees For Food Security 2: Developing Integrated Options And Accelerating Scaling Up Of Agroforestry For Improved Food Security And Resilient Livelihoods In Eastern Africa. London: Trade Journals.

Nahayo, A., Pan, G., Joseph, S., 2016. Factors influencing the adoption of soil conservation techniques in Northern Rwanda. *Journal of Plant Nutrition and Soil Science, 179*(3), 367-375. doi: 10.1002/jpln.201500403

Nyaga, J., Barrios, E., Muthuri, C. W., Öborn, I., Matiru, V., Sinclair, F. L., 2015. Evaluating factors influencing heterogeneity in agroforestry adoption and practices within smallholder farms in Rift Valley, Kenya. *Agriculture, Ecosystems and Environment, 212*(C), 106-118. doi: 10.1016/j.agee.2015.06.013

Ofoegbu, C., Speranza, I. C., 2017. Assessing rural peoples' intention to adopt sustainable forest use and management practices in South Africa. *Journal of Sustainable Forestry, 36*(7), 729-746. doi: 10.1080/10549811.2017.1365612

Oyana, T. J., Kayendeke, E., Bamutaze, Y., Kisanga, D., 2015. A field assessment of land use systems and soil properties at varied landscape positions in a fragile ecosystem of Mount Elgon, Uganda. *African Geographical Review, 34*(1), 83-103. doi: 10.1080/19376812.2014.929970

Pandey, D. N., 2002. Carbon sequestration in agroforestry systems. *Climate Policy, 2*(4), 367-377. doi: 10.3763/cpol.2002.0240

Pattanayak, S., Evan Mercer, D., Sills, E., Yang, J.-C., 2003. Taking stock of agroforestry adoption studies. *An International Journal incorporating Agroforestry Forum, 57*(3), 173-186. doi: 10.1023/A:1024809108210

Rahn, E., Liebig, T., Ghazoul, J., van Asten, P., Läderach, P., Vaast, P., . . . Jassogne, L., 2018. Opportunities for sustainable intensification of coffee agro-ecosystems along an altitudinal gradient on Mt. Elgon, Uganda. *Agriculture, Ecosystems and Environment, 263*, 31-40. doi: 10.1016/j.agee.2018.04.019

Reimer, A. P., Weinkauf, D. K., Prokopy, L. S., 2012. The Influence of Perceptions of Practice Characteristics: An Examination of Agricultural Best Management Practice Adoption in Two Indiana Watersheds. *Journal of Rural Studies, 28*(1), 118-128. doi: 10.1016/j.jrurstud.2011.09.005

Saba, A., Vassallo, M., 2002. Consumer attitudes toward the use of gene technology in tomato production. *Food Quality and Preference, 13*(1), 13-21. doi: 10.1016/S0950-3293(01)00052-0

Senger, I., Borges, J. A. R., Machado, J. A. D., 2017a. Using structural equation modeling to identify the psychological factors influencing dairy farmers' intention to diversify agricultural production. *Livestock Science*, *203*, 97-105. doi: https://doi.org/10.1016/j.livsci.2017.07.009

Senger, I., Borges, J. A. R., Machado, J. A. D., 2017b. Using the theory of planned behaviour to understand the intention of small farmers in diversifying their agricultural production. *Journal of Rural Studies, 49*(C), 32-40. doi: 10.1016/j.jrurstud.2016.10.006

Sood, K. K., Mitchell, C. P., 2006. Importance of human psychological variables in designing socially acceptable agroforestry systems. *Forests, Trees and Livelihoods*, *16*(2), 127-137. doi: 10.1080/14728028.2006.9752551

Thangata, P. H., Alavalapati, J. R. R., 2003. Agroforestry adoption in southern Malawi: the case of mixed intercropping of Gliricidia sepium and maize. *Agricultural Systems*, *78*(1), 57-71. doi: 10.1016/S0308-521X(03)00032-5

Tobi, H., & Kampen, J. K. (2017). Research design: the methodology for interdisciplinary research framework. *Quality & Quantity*. doi: 10.1007/s11135-017-0513-8

Tonglet, M., Phillips, P. S., Read, A. D., 2004. Using the Theory of Planned Behaviour to investigate the determinants of recycling behaviour: a case study from Brixworth, UK. *Resources, Conservation & Recycling, 41*(3), 191-214. doi: 10.1016/j.resconrec.2003.11.001

Tumwebaze, S. B., Byakagaba, P., 2016. Soil organic carbon stocks under coffee agroforestry systems and coffee monoculture in Uganda. *Agriculture, Ecosystems & Environment, 216*, 188-193. doi: doi: 10.1016/j.agee.2015.09.037

UBoS (2017), *Statistical Abstract.* Uganda Bureau of Statistics, Kampala, Uganda.

UGANDA., 2010. One million trees for Mt Elgon region. IRIN Africa English Service, 3 Nov. 2010.: Academic OneFile http://link.galegroup.com/apps/doc/A241222656/AONE?u=adelaide&sid=AONE&xid=ad60a518.

Van Asten, P. J. A., Wairegi, L. W. I., Mukasa, D., Uringi, N. O., 2011. Agronomic and economic benefits of coffee-banana intercropping in Uganda's smallholder farming systems.(Report). *Agricultural Systems*, *104*(4), 326. doi: 10.1016/j.agsy.2010.12.004

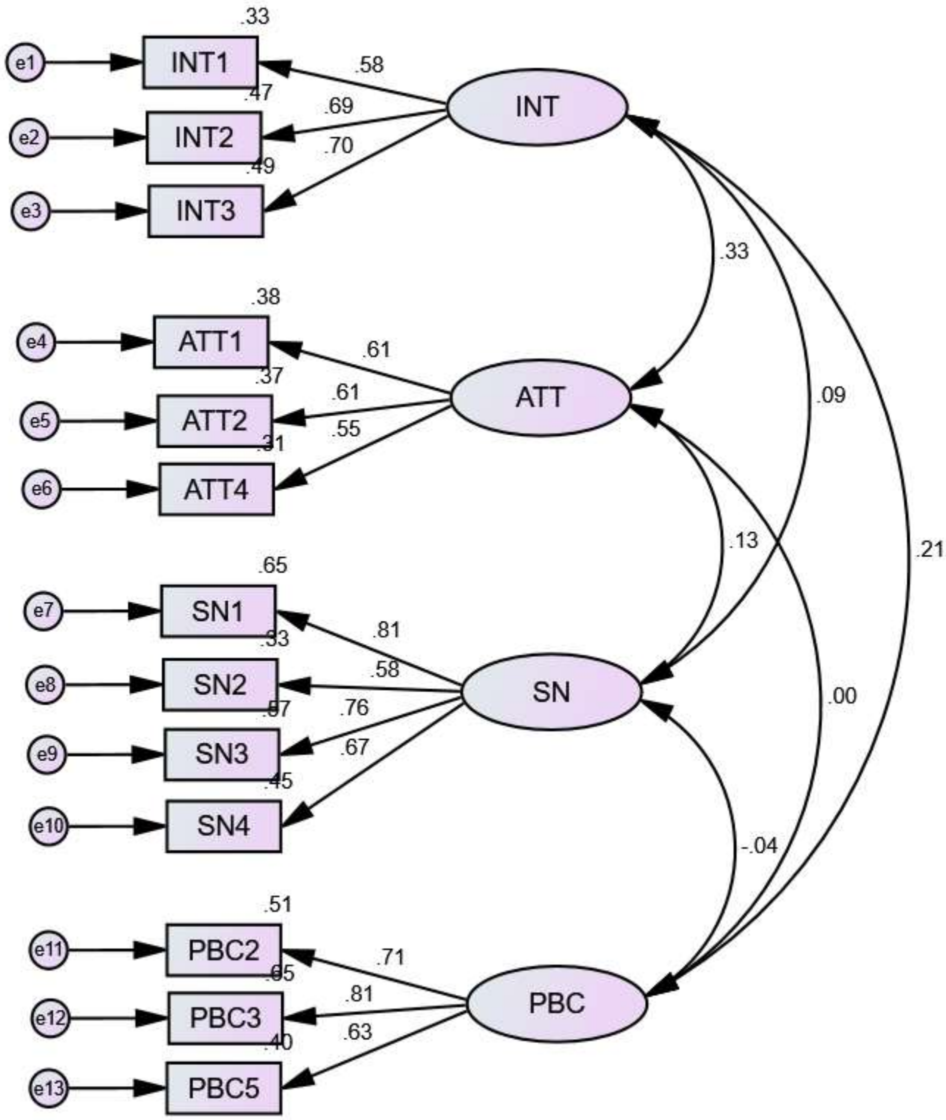
Wauters, E., Bielders, C., Poesen, J., Govers, G., Mathijs, E., 2010. Adoption of soil conservation practices in Belgium: An examination of the theory of planned behaviour in the agri-environmental domain. *Land Use Policy, 27*(1), 86-94. doi: https://doi.org/10.1016/j.landusepol.2009.02.009

Winterbottom, R., Reij C., Garrity D., Glover J., Hellums D., Mcgahuey M and Scherr S. 2013. Improving land and water management. Installment 4 of "Creating a Sustainable Food Future". World Resource Institute, working paper.

World Bank., 2016. UGANDA: World Bank Poverty Assessment. *Africa Research Bulletin: Economic, Financial and Technical Series, 53*(9), 21423A-21425A. doi: 10.1111/j.1467-6346.2016.07291.x

Yazdanpanah, M., Hayati, D., Hochrainer-Stigler, S., Zamani, G. H., 2014. Understanding farmers' intention and behaviour regarding water conservation in the Middle-East and North Africa: A case study in Iran. *Journal of Environmental Management, 135*, 63-72. doi: 10.1016/j.jenvman.2014.01.016

Supplementary figure I. Overall path diagram with four constructs unobserved variable and thirteen observed variables selected for the structural model



Supplementary Table 1. Demographic characteristics of the sample, minimum values (Min), maximum (Max), mean and standard deviation (SD)

Variable	Min.	Max.	Mean	SD
Age (years)	22	76	41.3	11.9
Household size (No. of males)	1	13	4.1	2.3
Household size (No. of females)	0	14	3.8	2.4
Total household size	2	20	7.9	3.5
Active farm workers in household (No. of males)	0	12	1.9	1.6
Active farm workers in household (No. of females)	0	11	2.9	1.5
Total active farm workers	1	14	4.8	2.2

Supplementary Table 2. Multi-collinearity test for the TPB measurable variables

Coefficients								
		Unstandardized Coefficients		Standardized Coefficients			Collinearity Statistics	
Model		B	Std. Error	Beta	T	Sig.	Tolerance	VIF
1	(Constant)	3.272	.762		4.293	.000		
	INT2	.082	.083	.057	.993	.321	.675	1.482
	INT3	.284	.075	.217	3.768	.000	.682	1.466
	INT1	.073	.077	.053	.955	.340	.730	1.370
	ATT1	.066	.068	.052	.972	.332	.785	1.274
	ATT2	.148	.080	.100	1.844	.066	.761	1.313
	ATT4	-.058	.077	-.040	-.756	.450	.794	1.260
	SN1	-.022	.051	-.029	-.423	.673	.494	2.024
	SN2	-.035	.040	-.050	-.877	.381	.701	1.427
	SN3	.034	.051	.044	.667	.505	.529	1.892
	SN4	.048	.045	.064	1.054	.292	.605	1.652
	PBC2	.001	.065	.001	.017	.987	.599	1.669
	PBC3	.041	.054	.048	.755	.451	.566	1.765
	PBC5	-.200	.060	-.203	-3.354	.001	.615	1.625

Supplementary Table 3. Mean, standard deviation (SD) and correlation of the TPB measured variables

	INT1	INT2	INT3	ATT1	ATT2	ATT4	SN1	SN2	SN3	SN4	PBC2	PBC3	PBC5
INT1	1												
INT2	.382**	1											
INT3	.399**	.493**	1										
ATT1	.124*	.140**	.110*	1									
ATT2	.157**	.228**	.129**	.358**	1								
ATT4	.083	.109*	.055	.356**	.339**	1							
SN1	.049	.114*	.020	.076	.017	.013	1						
SN2	-.001	.085	-.011	.062	.069	-.005	.512**	1					
SN3	-.016	.093	.057	.134**	.101*	.069	.602**	.387**	1				
SN4	.003	.029	-.006	.025	.072	.010	.526**	.363**	.549**	1			
PBC2	.099*	-.002	.067	.011	.120*	.055	.037	-.065	-.061	.053	1		
PBC3	.192**	.032	.139**	-.025	.024	.041	.013	-.124*	-.099*	.025	.582**	1	
PBC5	.262**	.037	.188**	-.114*	-.067	-.147*	.037	-.073	-.055	-.072	.449**	.499**	1
Mean	6.37	6.07	6.20	6.17	6.19	6.17	5.21	4.07	5.32	4.75	5.28	4.66	5.44
SD	0.81	0.78	0.854	0.88	0.76	0.77	1.47	1.09	1.42	1.52	1.05	1.30	1.14

***. Correlation is significant at the 0.01 level (2-tailed); *. Correlation is significant at the 0.05 level (2-tailed).*

Chapter 7: Assessing smallholder farmers' motivation to adopt agroforestry using a multi-group structural equation modeling approach

7.1 Statement of Authorship

Title of Paper	**Assessing smallholder farmers' motivation to adopt agroforestry using a multi-group structural equation modeling approach**
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Principal Author

Name of Principal Author (Candidate)	Joel Buyinza		
Contribution to the Paper	Identification of research gap, theoretical foundation, data collection and analysis, interpretation of finding, writing manuscript and acted as the first and corresponding author		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	16/04/2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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Contribution to the Paper	Supervision, evaluation and reviewing manuscript		
Signature		Date	6/07/2021

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Contribution to the Paper	Supervision, editing and reviewing the manuscript		
Signature		Date	22/06/2021

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Assessing smallholder farmers' motivation to adopt agroforestry using a multi-group structural equation modeling approach

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Abstract This study applied the multi-group structural equation modeling technique to identify differences in farmer motivations to adopting agroforestry practices in the Mt. Elgon region of Uganda. Data were collected from interviews with 400 smallholder coffee farmers belonging to four categories which included: (1) those actively participating in an Australian-funded trees for food security (T4FS) project from phase 1 (2014); (2) farmers neighbouring those actively participating in the T4FS project; (3) farmers actively participating in the T4FS project from phase 2 (2017) and; (4) farmers living distant and unaware of the T4FS project. We used the theory of planned behaviour framework to assess the adoption behaviour of these farmer categories resulting from project interventions. About 40% of the variation in farmer motivation to integrate trees in their coffee plantations was explained by the significant variables of 'attitude' and 'perceived behavioural control' among farmers actively participating in the T4FS project from phase 1. However, the neighbors of participating farmers and farmers who had never interacted with the project were only motivated by 'attitude' and 'social norms' respectively. Farmer motivation resulting from social pressure was strongest among farmers who had never interacted with the project, and in the absence of project interventions, rely on existing social structures to drive change in their community. Farmers' perceived behavioural control to overcome tree planting barriers and their attitude to the economic benefits of shaded coffee were significantly different among the four farmer categories ($p < 0.05$). The findings indicate that psychological factors are key drivers to the farmers' internal decision-making process in agroforestry technology adoption and can be context-specific. The adoption behaviour of smallholder farmers is mainly shaped by existing community social norms and beliefs that tend to promote knowledge exchange, as opposed to the conventional knowledge transfer extension approaches. Norms are therefore an inherent part of social systems and can create distinct farming practices, habits and standards within a social group. Researchers and extension agents can act upon these identified positive attitudes, norms and perceived behavioural controls to guarantee adoption and sustainability of agricultural technologies.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10457-020-00541-2) contains supplementary material, which is available to authorized users.

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Keywords Coffee agroforestry · Psychological drivers · Motivation · Adoption · Uganda

This study applied the multi-group structural equation modeling technique to identify the differences in farmer psychological drivers to adopt shaded coffee across four farmer categories in the Mt. Elgon region of Uganda. The selection of farmer categories was based on the duration of implementation of an Australian government funded project in the Mt. Elgon region of Uganda. The T4FS is an Australian

7.2 Introduction

Population growth in Sub-Saharan Africa has greatly contributed to the ever increasing intensive agriculture and related land use pressures (Meijer et al. 2015). Many smallholder farmers in Sub-Saharan Africa must deal with low and unpredictable crop yields and incomes. There is an urgent need for sustainable agricultural practices that can address these issues. However, most options to improve productivity involve the use of expensive inputs that inherently increase risks that farmers are often unable to bear. Agroforestry is a cheaper option that offers a wide range of benefits to farmers including increasing crop yield and food security (Garrity et al. 2010). Farming systems with fertilizer trees are inexpensive and significantly increase crop yields and food security while enhancing associated environmental services (Akinnifesi et al. 2010; Ajayi et al. 2011). Although the benefits of agroforestry are well known and various innovations are being used by farmers, there has not been widespread adoption (Meijer et al. 2015). There are also cases where some agroforestry technologies have been adopted, and later abandoned in some communities (Kiptot et al. 2007).

Although several studies have documented the extrinsic factors influencing agroforestry adoption (Mukadasi et al. 2007; Barungi et al. 2013; Gram et al. 2018; Rahn et al. 2018), the reasons for the relatively low adoption rates are still not fully understood. There is a general concern that researchers need to pay more attention to the internal decision-making process, and look beyond the mere characteristics of agricultural innovations and the household to include psychological factors in technology uptake (Sood and Mitchell 2006; Mekoya et al. 2008; Borges et al. 2014; Senger et al. 2017). However, these studies have rarely been applied to agroforestry adoption, especially in the Mt. Elgon region of Uganda.

This study applied the multi-group structural equation modeling technique to identify the differences in farmer psychological drivers to adopt shaded coffee across four farmer categories in the Mt. Elgon region of Uganda. The selection of farmer categories was based on the duration of implementation of an Australian government funded project in the Mt. Elgon region of Uganda. The T4FS is an Australian Centre for International Agricultural Research (ACIAR) funded project aimed at improving household food security and smallholder livelihoods through widespread adoption of appropriate locally adapted agroforestry practices in key agricultural landscapes in Ethiopia, Rwanda and Uganda. The project has been reaching out to smallholder farmers in rural regions where an estimated 10 million people are facing acute food security problems since 2012. It has demonstrated the importance of trees in fields and farming landscapes for enhancing and sustaining crop yield and food security in Eastern Africa. In Uganda, the T4FS project started in 2014 and currently in its second phase of implementation in the Mt. Elgon region of Uganda (www.worldagroforestry.org/project/trees-food-security-2-developing-integrated-options-and-accelerating-scaling-agroforestry).

The importance of trees in fields has been demonstrated among smallholder coffee farmers through participatory on-farm trials involving planting of trees in coffee farming systems in Eastern Uganda. Coffee is shade tolerant and traditionally grown under shade trees in complex agroforestry systems (Franck and Vaast 2009). However, there has been a general transformation of coffee farming by eliminating shade trees, increasing agrochemical inputs and selecting genotypes - all to increase short-term income (Jezeer and Verweij 2015). The question of whether coffee provides benefits from shade trees has been widely disputed where yield potential, competition for water and nutrients and pest and disease incidence are central issues in this controversy (Beer et al. 1997; Damatta 2004; DaMatta and Ramalho 2006). Nonetheless, there is substantial evidence that unshaded coffee plantations generally require high levels of external inputs to maximize yield (Damatta 2004; Jezeer et al. 2018), a cost smallholder farmers in the Mt. Elgon region can seldom afford. The cheaper alternative available to smallholder coffee farmers is the integration of shade trees, facilitated by the T4FS project, to sustain their coffee production. The study addresses the extent to which project interventions influenced smallholder farmers' motivations to integrate trees in their coffee farming systems.

7.2.1 Theoretical background of the study

To investigate smallholder farmers' motivation to adopt shaded coffee on their farms, this study employed the Theory of Planned Behaviour (TPB), which suggests that behavioural intentions are shaped by attitude, subjective norms and perceived behavioural control (Ajzen 2011). This study adopted the Theory of Planned Behaviour (TPB) due to the limitations associated with other theories such as Theory of Diffusion of Innovations (DIT) (Rogers 2003), Theory of Reasonable Action (TRA) (Fishbein and Ajzen 2010) and the Technology Acceptance Model (TAM) (Rafique et al., 2020; Scherer et al., 2019; Venkatesh and Davis 1996). For example, while the DIT has been reported to be market focused (Lai 2017), rendering it vital for organization implementation, TRA ignores the perceived behavioural control construct, which was reported to be vital by Buyinza et al. (2020). The final version of TAM eliminates the need for the attitude construct (Lai 2017), a key social aspect among smallholder farmers.

The TPB used in this study is an expectancy-value model that provides a useful framework for understanding the correlation between attitude and the underlying beliefs (Meijer et al. 2015). It offers a theoretical foundation for studying psychological factors that influence people's intentions and behaviours. The components of the TPB (attitude, subjective norm and perceived behavioural control) relate to the key aspects influencing smallholder farmers' decision-making on integration of trees in their coffee plantations in the Mt. Elgon region of Uganda (Buyinza et al. 2020). Attitude is the degree to which execution of a behaviour is positively or negatively evaluated (Wauters et al. 2010). Subjective norm refers to a person's perception of the social pressure upon them to perform or not perform a behaviour, and perceived behavioural control is the perceived personal capability (perceptions of difficulties and possibilities) to successfully perform the behaviour (Borges and Lansink 2016).

7.3 Methods

7.3.1 Study area

The study was conducted in three districts including Manafwa, Bududa and Sironko, located in Mt. Elgon region of Uganda (Fig. 1). The study was conducted in three districts including Manafwa, Bududa and Sironko, located on the slopes of Mt. Elgon in Eastern Uganda (Fig. 1). In terms of climate, the area receives a bimodal pattern of rainfall with an average annual rainfall of 1500 mm. The region has peak rainy seasons that occur in the months of April-May and September-November, occasionally characterized by landslides (Atuyambe et al. 2011; Broeckx et al. 2019; Nakileza et al. 2017). However, a pronounced dry period occurs from December to February, with a mean annual temperature of 23^{o}C. The soils are generally classified as inorganic clays of high plasticity (Mugagga et al. 2012) and local farming communities live between 1000 m.a.s.l. at the foothill and 2200 m.a.s.l. close to the protected Mt. Elgon National Park. Due to the relatively high population density of approximately 250-300 inhabitants per km^2 (Gram et al. 2018), the landscape mainly consists of smallholder farms (<2 acres) with intensive and mixed coffee (*C. arabica*) agricultural systems. However, coffee productivity has been reported to be substantially lower than its potential due to low soil fertility and poor land and coffee tree management practices (Wang et al. 2015).

In terms of the general social setting of the community, participation in farmer group activities has been reported to be generally dominated by male farmers and coffee has been categorized as a male-controlled crop (Ochago 2017). Women have been reported to have limited access to and control over coffee management inputs and benefits (Ochago 2017), a key barrier to their coffee farming decision making. However, local knowledge on agroforestry has been reported to be gender blind in the region, with no differences observed in ranking of tree species and ecosystem services between men and women (Gram et al. 2018). Communities close to the National Park are reluctant to invest in long term conservation techniques due to the land tenure insecurity (Mugagga and Buyinza 2013).

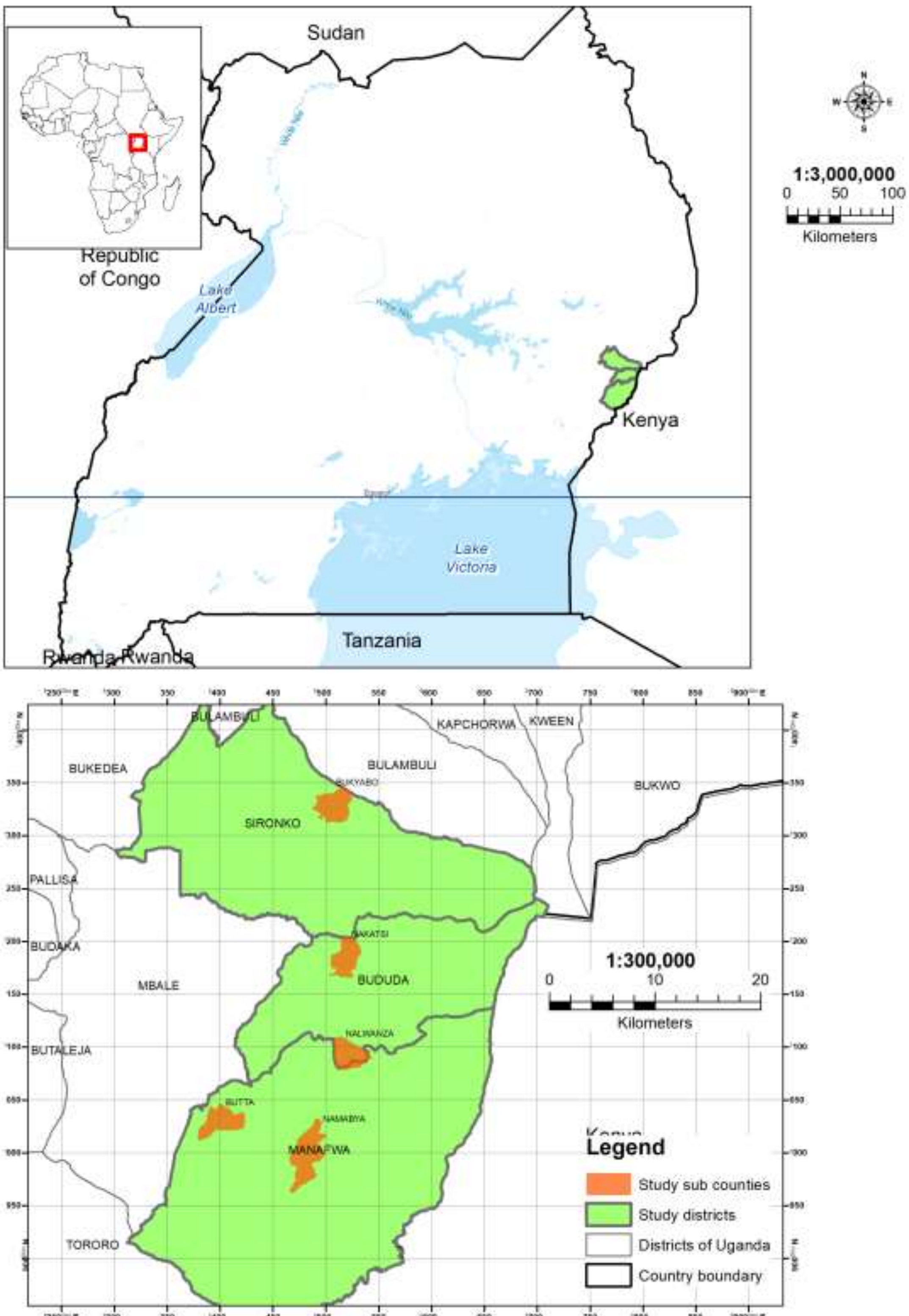

Fig. 1 Map showing study sites

7.3.2 Sampling and survey

In this study, four respondent categories were purposively selected and these were: (1) farmers actively participating in the T4FS project from phase one beginning in 2014; (2) farmers neighbouring those actively participating in the T4FS project; (3) farmers actively participating in the T4FS project from phase 2 beginning in 2017; and (4) farmers who have never participated in the T4FS project and living far from project participating farmers. The farmers actively participating in the project since its inception and those neighbouring active project participants, were selected from Manafwa district, the only area where the T4FS project has been operating since 2014. Farmers actively participating in the second phase of the project and those who had never participated in the T4FS project were selected from Bududa and Sironko districts respectively. While Bududa district is among the districts where the second phase of the project is being implemented (since 2017), there are no T4FS project interventions in Sironko district. However, the farming systems, ethnicity and culture are identical across the three districts.

Prior to the main survey, a pre-test was carried out with 15 farmers to ensure that the questions could be clearly understood. The final version of the survey tool consisted of three groups of questions: socio-demographic characteristics; farmers' opinions and assessment of existing agroforestry practices; and questions based on TPB. This paper only addresses socio-demographic characteristics and TPB questions in relation to the four respondent categories. A sample of 100 respondents was randomly selected for each respondent category, giving a total of 400 respondents for the entire study. While a random sample of farmers actively participating in the project since its inception and farmers actively participating in phase 2 of the project was obtained from the list of project beneficiaries, farmers who had never participated in the project were randomly selected from a list of households from the local council leaders. A list of farmers neighbouring project beneficiaries was generated with the help of local leaders, from which a random sample was obtained. A simple random sampling technique was used to select random samples. The data collection took place from May to July 2018.

7.4 Data analysis

7.4.1 Model estimation

Structural equation modeling (SEM) quantifies the underlying relationships between latent constructs. SEM is a series of models that are combined in a single platform (Hair et al. 2010). However, two fundamental models are included in SEM: (1) a measurement model, which is a linear model that generates the latent constructs as a function of the observed variables; and (2) a structural model (also known as a path analysis), that quantifies the relationships between the latent constructs (Hair et al. 2010; Fonseca 2013). Multi-group SEM provides a simultaneous estimation of different interdependent multiple regressions (Hair et al. 2010) that allows analysis of several groups of data from a population. While SEM can be conducted with each separate subset of data individually, simultaneous analysis is preferred because it allows testing of the significance of any differences among groups. Simultaneous analysis also provides a more accurate estimation of the group parameters, whether there are group differences or not.

The structural model validated by Buyinza et al (2020) was used to proceed with the multi-group analysis in this paper (Fig. 2). The four groups of data were the farmer sample groups mentioned above. Multi-group SEM aims to identify the differences in farmer psychological motivations to adopt agroforestry practices across these farmer categories in the Mt. Elgon region of Uganda. The differences concern whether farmers at different levels of interaction with the T4FS research project differ from each other in psychological factors that influence their intention to incorporate trees in coffee plantations. The results address to what extent project interventions influence smallholder farmers' adoption of agroforestry practices. The four TPB latent constructs (attitude, subjective norm, perceived behavioural control and intention) are used in the structural model. The variables that represent the constructs are shown in Table 1.

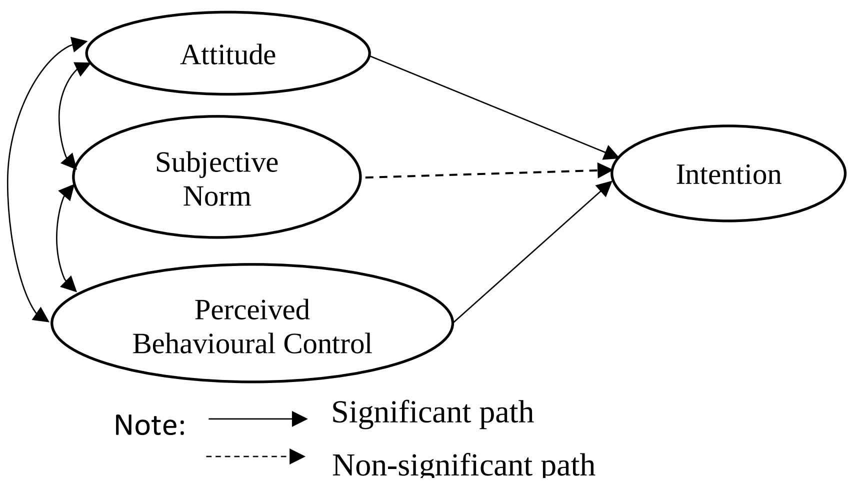

Fig. 2 Structural model for farmers' intention to adopt trees on-farm (Adapted from Buyinza et al. 2020)

Estimation was run by IBM SPSS Amos 25. Although goodness-of-fit (GOF) indices have four categories, (including Chi-square test, absolute fit indices, incremental fit indices and parsimonious fit indices), using the Chi-square test and at least one index from each of the other groups is the rule of thumb (Hair et al. 2010). This approach has also been seen in other SEM studies (van Der Veen and Song 2014; Dang et al. 2018). Other model fit indices estimated include the Ratio of Confirmatory Fit Index to degrees of freedom (CMIN/DF), Incremental Fit Index (IFI), Comparative Fit Index (CFI), Root Mean Square Error of Approximation (RMSEA) and the

Probability of getting a sample RMSEA as large as its calculated value in the given model (PCLOSE). The structural model in Figure 1 shows an acceptable model fit (χ^2 = 141.631, df= 59, *p*= .000, CMIN/DF= 2.401, IFI= 0.933, TLI= 0.910, CFI= 0.932, RMSEA= 0.059 and PCLOSE=0.107).

7.4.2 Multi-group Structural Equation Analysis

Using the validated structural model, two structural models were estimated as meeting the requirements of the multi-group SEM technique. The first was the unconstrained structural model in which all parameters were to be estimated for each of the four groups. The second model was estimated with selected controlled path coefficients. In this study, the controlled path coefficient was the subjective norm, which was insignificant in the structural model (Fig. 2). This second model assumes that some parameters in one group are equal to those in the other groups. The two models were then assessed using the Chi-square test to decide which model was better to address factors that influenced the adaptation intentions across the four farmer categories at different levels of interaction with the T4FS project in the Mt. Elgon region of Uganda.

7.5 Results

7.5.1 Socio-economic characteristic of the sample

Overall, out of the 400 respondents interviewed, 228 (57%) were males and there was a uniform distribution of male and female respondents across the four farmer categories. Over 50% of the respondents were aged between 31-50 years and the majority had only attained primary education and owned less than 2 acres of land. While most of the households had 4-7 family members, active farm work was mostly done by less than 3 male and female household members.

Descriptive statistics for the attitudinal statements stratified by farmer category are presented in Table 1. Farmers generally displayed a high intention to plant shade trees in their coffee plantations. Farmers evaluated planting of trees in coffee as being highly favorable, expressed by means above 6 out of 7 for all variables measuring attitude across all farmer categories. However, farmers perceived relatively low social pressure to plant trees in coffee plantations, especially among farmers actively participating in the project activities (group 1 and 3). Generally, farmers displayed a moderate perception of control on planting scattered trees on their farms. The main limiting factors appear to be resources (including seedlings, labour and land) and the technical skills involved in planting and managing trees on farm.

The analysis of variance between the construct variables and farmer categories showed significant differences in farmer perceptions of social pressure to plant trees from their peers and extension workers across the farmer categories ($p<0.01$) (Table 1). Farmers' perceived own capability (perceived behavioural control) to overcome tree planting barriers and their evaluation of the economic benefits of shaded coffee (attitude) were significantly different among the four farmer categories ($p<0.05$).

Table 1: Group-specific descriptive statistics "mean (standard deviation)" of attitudinal measurable variables on a scale of 1-7 and Analysis of variance (ANOVA) between TPB construct variables and farmer categories (*p*- value)

Statement/question	Overall	Group1[a]	Group2[a]	Group3[a]	Group4[a]	*P*-Value
Intention	**6.21 (0.82)**	**6.35 (0.72)**	**6.19 (0.79)**	**6.01 (0.96)**	**6.29 (0.72)**	
INT1: Do you intend to plant trees for shade in at least part of your farm in the next 5 years?	6.37 (0.81)	6.50 (0.73)	6.36 (0.80)	6.17 (0.97)	6.44 (0.70)	.024*
INT2: How likely is it that you will plant trees for shade in at least part of your farm in the next 5 years?	6.07 (0.78)	6.17 (0.70)	6.09 (0.73)	5.93 (0.96)	6.08 (0.72)	.180
INT3: How strong is your intention to plant trees for shade in coffee in at least part of your farm in the next 5 years?	6.20 (0.85)	6.37 (0.76)	6.12 (0.84)	5.94 (0.98)	6.35 (0.74)	.001**
Attitude	**6.17 (0.80)**	**6.20 (0.92)**	**6.26 (0.79)**	**6.11 (0.73)**	**6.13 (0.75)**	
ATT1: Planting trees in my coffee garden reduces the amount of inputs (e.g., fertilizers) into the farm	6.17 (0.88)	6.18 (1.10)	6.26 (0.84)	6.12 (0.73)	6.11 (0.82)	.608
ATT2: Planting trees in my coffee garden provides more economic benefits compared to unshaded gardens	6.19 (0.76)	6.28 (0.87)	6.29 (0.77)	6.02 (0.72)	6.16 (0.63)	.039*
ATT3: I need to use shade trees on my coffee farm to maximize production	6.17 (0.77)	6.14 (0.79)	6.23 (0.76)	6.20 (0.73)	6.12 (0.81)	.725
Subjective norm	**5.08 (1.49)**	**4.98 (1.66)**	**5.21 (1.47)**	**4.83 (1.71)**	**5.31 (0.94)**	
SN1: Most people who are important to me think I should plant shade trees on my coffee farm	5.21 (1.47)	5.04 (1.60)	5.45 (1.43)	4.86 (1.72)	5.48 (0.90)	.004**
SN2: Extension workers think I should plant shade trees on my coffee farm	5.07 (1.58)	4.87 (1.80)	4.85 (1.69)	4.85 (1.66)	5.69 (0.85)	.000**
SN3: Other farmers whom I regularly interact with would approve that I should plant shade trees on my coffee farm	5.32 (1.42)	5.32 (1.57)	5.52 (1.33)	5.02 (1.69)	5.40 (0.93)	.079
SN4: I feel under social pressure from fellow farmers to plant shade trees on my coffee farm	4.75 (1.51)	4.70 (1.65)	5.03 (1.46)	4.58 (1.78)	4.67 (1.06)	.168
Perceived behavioural control	**5.13 (1.16)**	**5.08 (1.12)**	**5.18 (1.19)**	**5.02 (1.22)**	**5.22 (1.07)**	
PBC1: I feel that I have sufficient knowledge on planting shade trees in my coffee farm	5.28 (1.05)	5.25 (1.03)	5.38 (1.14)	5.08 (1.15)	5.41 (0.83)	.105
PBC2: I have all the resources (e.g seedlings, labour and land) I need to plant shade trees in my coffee farm.	4.66 (1.29)	4.68 (1.27)	4.82 (1.22)	4.60 (1.29)	4.54 (1.41)	.458
PBC3: How confident are you that you could overcome barriers that prevent you from using scattered trees in at least part of your farm within the next 5 years?	5.44 (1.36)	5.31 (1.05)	5.35 (1.23)	5.38 (1.23)	5.72 (0.98)	.040*

*[a]Group 1= farmers actively participating in the T4FS project from phase 1 (2014); Group 2= farmers neighbouring those actively participating in the T4FS project; Group 3= farmers actively participating in the T4FS project from phase 2 (2017) and; Group 4= farmers living distant and unaware of the T4FS project. N=400; df=3; *significant at 5% significance level; **significant at 1% significance level*

7.5.2 Model estimates based on groups

Following validation of the proposed model conducted to obtain an appropriate model fit, an unconstrained structural model was developed based on four groups representing the study farmer categories. The constrained model was obtained by controlling the subjective norm path coefficient, which was insignificant in the structural model (see Fig. 2). The corresponding model fit indices for the unconstrained and constrained models are shown in Table 2. All indices for the unconstrained and constrained models indicate an acceptable fit.

Table 2 Model fit indices for the unconstrained and constrained models

Statistic	Threshold	Unconstrained model	Constrained model
CMIN/DF	1-3	1.517	1.511
IFI	≥ 0.900	0.910	0.907
CFI	≥ 0.900	0.904	0.905
RMSEA	≤ 0.06	0.036	0.036
PCLOSE	≥ 0.05	0.999	0.999
χ^2, df, *p*	-	χ^2=358.012, df= 236, *p*= .000	χ^2=358.136 df= 237, *p*=.000

7.5.3 Multi-group analysis model parameter outputs

The model parameter outputs in Table 3 and 4 show the structural relations of attitude, subjective norms, and perceived behavioural control on farmers' intention to plant shade trees among the four farmer categories of the study. The estimation results of the unconstrained structural model show that there are differences across the four groups (farmer categories) regarding factors that influence farmers' intentions to integrate trees in their coffee plantations (Table 3). The intention of farmers actively participating in the T4FS project from phase 1 to plant trees in coffee is significantly influenced by their attitude and perceived behavioural control. Only the attitude construct influences farmers neighbouring those actively participating in the T4FS project to plant trees in coffee plantations, and none of the TPB constructs influences the intentions of the farmers who have never participated in the T4FS project and who are living far from the farmers participating in the project, to plant trees in coffee plantations. There was also an insignificant negative influence of perceived behavioural control to plant trees in coffee among farmers who had never participated in the T4FS project and living far from project participating farmers.

Table 3 Multi-group analysis – unconstrained model standardized parameter estimates

Group/ farmer category	Endogenous TPB construct variable	Exogenous TPB construct variables			Structural equation fit (R^2)
		ATT	SN	PBC	
Farmers actively participating in the T4FS project from phase 1	INT	0.180*	-0.001	0.260*	0.371
Farmers neighbouring those actively participating in the T4FS project	INT	0.414**	-0.025	0.132	0.284
Farmers actively participating in the T4FS project from phase 2	INT	0.378	0.045	0.190*	0.166
Farmers who have never participated in T4FS project and living far from project participating farmers	INT	0.162	0.343	-0.034	0.144

The results of the constrained model are similar to the unconstrained model but with an additional positive subjective norm coefficient for the group of farmers who have never participated in the T4FS project and are living far from project participating farmers (Table 4). The constrained model also shows an improvement in the variation of farmer intentions that can be explained by the significant variables (attitude and perceived behavioural control) among farmers actively participating in the T4FS project from phase 1 (R^2=0.398).

Table 4 Multi-group analysis – constrained model standardized parameter estimates, with the subjective norm path coefficient controlled for the four groups or farmer categories.

Group/ farmer category	Endogenous TPB construct variable	Exogenous TPB construct variables			Structural equation fit (R^2)
		ATT	SN	PBC	
Farmers actively participating in the T4FS project from phase 1	INT	0.190*	-0.018	0.251*	0.398
Farmers neighbouring those actively participating in the T4FS project	INT	0.415**	-0.018	0.133	0.282
Farmers actively participating in the T4FS project from phase 2	INT	0.378*	0.045	0.190*	0.166
Farmers who have never participated in the T4FS project and living far from project participating farmers.	INT	0.162	0.343*	-0.034	0.144

The Chi-square test to compare the two models shows an insignificant result (*p*-value =0.725), indicating that the four groups are not different at model level but may differ at path level (Table 5). This further implies that the constrained structural model is better able to reflect the influences of TPB constructs on farmers' intentions to adopt agroforestry practices across the four farmer categories.

Table 5 Chi-square test for comparison between the constrained and unconstrained model

Model	Chi-square	Df	*p*-value
Unconstrained model	358.012	236	
Constrained model	358.136	237	
Difference	0.124	1	0.725

7.6 Discussion

7.6.1 Farmers' motivation to adopt shaded coffee farming systems

The results of this study indicate that there are differences in farmer motivations to integrate trees in their coffee plantations across the four farmer categories. The squared multiple correlation (R^2) for farmers' intention to plant trees in coffee plantations shows 39.8%, 28.2%, 16.6% and 14.4% variation of farmer intentions among the 4 respective farmer groups. This can be explained by the corresponding significant constructs in each farmer category. The constrained model estimates show that the constructs of ‘attitude’ and ‘perceived behavioural control’ had a positive significant influence on farmers’ intentions among project participating farmers (Table 4). This implies that the motivation of project participating farmers (phase 1 and 2) to adopt shaded coffee was a result of their positive evaluation of shaded coffee as being more favorable and their own perceived capability to implement the practice of integrating trees in their coffee plantations.

A related agroforestry adoption study in Southern Bahia, Brazil revealed that perceived behavioural control proved to have the most significant correlation with farmers’ intentions to adopt or maintain agroforestry (McGinty et al. 2008). They expected support from government, non-governmental organizations and research institutions in addressing their hindrances (such as lack of seedlings, labour and land) when making land use decisions. Farmers often argue that adopting agroforestry practices on their farms is out of their control without extensive support from such agencies and organizations. It is therefore not surprising that perceived behavioural control is an important motivation among project beneficiaries (phase 1 and 2) who often receive free seedlings and capacity building trainings from the T4FS project.

However, the neighbours of project participating farmers and farmers that had never interacted with the project were only motivated by ‘attitude’ and ‘social norms’ respectively. Norms are an inherent part of social systems and structures (such as smallholder farming communities), typically developed through a process of socialisation within a given social context and can create distinct farming practices, habits and standards within a social group. Social norms can influence farmer behaviours through the process of diffusion (Mankad 2016), where an innovation is communicated through social channels within a social structure (Rogers 2004). Early research in the agricultural context found that the process of diffusion exerted social pressure on farmers to adopt innovative farming practices championed by early adopters in the neighbourhood. The rationale was that evidence of implementation and success of innovative practices was the most effective way to change farmers' behaviours. A potential reason why social norms do not seem to play a key psychological influence on farmer decisions among farmers interacting with researchers (category 1 and 3 farmers) and their neighbours (category 2) could be because some research outputs may undermine or conflict with the pre-existing social cultural attachments among communities. This could explain why social norms are predominant in Sironko, where farmers have never interacted with the T4FS research project.

7.6.2 Underlying farmer motivations across farmer categories

Each of the four constructs (intention, attitude, perceive behavioural control, social norms) had at least three subsidiary construct variables that also demonstrated significant differences across the four farmer categories (see Table 1). For example, there were clear differences in attitude based on their evaluation of the economic benefits that can be accrued from shaded and unshaded coffee ($p<0.05$, Table 1, ATT2). Economic benefits from shaded coffee were more positively perceived by farmers actively participating in the project from phase 1, and their neighbours. This category of farmers had interacted with the project and project neighbours for a longer period than the other farmer categories. It is likely that these farmers had learnt from project interventions such as training, tree seedling distribution and participatory trial establishment. The neighbours may have learnt through observations and knowledge sharing with project beneficiaries.

The study revealed differences in farmer perceptions of the social pressure from other important people and extension workers across the four farmer categories ($p<0.05$, Table 1, SN1 & SN2). Farmer motivation resulting from social pressure was strongest among farmers who had never interacted with the project and lived far from project beneficiaries. This could indicate that these farmers have stronger social structures that drive change in their community compared with other farmer categories. The lack of any project intervention in the area could have resulted in the use of existing norms and government extension systems among communities as the only source of information regarding agroforestry. Conventionally, extension has assumed that innovations originate from science and are transferred to farmers who adopt them (Black 2000). However, extension theory and practice has seen a paradigm shift from knowledge transfer approaches to knowledge exchange approaches (Blackstock et al. 2010). The expression of social norms as drivers towards integration of trees in coffee systems among farmers who had never interacted with the project and lived far from project beneficiaries seems to demonstrate this theory. Rural people tend to rely more on indigenous knowledge when engaging in tree planting and less on formal knowledge (Meijer et al. 2015; Ofoegbu and Speranza 2017). While knowledge transfer approaches promote the adoption of predetermined practices, knowledge exchange approaches emphasise the need for people to develop their own solutions to problems. Therefore, the relationship between farmers and researchers, and extension workers should shift from knowledge transfer to knowledge exchange.

Knowledge exchange involving communication within a social group is an important process in articulating, sharing and exchanging ideas amongst farmers. Although knowledge exchange fails to recognise the difficulties and dangers in working with multiple forms of knowledge (Morgan and Murdoch 2000), there are implications for how science underpinning agroforestry in smallholder farming systems should be conceptualised, conducted and communicated. The role of social norms in agricultural technology adoption should not be underestimated and should be integrated into agricultural research and extension. This is because social norms are instrumental in building social pressure among local communities towards a behaviour.

The Theory of Planned Behaviour framework and multi-group SEM analytical technique demonstrated potential for understanding the complex behaviour of smallholder farmers towards agroforestry adoption. However, to improve their predictive power, we recommend inclusion of additional constructs in the TPB framework. Ajzen (1991) accepts that additional variables may be required but argues that they should contribute significantly to the explanation provided by the model. On this basis, future applications of the TPB and multi-group SEM should include additional constructs such as environmental concern by farmers (e.g willingness to protect existing trees, plant new trees on bare landscapes) and incentives from having shaded coffee (e.g government support towards tree management, carbon trade initiatives, premium prices for shade coffee). Incorporation of background factors such as age, education, land size and sex could also provide a more comprehensive analysis of the motivations of smallholder farmers to adopt agroforestry practices. However, a related study on farmers' response to rural development policy challenges found that the influence of background factors on behavioural intentions was less pronounced (Martinovska et al. 2016). Nonetheless, background factors can be context-specific, thus there is a need to include them in future related studies, especially in developing countries.

7.7 Conclusion

Sustainable agricultural technology adoption requires that researchers and development agencies pay more attention to the internal decision-making processes, and look beyond the mere characteristics of agricultural innovations and the household to include psychological factors in technology uptake. The Theory of Planned Behaviour provides a useful model for exploring the psychological factors that influence smallholder farmers' tree planting decisions. Multi-group Structural Equation Modeling employed by this study provides a simultaneous estimation of different interdependent multiple regressions (Hair et al. 2010) which allows analysis of several groups of data from a population. The findings indicate that psychological factors are key drivers to the farmers' internal decision-making processes in agroforestry technology adoption. However, the psychological factors vary among different groups of farmers, usually shaped by the existing community social norms and beliefs. These norms tend to promote knowledge exchange, as opposed to the traditional knowledge transfer approaches. The TPB collectively explained about 40% of the variance in farmers' intensions to integrate trees in coffee plantations with attitude and perceived behavioural control being the statistically significant predictors. Future applications of the TPB and multi-group SEM should include additional constructs such as environmental concern by farmers and incentives to farmers for having shaded coffee. This would provide a more comprehensive analysis of the motivations of smallholder farmers to adopt agroforestry practices.

7.8 References

Ajayi OC, Place F, Akinnifesi FK, Sileshi GW (2011) Agricultural success from Africa: the case of fertilizer tree systems in southern Africa (Malawi, Tanzania, Mozambique, Zambia and Zimbabwe). Int J Agric Sustain 9(1):129-136. doi: 10.3763/ijas.2010.0554

Ajzen I (2011) The theory of planned behaviour: Reactions and reflections. Psychol & Health 26(9):1113-1127. doi: 10.1080/08870446.2011.613995

Akinnifesi FK, Ajayi OC, Sileshi G, Chirwa PW, Chianu J (2010) Fertiliser trees for sustainable food security in the maize-based production systems of East and Southern Africa. A review. Agron Sustain Dev 30(3):615-629. doi: 10.1051/agro/2009058

Atuyambe LM, Ediau M, Orach CG, Musenero M, Bazeyo W (2011) Land slide disaster in eastern Uganda: rapid assessment of water, sanitation and hygiene situation in Bulucheke camp, Bududa district. Environ Health, 10(1): 38. doi: 10.1186/1476-069X-10-38

Barungi M, Ng'ong'ola DH, Edriss A, Mugisha J, Waithaka M, Tukahirwa J (2013) Factors Influencing the Adoption of Soil Erosion Control Technologies by Farmers along the Slopes of Mt. Elgon in Eastern Uganda. J Sustain Develop 6(2). doi: 10.5539/jsd.v6n2p9

Black A (2000) Extension theory and practice: a review. Australian J Experiment Agric 40(4):493. doi: 10.1071/EA99083

Blackstock KL, Ingram J, Burton R, Brown KM, Slee B (2010) Understanding and influencing behaviour change by farmers to improve water quality. Sci Total Environ 408(23):5631-5638. doi: 10.1016/j.scitotenv.2009.04.029

Borges JAR, Lansink OAGJM (2016) Identifying psychological factors that determine cattle farmers' intention to use improved natural grassland. J Environ Psychol 45(C):89-96. doi: 10.1016/j.jenvp.2015.12.001

Borges JAR, Lansink OAGJM, Marques Ribeiro C, Lutke V (2014) Understanding farmers' intention to adopt improved natural grassland using the theory of planned behaviour. Livest Sci, 169:163-174. doi: https://doi.org/10.1016/j.livsci.2014.09.014

Broeckx J, Maertens M, Isabirye M, Vanmaercke M, Namazzi B, Deckers J. . . . Poesen J (2019) Landslide susceptibility and mobilization rates in the Mount Elgon region, Uganda. Landslides, 16(3): 571-584. doi: 10.1007/s10346-018-1085-y

Buyinza J, Nuberg I, Muthuri C, Denton M (2020) Psychological factors influencing farmers' intention to adopt agroforestry: A structural equation modeling approach. J Sustain For. 1-12, doi: 10.1080/10549811.2020.1738948.

DaMatta FM (2004) Ecophysiological constraints on the production of shaded and unshaded coffee: a review (Vol. 86, pp. 99-114): Elsevier B.V

DaMatta FM, Ramalho JDC (2006) Impacts of drought and temperature stress on coffee physiology and production: a review. Brazilian J Plant Physio, 18: 55-81

Dang HL, Li E, Nuberg I, Bruwer J (2018) Vulnerability to climate change and the variations in factors affecting farmers' adaptation: A multi-group structural equation modeling study. Climate & Develop, 10(6):509-519. doi: 10.1080/17565529.2017.1304885

Fishbein, M, Ajzen, I (2010) Predicting and Changing Behaviour: The Reasoned Action Approach New York: Taylor and Francis.

Fonseca M (2013) Principles and Practice of Structural Equation Modeling, Third Edition by Rex B. Kline (Vol. 81, pp. 172-173). Oxford, UK.

Garrity D, Akinnifesi F, Ajayi O, Weldesemayat S, Mowo J, Kalinganire A et al (2010) Evergreen Agriculture: a robust approach to sustainable food security in Africa. Sci, Sociol Econ Food Prod Access Food, 2(3):197-214. doi: 10.1007/s12571-010-0070-7

Gram G, Vaast P, Wolf J, Jassogne L (2018) Local tree knowledge can fast-track agroforestry recommendations for coffee smallholders along a climate gradient in Mount Elgon, Uganda. Intern J incorpor Agrofor Forum 92(6):1625-1638. doi: 10.1007/s10457-017-0111-8

Hair JF, Black WC, Babin BJ, Anderson RE (2010) Multivariate data analysis (7th ed. ed.). Upper Saddle River, NJ: Prentice Hall

Jezeer RE, Santos MJ, Boot RGA, Junginger M, Verweij PA (2018) Effects of shade and input management on economic performance of small-scale Peruvian coffee systems. Agric Syst 162:179-190. doi: 10.1016/j.agsy.2018.01.014

Jezeer RE, Verweij PA (2015) Shade Grown Coffee: Double dividend for biodiversity and small-scale coffee farmers in Peru. The Hague, the Netherlands: Utrecht University and Hivos

Kiptot E, Hebinck P, Franzel S, Richards P (2007) Adopters, testers or pseudo-adopters? Dynamics of the use of improved tree fallows by farmers in western Kenya. Agric Syst 94(2):509-519. doi: 10.1016/j.agsy.2007.01.002

Lai PC (2017) The literature review of technology adoption models and theories for the noelty technology. JISTEM – J. Infor Syst & Tech Manag, 14(1): 21-38. doi: 10.4301/S1807-17752017000100002

Mankad A (2016) Psychological influences on biosecurity control and farmer decision-making. A review. Agron Sustain Develop 36(2):40. doi: 10.1007/s13593-016-0375-9

Martinovska SA, Kotevska A, Bogdanov N, Nikolić A (2016) How do farmers respond to rural development policy challenges? Evidence from Macedonia, Serbia and Bosnia and Herzegovina. Land Use Policy 59:71-83. doi: 10.1016/j.landusepol.2016.08.019

McGinty MM, Swisher ME, Alavalapati J (2008) Agroforestry adoption and maintenance: self-efficacy, attitudes and socio-economic factors. Agrofor Syst 73(2):99-108. doi: 10.1007/s10457-008-9114-9

Meijer SS, Catacutan D, Ajayi OC, Sileshi GW, Nieuwenhuis M (2015) The role of knowledge, attitudes and perceptions in the uptake of agricultural and agroforestry innovations among smallholder farmers in sub-Saharan Africa. Int J Agric Sustain 13(1):40-54. doi: 10.1080/14735903.2014.912493

Mekoya A, Oosting SJ, Fernandez-Rivera S, Zijpp AJ (2008) Farmers' perceptions about exotic multipurpose fodder trees and constraints to their adoption.(Report). Agrofor Syst 73(2):141.

Mugagga F, Buyinza M (2013) Land tenure and soil conservation practices on the slopes of Mt Elgon National Park, Eastern Uganda. J Geog and Regional Planning, 6(7): 255-262. doi: 10.5897/JGRP2013.0398

Mugagga F, Kakembo V, Buyinza M (2012) Land use changes on the slopes of Mount Elgon and the implications for the occurrence of landslides. Catena, 90: 39-46. doi: 10.1016/j.catena.2011.11.004

Nakileza BR, Majaliwa MJ, Wandera A, Nantumbwe CM (2017) Enhancing resilience to landslide disaster risks through rehabilitation of slide scars by local communities in Mt Elgon, Uganda. Jàmbá: J Disaster Risk Studies, 9: 1-11.

Ochago R (2017) Barriers to women's participation in coffee pest management learning groups in Mt Elgon Region, Uganda. Cogent Food & Agric, 3(1): 1358338. doi: 10.1080/23311932.2017.1358338

Ofoegbu C, Speranza IC (2017) Assessing rural peoples' intention to adopt sustainable forest use and management practices in South Africa. J Sustain For 36(7):729-746. doi: 10.1080/10549811.2017.1365612

Rafique, H., Almagrabi, A. O., Shamim, A., Anwar, F., & Bashir, A. K. (2020). Investigating the Acceptance of Mobile Library Applications with an Extended Technology Acceptance Model (TAM). *Computers & Education*, *145*, 103732. doi: https://doi.org/10.1016/j.compedu.2019.103732

Rahn E, Liebig T, Ghazoul J, van Asten P, Läderach P, Vaast P, et al (2018) Opportunities for sustainable intensification of coffee agro-ecosystems along an altitudinal gradient on Mt. Elgon, Uganda. Agric, Ecosyst Environ 263:31-40. doi: 10.1016/j.agee.2018.04.019

Rogers EM (2003) Diffusion of innovations (5th ed.) (5 ed.). New York: Free Press.

Rogers EM (2004) A Prospective and Retrospective Look at the Diffusion Model. J Health Communic, 9(sup1):13-19. doi: 10.1080/10810730490271449

Scherer, R., Siddiq, F., & Tondeur, J. (2019). The technology acceptance model (TAM): A meta-analytic structural equation modeling approach to explaining teachers' adoption of digital technology in education. *Computers & Education, 128*, 13-35. doi: https://doi.org/10.1016/j.compedu.2018.09.009

Senger I, Borges JAR, Machado JAD (2017) Using the theory of planned behaviour to understand the intention of small farmers in diversifying their agricultural production. J Rural Studies, 49(C):32-40. doi: 10.1016/j.jrurstud.2016.10.006

Sood KK, Mitchell CP (2006) Importance of human psychological variables in designing socially acceptable agroforestry systems. For, Trees and Livelihoods, 16(2):127-137. doi: 10.1080/14728028.2006.9752551

van Der Veen R, Song H (2014) Impact of the Perceived Image of Celebrity Endorsers on Tourists' Intentions to Visit. J. Travel Res 53:211-224

Wang N, Jassogne L, van Asten PJA, Mukasa D, Wanyama I, Kagezi G, Giller KE (2015) Evaluating coffee yield gaps and important biotic, abiotic, and management factors limiting coffee production in Uganda. European J. Agron, 63(40): 1-11. doi: 10.1016/j.eja.2014.11.003

Wauters E, Bielders C, Poesen J, Govers G, Mathijs E (2010) Adoption of soil conservation practices in Belgium: An examination of the theory of planned behaviour in the agri-environmental domain. Land Use Policy 27(1):86-94. doi:10.1016/j.landusepol.2009.02.009

Supplementary Table 1 Socio –economic characteristics of the different farmer categories

Variable	Farmers actively participating in T4FS project from phase 1 (%)	Farmers neighbouring those actively participating in T4FS project (%)	Farmers actively participating in T4FS project phase 2 (%)	Farmers who have never participated in T4FS project and living far from project farmers (%)	Total (%)
Sex					
Male	57	52	56	51	57.0
Female	43	48	44	49	43.0
Age (years)					
18-30	12	20	21	26	19.8
31-50	60	57	57	51	56.3
>50	28	23	22	23	24.0
Level of education					
None	0	4	5	12	5.3
Primary	60	60	72	65	64.3
Secondary	15	15	18	16	23.8
Tertiary	13	9	3	2	6.8
Household size					
≤3 members	5	13	10	10	9.5
4-7 members	55	45	45	56	50.2
8-11 members	33	34	35	27	32.3
>11 members	7	8	10	7	8.0
Male active farm workers					
≤3 males	73	82	80	83	79.5
4-7 males	27	17	19	17	20.0
8-11 males	0	0	1	0	0.3
>11 males	0	1	0	0	0.3
Female active farm workers					
≤3 females	77	87	82	81	81.8
4-7 females	21	12	17	18	17.0
8-11 females	0	1	1	1	0.8
>11 females	2	0	0	0	0.5
Size of land					
≤2 acres	43	57	49	37	46.5
3-5 acres	48	34	40	49	42.8
6-8 acres	6	4	9	12	7.8
>8 acres	3	5	2	2	3.0

Chapter 8: Farmers' knowledge and perceptions of management and impact of trees on-farm in the Mt. Elgon region of Uganda

8.1 Statement of Authorship

Title of Paper	**Farmers' knowledge and perceptions of management and the impact of trees on-farm in the Mt. Elgon region of Uganda**
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Principal Author

Name of Principal Author (Candidate)	Joel Buyinza		
Contribution to the Paper	Identification of research gap, theoretical foundation, data collection and analysis, interpretation of finding, writing manuscript and acted as the first and corresponding author		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	21/06/2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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Contribution to the Paper	Supervision, editing and reviewing the manuscript		
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ORIGINAL RESEARCH

Farmers' Knowledge and Perceptions of Management and the Impact of Trees on-Farm in the Mt. Elgon Region of Uganda

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Abstract

Understanding farmers' underlying perceptions and knowledge of the impact of trees on-farm is essential to develop appropriate agroforestry practices that meet farmers' aspirations. Using the Australian-funded Trees for Food Security (T4FS) project as a case study, we obtained quantitative data from questionnaire interviews with 400 smallholder farmers belonging to four farmer categories in the Mt. Elgon region of Uganda. The categories were: (1) those actively participating in the T4FS project from phase 1 (2014); (2) farmers neighbouring those actively participating in the T4FS project from phase 1; (3) farmers actively participating in the T4FS project from phase 2 (2017) and; (4) farmers living distant and unaware of the T4FS project. Farmer perceptions and knowledge of the impact of trees on farm and their management varied across the farmer categories studied. The intended purpose of trees on farm was perceived differently by the four farmer categories ($p < 0.05$), which may have implications to their adoption and scaling up. Unlike other farmer categories, the majority of farmers actively participating in the T4FS project from phase 1 perceived planting of trees for shade as not being too much trouble for what it is worth (complexity), and that a garden shaded with trees has more general benefits than an unshaded garden (relative advantage). While 50% of farmers actively participating in the T4FS project from phase 1 indicated that they pruned their tree canopies, tree pruning was mainly driven by the need for fuelwood, rather than the need to reduce tree shade. All the four farmer categories perceived that coffee grown under shade was more likely to be infected by diseases than unshaded coffee, attributing it to poor shade tree management. Managing these trees would otherwise control the negative effects of over shading and prolong the period of intercropping. This study shows the importance of context-specific design of research and development projects aiming for local impact.

Keywords Perceptions · Tree pruning · Scattered trees on-farm · Coffee · Gender · Agroforestry · Relative advantage

8.2 Introduction

Smallholder farmers are most vulnerable to the effects of environmental degradation, since their lack of economic resources restricts access to alternative livelihoods. The implementation of agroforestry among such communities has improved their livelihoods through crop yield stability under rain-fed agriculture (Sileshi et al. 2011; Nasielski et al. 2015), while providing various ecosystem services (Palacios and Bokelmann 2017; Rigal et al. 2018) and providing additional sources of household income. Recent agroforestry research and development efforts in Africa, such as the Trees for Food Security (T4FS) project, have prioritised scaling up trees in fields and farming landscapes to enhance and sustain crop yield, food security and resilient livelihoods (Buyinza et al. 2019; Muthuri, 2017; Smethurst et al. 2017). Increasing tree diversity in farmers' fields and farming landscapes is a cornerstone of system intensification that could eventually contribute to more resilient livelihoods (Iiyama et al. 2017). While integrating trees with other crops (such as coffee) can increase and stabilize crop yields, poor management of the tree component has limited the realization of anticipated benefits from such systems. In some cases, farmers have not been trained in appropriate tree management and some tree management practices contrast with existing cultural norms and practices. This problem has also been exacerbated by high tree species diversity (including deciduous and non-deciduous trees) on farms, which has hindered development of appropriate tree management practices.

The principal disadvantage of using trees on-farm is the competition with the associated crops (Ndoli et al. 2017; Albertin and Nair 2004) and higher incidence of fungal attacks due to increased humidity in the system (Souza et al. 2010). There have been several cases where communities have abandoned agroforestry technologies (Dahlquist et al. 2007; Kiptot et al. 2007; Meijer et al. 2015), resulting from such negative impacts. Therefore, careful consideration must be applied to assess the benefits and disadvantages of implementing agroforestry interventions, such as scattered trees in coffee gardens, particularly in the context of smallholder farmers.

Studies of farmers' knowledge of shade trees in agroforestry systems have evaluated farmers' shade tree preferences (Cardinale et al. 2012), the effects of tree cover on ecosystem services such as soil fertility (Pauli et al. 2012) and disease and pest control (Segura et al. 2004). However, there are limited studies on farmers' perceptions and knowledge of the management and impact of shade trees (scattered trees) existing in coffee farming systems, especially in Africa. In sub-Saharan Africa, Meijer et al. (2015) suggested that farmer characteristics and economic variables influence knowledge, attitudes and perceptions, which in turn influence farmers' decision-making processes for the adoption of agricultural innovations. In North America, Reimer et al. (2012) identified Rogers (2003) perceived practice characteristics – observability, relative advantage and compatibility operating in farmers' decisions to adopt conservation practices for catchment management. Beyond the forestry discipline, the Theory of Planned Behaviour (TPB) is arguably the most comprehensive framework for understanding the psychological construct of an individual's intention and their resultant behaviour (Ajzen 2011). Farmers may also have knowledge of physiological features of trees on their farms that could be useful in designing alternative sustainable farming practices. Understanding these key aspects is essential for the development of appropriate agroforestry practices that meet farmers' aspirations, which may influence adoption outcomes. This study identified the existing tree species on farms, their establishment and management, and assessed farmers' underlying perceptions and knowledge of the impact of scattered trees in coffee and the perceived practice characteristics influencing adoption of trees on farm to inform agroforestry adoption pathways of smallholder farmers in the Mt. Elgon region of Uganda.

8.2.1 Theoretical and analytical background of the study

We assessed farmers' knowledge and perceptions of the impact and management of shade trees using a holistic approach that integrates background factors, perceived practice characteristics and behavioural and psychological factors (Reimer et al. 2012) relating to the specific agroforestry practices that they consider adopting. The framework adopted by the study considers the interaction of these various factors in decision-making (Fig. 1). Within this framework, background factors (farmer and farm characteristics, and farm external factors) have indirect effects on adoption behaviour by influencing the perceived practice characteristics (Rogers 2003), which in turn influence behavioural, normative, and control beliefs (Fishbein and Ajzen 2010). The Theory of Planned Behavior (TPB) suggests that behavioural intentions are shaped by attitude, subjective norms and perceived behavioural control (Ajzen 2011). It is an expectancy-value model that provides a framework for understanding the relationship between a person's attitudes and their underlying beliefs (Meijer et al. 2015).

We propose that the best way to understand the adoption pathways of smallholder farmers is to look at a complete picture involving farmers' background factors, perceived practice characteristics and behavioural and psychological factors, as illustrated in figure 1. The approach would help practitioners understand how each of these informs an individual's decision to adopt a particular practice and how adoption may be encouraged among smallholder farmers. While the behavioural factors have been considered in detail previously within the same study population (Buyinza et al. 2020a; Buyinza et al. 2020b), we examine the role of perceived practice characteristics in the adoption of scattered trees by smallholder farmers within this larger framework.

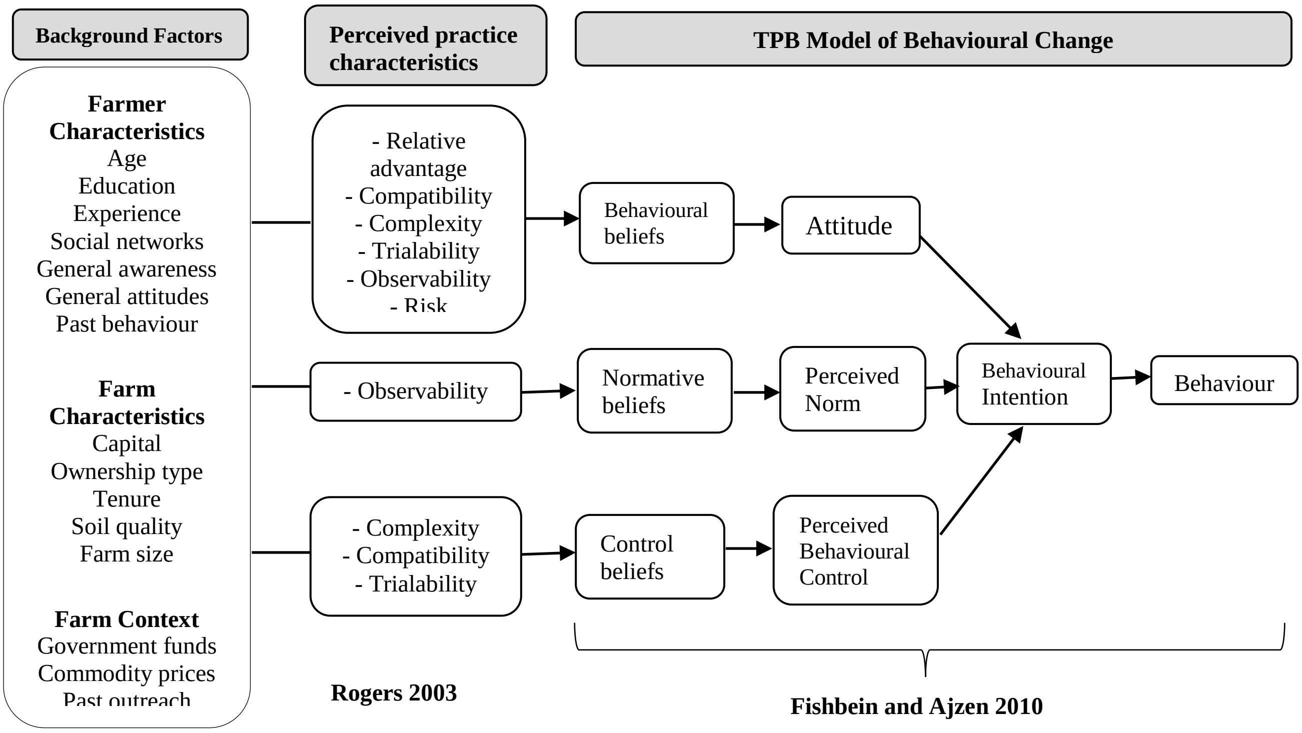

Fig. 1 A framework integrating background factors, perceived practice characteristics and psychological factors that inform farmers' decision making (Adapted from Reimer et al. 2012)

8.3 Methods

8.3.1 Study area

This study provides an empirical explanation of farmers' knowledge and perceptions of the management and impact of trees on-farm in the Mt. Elgon region of Uganda. The study was conducted in the districts of Manafwa, Bududa and Sironko, located in Mt. Elgon region of Uganda (Fig. 2). About 98% of the population in this region is rural based, with an annual population growth rate of 3.4%. In terms of climate, the average annual rainfall is 1500 mm, with two peak rainy seasons that occur in the months of April–June and August–November, occasionally characterized by landslides (Broeckx et al. 2019; Nakileza et al. 2017).

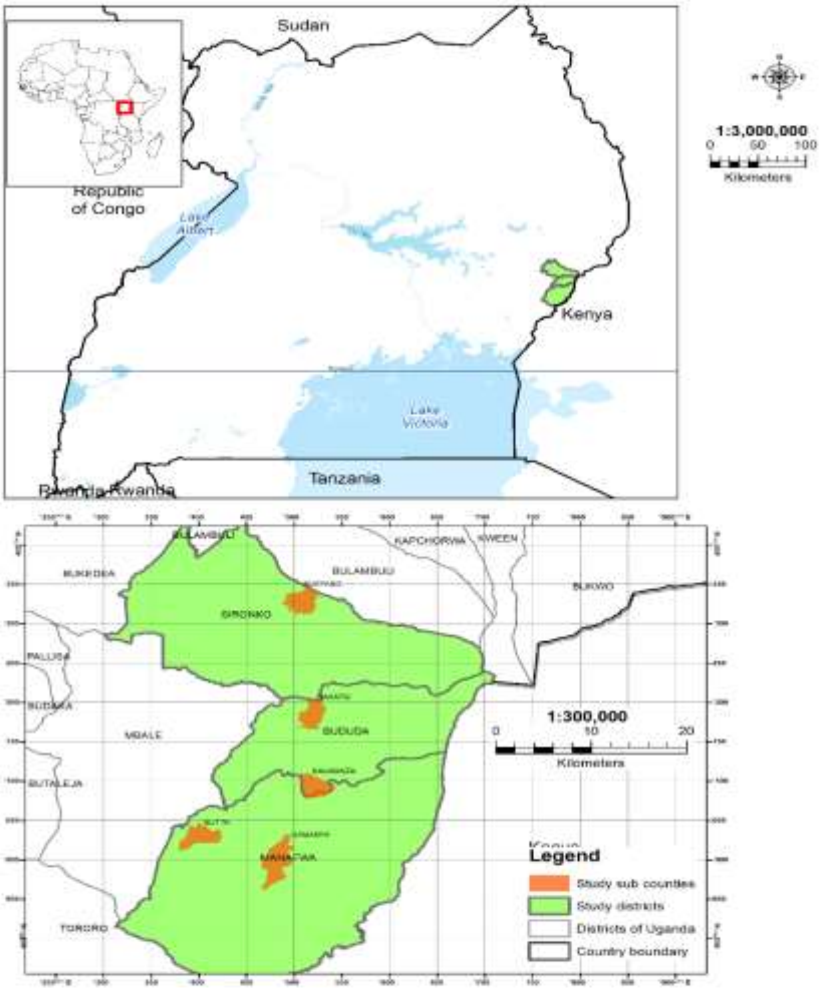

Fig. 2 Map showing location of study sites in the Mt. Elgon region of Uganda

8.3.2 The Trees for Food Security (T4FS) project in Eastern Africa

These study sites form part of the Trees for Food Security (T4FS) project sites. The T4FS is an Australian Centre for International Agricultural Research (ACIAR) funded project implemented by the World Agroforestry Centre (ICRAF) in partnership with national level stakeholders. The T4FS project aims to improve household food security and smallholder livelihoods through widespread adoption of appropriate locally adapted agroforestry practices in key agricultural landscapes in Ethiopia, Rwanda and Uganda. The project has been reaching out to smallholder farmers in rural regions where an estimated 10 million people are facing acute food security problems since 2012. The second phase of the T4FS project focuses on tree diversity as the cornerstone of smallholder system intensification and integrates tree management with value chain development and sustainable water management. The project also aims to sustain food security and create livelihood gains for farmers by establishing cross-sector communities of practice and capacity development in locally adaptable agroforestry options that many farmers can adopt. The T4FS project has also established that trees in fields, farm and landscape niches can provide products and services that underpin and improve food security through system intensification and management of interactions amongst components.

In Uganda, the T4FS project started in 2014 and currently in its second phase of implementation in the Manafwa, Bududa and Mbale districts in Eastern Uganda. Agroforestry technologies such as fodder banks, boundary planting, riverbank restoration using trees, scattered trees on-farm, woodlots and the use of vegetation strips and woodlots to control soil erosion are being widely promoted among some of the most vulnerable farming communities in the Mt. Elgon region of Uganda.

8.3.3 Sampling and survey

In this study, four respondent categories were deliberately selected: 1] those actively participating in the T4FS project from phase 1 (2014), also referred to as Phase 1 farmers; 2] farmers neighbouring those actively participating in the T4FS project from phase 1, also referred to as Neighbours; 3] farmers actively participating in the T4FS project from phase 2 (2017), similarly referred to as Phase 2 farmers and; 4] farmers living distant and unaware of the T4FS project, also referred to as Remote farmers . The farmers actively participating in the project since its inception and those neighbouring active project participants were selected from Manafwa district. Farmers actively participating in the second phase of the project and those that have never participated in the T4FS project were selected from Bududa and Sironko districts respectively. These farmer categories were selected to establish the extent to which project interventions influenced smallholder farmers' knowledge and perceptions of scattered trees and their management, to inform agroforestry adoption pathways of smallholder farmers.

This paper addresses farmers' knowledge and perception of the impact of existing agroforestry practices being promoted by the T4FS project. Prior to the main survey, a pilot survey (pre-test) was carried out with 15 farmers to ensure that the questions could be clearly understood. The final version of the survey tool consisted of three groups of questions: 1) socio-demographic characteristics, 2) farmers' knowledge and perception of the impact of existing agroforestry practices, and, 3) questions based on theory of planned behaviour (TPB).

A sample of 100 respondents was randomly selected for each of the four respondent categories that varied in their interaction with T4FS, giving a total of 400 respondents for the entire study. While a random sample of farmers actively participating in the project since its inception and farmers actively participating in phase 2 of the project was obtained from the list of project beneficiaries, farmers who have never participated in the project were randomly selected from a list of households from the local council leaders. A list of farmers as neighbouring project beneficiaries was generated with the help of local leaders, from which a random sample was obtained. A simple random sampling technique was used to select random samples. The range of question categories is listed in Table 1, assessing farmers' knowledge and perception of the different agroforestry practices, impact of shade on coffee, gender roles in coffee production and perceived practice characteristics of scattered trees. The perceived practice characteristics relate to Rogers' factors of adoption – relative advantage, compatibility, observability, complexity and trialability (Rogers 2003). Responses to questions were recorded on 1-7 Likert scales. Likert values either below or above L4 indicate the relative valence to the question under consideration. This study also collected qualitative data from focus group discussions

(FGDs). One FGD consisting of 8-15 participants was held with farmers from each of the four farmer categories.

Table 1: Description of statements used

Statement and description	Scale used
Likelihood of existing agroforestry practices to serve their purpose (*purpose in parentheses*)	
Scattered trees on farm *(to provide shade and modify microclimate)*	1-7 scales (unlikely - most likely)
Fodder banks *(to provide nutritious fodder with ease)*	1-7 scales (unlikely - most likely)
Soil erosion control using vegetation strips *(for keeping soils in place during runoff)*	1-7 scales (unlikely - most likely)
Riverbank restoration using trees *(to stop river from washing away farmland)*	1-7 scales (unlikely - most likely)
Woodlots *(to provide timber, poles and fuelwood)*	1-7 scales (unlikely - most likely)
Boundary planting *(to delineate land boundary and provide tree product to owner but not neighbour)*	1-7 scales (unlikely - most likely)
Comparing coffee grown under shade with coffee grown in full sun	
Coffee grown under shade is more likely to be attacked by pests and diseases	1-7 Likert scales (strongly disagree – strongly agree)
Coffee grown under shade in a garden produces more yields than one in open	1-7 Likert scales (strongly disagree – strongly agree)
Coffee under shade is larger and heavier than unshaded coffee	1-7 Likert scales (strongly disagree – strongly agree)
Coffee beans under shade take longer to mature and ripen than those on unshaded coffee	1-7 Likert scales (strongly disagree – strongly agree)
Coffee processed from coffee beans grown under shade tastes better than unshaded coffee	1-7 Likert scales (strongly disagree – strongly agree)
Comparing women and men's roles in coffee production	
Women are generally more involved than men in planting of coffee	1-7 Likert scales (strongly disagree – strongly agree)
Women are generally more involved than men in managing coffee plants	1-7 Likert scales (strongly disagree – strongly agree)
Men are generally more involved than women in marketing coffee	1-7 Likert scales (strongly disagree – strongly agree)
Men decide when and where to plant trees on our farm	1-7 Likert scales (strongly disagree – strongly agree)
Statements on perceived practice characteristics	
a) A garden shaded with trees has more general benefits than an unshaded garden (relative advantage)	1-7 Likert scales (strongly disagree – strongly agree)
b) Planting trees in the garden is compatible with existing farm practices (compatibility)	1-7 Likert scales (strongly disagree – strongly agree)
c) Planting trees for shade is too much trouble for what it is worth (complexity)	1-7 Likert scales (strongly disagree – strongly agree)
d) I am likely to plant trees in my garden after seeing other farmers doing the same (observability)	1-7 Likert scales (strongly disagree – strongly agree)
e) I am likely to plant shade trees on a small scale first before planting more (trialability)	1-7 Likert scales (strongly disagree – strongly agree)

8.3.4 Data analysis

Data from the household survey was checked for consistency, coded and entered into Statistical Package for Social Scientists (SPSS version 25) software for analysis. Descriptive statistics were used to generate summaries of existing tree species and agroforestry practices being promoted, farmers' knowledge on tree establishment and management from the data in form of frequency tables and histograms. Analysis of variance (ANOVA) was used to determine whether any differences existed in farmers' knowledge and perceptions of the impact of shade trees on coffee production across the four farmer categories under study. The box and whisker plots were used to provide the shape, central values and variability of the influence of perceived practice characteristics (Rogers' factors of adoption in Fig. 1) on farmers to integrate shade trees in their coffee gardens.

8.4 Results

8.4.1 Socio economic characteristics of respondents

There was a uniform distribution of male and female respondents across the four farmer categories, with over 50% of the respondents aged between 31-50 years. Most of the respondents had only attained primary education and owned less than 2 acres of land. While majority of the households had 4-7 family members, active farm work was mostly done by less than 3 males and female household members (see supplementary table 1).

8.4.2 Existing tree species on-farm

Overall, *Cordia africana* was the most reported tree species existing in farmers' fields, followed by *Albizia coriaria* and *Grevillea robusta* (Table 2). However, farmers' responses on existing tree species differed across the four farmer categories. For example, while *A. coriaria* had a rank of 1 from phase 1, neighbours and remote farmers, it got a rank of 7 from phase 2 (farmers actively participating in the T4FS project from phase 2) farmer responses. Phase 2 farmers and farmers living distant and unaware of the T4FS project (remote farmers) tend to have a higher preference for fruit trees compared with other farmer categories (Table 2). Although this study did not conduct tree preference ranking among farmers, the assumption is that the trees planted and or retained on farms are the ones preferred by the farmers.

Table 2: Tree species presence reported on farm (rank in parenthesis based on responses, where a score of 1 represents the highest % responses for a species)

Tree species	Common/ local name	Phase 1 farmers* % (rank)	Neighbours % (rank)	Phase 2 farmers % (rank)	Remote farmers % (rank)	Overall % (rank)
Cordia africana	Chichikiri	63 (2)	59 (2)	68 (1)	66 (2)	64.2 (1)
Albizia coriaria	Kumoluko	64 (1)	67 (1)	22 (7)	76 (1)	57.4 (2)
Grevillea robusta	Mitikawo	38 (4)	32 (4)	57 (2)	20 (8)	36.8 (3)
Eucalyptus grandis	Kalitusi	36 (5)	24 (5)	48 (3)	35 (6)	35.8 (4)
Ficus natalensis	Gumutoto	34 (6)	45 (3)	13 (10)	36 (5)	31.6 (5)
Mangifera indica	Muyembe	23 (7)	24 (5)	33 (5)	38 (4)	29.6 (6)
Persie americana	Fokedo	12 (10)	22 (8)	42 (4)	27 (7)	25.8 (7)
Autocarpus heterophylus	Sifenesi	10 (11)	17 (10)	29 (6)	40 (3)	24.1 (8)
Markhamia lutea	Lusola	12 (9)	18 (9)	20 (9)	20 (8)	17.5 (9)
Neolamarckia cadamba	Proscovia	41 (3)	24 (5)	2 (13)	2 (12)	17.3 (10)
Maesopisis eminii	Musizi	22 (8)	12 (11)	21 (8)	7 (10)	15.5 (11)
Melicia excelsa	Gumutumba	5 (12)	4 (13)	0	5 (11)	3.5 (12)
Melia volkensii	Lira lira	4 (13)	8 (12)	1 (15)	0	3.3 (13)
Ficus syncomorus	Gukuyu	3 (14)	0	2 (13)	0	1.3 (14)
Calliandra calothyrsus	Calliandra	0	1 (14)	3 (12)	1 (13)	1.3 (14)
Erithrina abysinica	Chitugutu	0	0	4 (11)	0	1.0 (16)
Ficus ovata	Gudodo	1 (15)	1 (14)	0	0	0.5 (17)

**Category 1= farmers actively participating in the T4FS project from phase 1 (2014); Category 2= farmers neighbouring those actively participating in the T4FS project from phase 1; Category 3= farmers actively participating in the T4FS project from phase 2 (2017) and; Category 4= farmers living distant and unaware of the T4FS project*

8.4.3 Existing agroforestry practices in the Mt. Elgon region

A total of six agroforestry practices were reported by the study respondents and are given in Fig. 3. The most common agroforestry practice among farmers participating in the T4FS from phase 1 was boundary planting, followed by scattered trees in coffee gardens. This may be attributed to the small land holdings that have limited space to establish fodder banks and woodlots. Riverbank restoration using trees was limited to farmers who had land through which rivers (such as River Manafwa) and streams flow. Agroforestry practices such as fodder banks, scattered trees in coffee gardens and vegetation strips for erosion control were predominantly reported by farmers participating in the T4FS from phase 1 (2014). Woodlots were mainly reported by phase 2 farmers, who are located in Bududa districts with larger land holding than Manafwa (Phase 1 farmers and their neighbours). These farmers have also received free seedlings from the project, and had a greater preference for plantation tree species such as *Eucalyptus grandis* and *Grevillea robusta* (see Table 2).

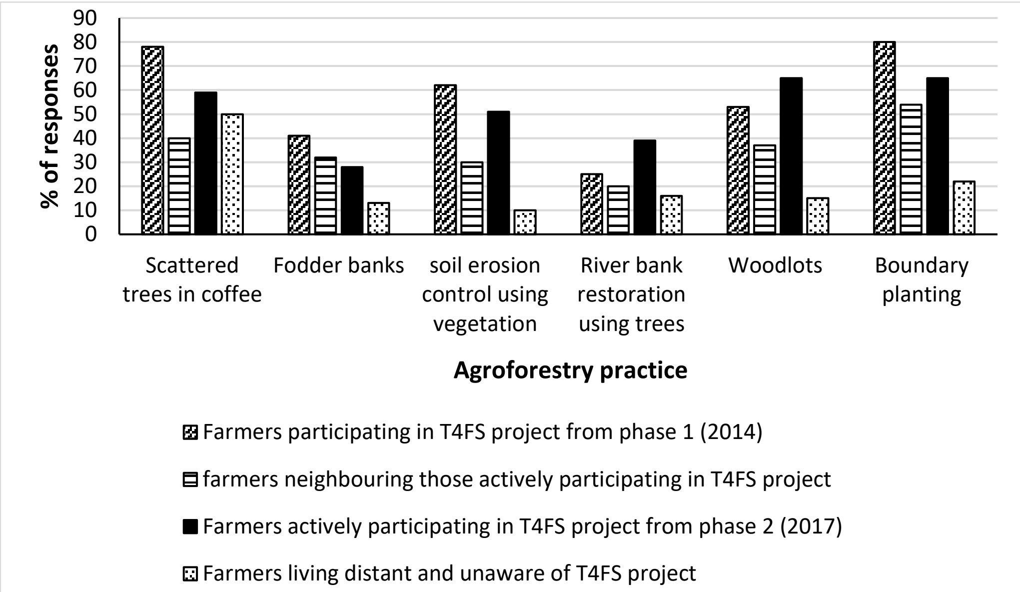

Fig. 3 Existing agroforestry practices promoted by the T4FS project

8.4.4 Farmers' perceptions on relevance of existing agroforestry practices

Farmers were asked whether the agroforestry practices being promoted served their purpose. The intended purpose of each agroforestry practice is shown in Table 1. Soil erosion control using vegetation strips and boundary planting were generally perceived as practices that reduced soil erosion during runoff, to delineated land boundaries and provided tree products to the owner but not to the neighbour. This could be because farmers viewed soil erosion as a major problem affecting their farming systems and perceived a need to demarcate boundaries of their small land holdings to avoid encroachment from neighbours. However, apart from boundary planting, there were significant differences in farmer perceptions about the relevance of other agroforestry practices being promoted across the four farmer categories ($p<0.05$) (see supplementary table 2). This implies that the intended purpose of the different agroforestry practices was perceived differently by the four farmer categories. For example, on a scale of 1-7, farmers that have never interacted with the T4FS project had negative perceptions of the likelihood of fodder banks (L3.1) and river bank restoration using trees (L3.3) to serve their purpose. They generally disagreed that these practices would provide nutritious fodder with easy access, and would stop the rivers washing away farmlands, respectively.

Overall, phase 1 farmers perceived the agroforestry practices promoted as being more likely to serve their purpose (L6.1), while the remote farmers were undecided (L4.0). This could be attributed to the continued promotion, farmer trainings and participatory on-farm trials by the T4FS project among phase 1 farmers. Farmers neighbouring project beneficiaries were generally unsure (L4.0) about the likelihood of woodlots achieving their purpose, probably due to lack of land to establish the woodlots.

8.4.5 Farmers' knowledge on establishment and management of scattered trees in coffee

Overall, the majority (76%) of the respondents established their trees through planting seedlings. However, over 40% of the respondents lived some distance away and were unaware of the T4FS project; those farmers established their trees through retention of naturally regenerated seedlings on their farms. Farmers were asked whether they did any canopy tree pruning on the existing tree species (Fig. 4). While 50% of farmers actively participating in the T4FS project from phase 1 indicated that they pruned their trees, only 6% of the farmers living at distance, and unaware of the T4FS project, were pruning their trees in coffee gardens. This may imply that, unlike non-project beneficiaries, continued interaction of the project beneficiaries with the project through capacity building activities and on-farm demonstrations on the tree pruning may have encouraged them to prune their trees.

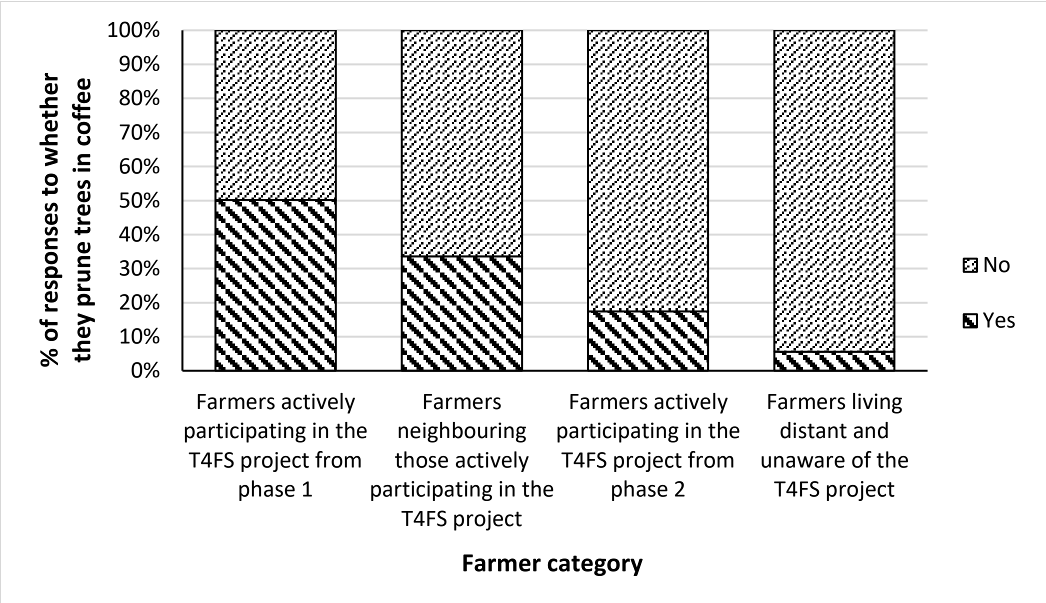

Fig. 4 A stacked column graph showing farmers' responses to whether they did any tree canopy pruning of the trees in their coffee gardens

Farmers with mature trees growing in their coffee plantations were hesitant to prune the trees mainly for fear of destroying their coffee (from falling branches) during pruning. Other farmers thought that the unpruned trees would accumulate more compost (for coffee and beans) from leaves that fall on the ground during leaf shedding. A section of farmers thought that pruning would kill the trees while others believe that it is taboo to prune or even cut trees planted by ancestors. One farmer reported, *"If you are not the one who planted the tree, you are not supposed to prune it. It is actually a taboo to climb some of the tree species existing in our coffee plantations. So how can one prune a large tree without climbing it?"*

8.4.6 Pruning frequency of shade trees scattered in coffee

Of those farmers that prune, there was no significant difference in pruning frequency reported by respondents across the four farmer categories ($p>0.05$), indicating that farmers' perceptions about tree pruning frequency did not vary among the four categories of farmers studied.

However, overall, most farmers (62%) pruned their on-farm trees at least once a year. Other farmers pruned their trees quarterly, twice a year and every 2 years, as reported by 6%, 21% and 11% of the respondents, respectively. Information obtained from focus group discussions indicated that tree pruning was mainly driven by the need for fuelwood, rather than the need to reduce tree shade. Farmers were therefore unable to quantify the proportion of the tree crown removed during pruning so long as enough fuelwood would be collected from a given tree.

8.4.7 Farmers' perception on impact of trees on coffee

This study conducted a one-way ANOVA on the perception of farmers on yield, weight, size, taste, maturity and ripening of coffee beans, as well as disease and pest tolerance of shaded and unshaded coffee, across the four farmer categories (see supplementary table 3). Although there was no significant difference in farmer perceptions on pest and disease tolerance ($p>0.05$), there was a significant difference in farmer perceptions towards yield, weight, size, taste, maturity and ripening of coffee beans from shaded and unshaded coffee, across the four farmer categories ($p<0.05$). All four farmer categories perceived that coffee grown under shade was more likely to be attacked by pests and diseases than unshaded coffee.

However, unlike other farmer categories, the majority of the farmers that had never interacted with the T4FS project disagreed with the perception that coffee grown under shade produces more yields than those in the open. Recent project beneficiaries perceived no differences in size, weight, maturity and ripening period of coffee beans from shaded and unshaded coffee, as opposed to other farmer categories who generally perceived that coffee under shade produces larger and heavier coffee beans that take longer to mature and ripen. Farmers that have been with the T4FS project for a long time (since 2014), along with their neighbours, perceived that coffee processed from coffee trees growing under shade tastes better than unshaded coffee, as opposed to recent project beneficiaries and farmers that have never interacted with project, who were generally uncertain of any differences in taste.

8.4.8 Gender roles in coffee production across farmer categories

Apart from management of coffee, there were no significant differences in farmer perceptions on gender roles in planting and marketing of coffee or the decision maker on where to plant trees on farm ($p>0.05$) across the four farmer categories (see Supplementary table 3). Men were generally perceived to be more involved than women in planting of coffee, marketing and decision making on where to plant trees on the farm across the four farmer categories. However, while farmers living distant and unaware of the T4FS project perceived men as being more involved in managing coffee (which mainly involves weeding of coffee gardens) than women, farmers that have never interacted with the project perceived otherwise.

8.4.9 Perceived practice characteristics influencing adoption of scattered trees on-farm

Analysis of variance showed that farmer motivation resulting from the relative advantage and complexity of an agroforestry technology was significantly different across the four farmer categories studied ($P<0.05$) (Table 3). The box and whisker plots below provide the distribution and variability of the farmer motivations, based on perceived practice characteristics that represent Rogers' factors of adoption recorded on 1-7 Likert scales (Fig. 5). The results show that 50% of farmers that had never participated in the project (referred to as "remote" in the box plots) were uncertain (L4) about the relative advantage of shade trees in their gardens over unshaded gardens (see Fig. 5a). A section of recent project beneficiaries (also referred to as "Phase 2") did not perceive any relative advantage of having shaded gardens over a garden without trees (see Fig. 5a). This could be because either these farmers had no trees on their farms (especially category 4 farmers) or the trees were too young to determine any comparable results (especially among Phase 2 project beneficiaries).

Table 3: Analysis of variance of the influence of perceived practice characteristics on farmers to plant scattered trees on their farms, across the four farmer categories

Variable statement		Sum of Squares	Df	Mean Square	F	Sig.
A garden shaded with trees has more general benefits than an unshaded garden (Relative advantage) * Respondent category	Between Groups	9.887	3	3.296	4.183	.006
	Within Groups	312.010	396	.788		
	Total	321.898	399			
Planting trees in the garden is compatible with existing farm practices (Compatibility) * Respondent category	Between Groups	3.108	3	1.036	1.300	.274
	Within Groups	315.570	396	.797		
	Total	318.678	399			
Planting trees for shade is too much trouble for what it is worth (Complexity) * Respondent category	Between Groups	103.380	3	34.460	11.531	.000
	Within Groups	1183.460	396	2.989		
	Total	1286.840	399			
I am likely to plant trees in my garden after seeing other farmers doing the same (Observability) * Respondent category	Between Groups	9.900	3	3.300	.686	.561
	Within Groups	1906.060	396	4.813		
	Total	1915.960	399			
I am likely to plant shade trees on a small scale first before planting more (Trialability) * Respondent category	Between Groups	15.047	3	5.016	.747	.525
	Within Groups	2659.390	396	6.716		
	Total	2674.438	399			

Farmers that are non-project beneficiaries (also referred to as “remote”) were uncertain about the complexity of planting trees on their farms (Fig. 5b) since several of them were retaining naturally growing seedlings in their gardens. However, farmer motivation by compatibility, trialability and observability of scattered trees on-farm was not significantly different among the four farmer categories (Fig. 5c, 5d and 5e). This implies that perceived practice characteristics such as technology compatibility, trialability and observability generally influenced farmers’ decision to adopt trees on farm, irrespective of farmer category. The box plots further show that farmers were mainly motivated to take on scattered trees on-farm due to its compatibility with the existing farming practices irrespective of farmer category (see Fig. 5c). The high variability (shown by large boxes) in factors such as trialability and observability indicates that such factors may not be critical in motivating farmers to adopt scattered trees on their farms.

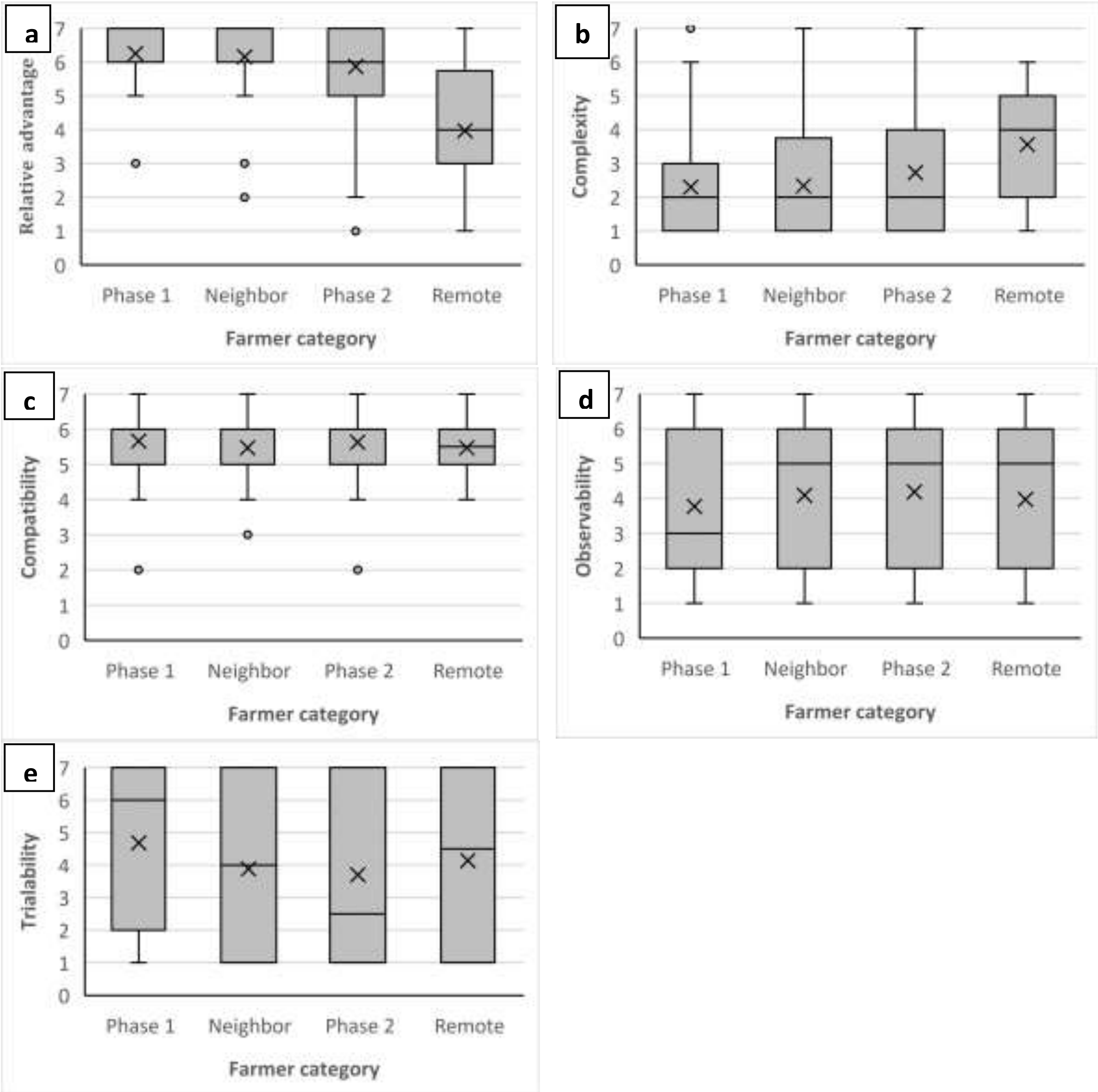

Fig. 5 Box and whisker plots showing how perceived practice characteristics motivate farmers to adopt scattered trees on their farms across the four farmer categories. *The likert values on the Y-axis provide the distribution and variability of the farmer motivation based on relative advantage of the technology (a), complexity (b), compatibility (c), observability (d) and trialability (e) of the agroforestry practice*

8.5 Discussion

8.5.1 Tree establishment and management

The survival of shade trees in agroforestry systems is often the result of farmers' deliberate selection, usually influenced by their needs. Results from this study show that tree preference differed across the four farmer categories studied, apart from *C. africana* that was ranked highly in all the farmer categories. Tree species such as *A. coriaria* had a ranking of 1 from farmer responses in categories 1, 2 and 4, and a score of 7 from phase 2 farmers, who favoured faster growing plantation species such as *Eucalyptus grandis* and *Grevillea robusta*. The results also show that farmers living distant and unaware of the T4FS project tended to have a higher preference for fruit trees compared with other farmers categories (see Table 2). While farmers involved in phase 1 were more concerned about planting trees for shade, and those engaged in phase 2 farmers preferred fast growing tree species for supply of fuelwood, the majority of the remote farmers were more inclined towards planting and retaining fruit trees on their farms. In this study, over 40% of the remote farmers established their trees through retention of naturally growing seedlings on their farms. Studies have shown that farmers facilitate tree regeneration only when the benefits of their investment are guaranteed and as a response to the economic value such trees can provide to the household (Obua 2002; Buyinza and Okullo 2015).

In cases where trees have been planted or retained for shade, farmers rarely manage them. There is normally no deliberate effort towards canopy pruning of mature trees for fear of destroying coffee during pruning and the assumption that unpruned trees would accumulate more organic matter input through leaf fall. While shade trees can extend the life of the coffee plantation by regulating light transmission to coffee plants (which regulates coffee yields), greater shading can result in lower coffee yields (DaMatta et al. 2007). High infestation of the coffee berry borer have been reported in coffee grown under the shade of unpruned trees (Bosselmann et al. 2009; Ayalew 2018). Tree management practices such as tree canopy pruning would also prolong the period of intercropping, allowing the farmer to cultivate the land for a longer period. Pruning would control competition for the limited plant and soil resources while enhancing sustainable smallholder agroforestry farming systems. It is therefore important that appropriate canopy pruning regimes are developed for both the existing mature and young shade trees.

8.5.2 Perceptions of the relevance of existing agroforestry practices

The T4FS project is promoting six agroforestry practices that include scattered trees on-farm, fodder banks, soil erosion control using vegetative strips, woodlots, riverbank restoration using trees and boundary planting. The key concept in agroforestry is putting the right tree, in the right place, for the right purpose. The results from this study showed that soil erosion control using vegetation strips and boundary planting were generally perceived as practices that most served their purpose among the smallholder farming communities. Indeed, soil loss rates from the soil erosion risk assessment in Uganda showed that Mt. Elgon was among the most erosion prone areas with mean annual soil loss rates of 46.3 $t \cdot ha^{-1} \cdot y^{-1}$ and 14.6 $t \cdot ha^{-1} \cdot y^{-1}$ in Bududa and Sironko respectively (Karamage et al. 2017). Land related conflicts have also been reported in the region, especially among communities neighbouring the National Park (Vedeld et al. 2016). The communities therefore view soil erosion as a major issue affecting their farming systems and the need to demarcate boundaries of their small land holdings to avoid encroachment and land related conflicts from neighbours. The results also show that the intended purpose of other agroforestry practices was perceived differently by the four farmer categories ($p<0.05$). This may have implications for adoption and scaling up of these agroforestry practices.

8.5.3 Farmers' perceptions of the impact of trees on coffee production and quality

Shading coffee can have both positive and negative impacts on the coffee (Bosselmann et al. 2009; Rahn et al. 2018). It is therefore not surprising that in this study, farmer perceptions of the impact of shade trees on coffee yield, weight, size, taste, maturity and ripening differed across the four farmer categories ($p<0.05$). While most studies on these attributes have not been conclusive, shaded coffee has been reported to have an economic advantage over unshaded coffee. For example, with an increase in "green consumerism" (Boström and Klintman 2008), the role of shade trees in coffee production has received renewed attention globally for specialty coffee markets (Bosselmann et al. 2009; Silva Neto et al. 2018). While this is not yet well-developed in Uganda, becoming certified under a specialty coffee label, such as organic, is a promising option for smallholder coffee farmers, as such coffee can be sold at a premium price. Shading also reduces the quantity of weeds in the plantation (Staver et al. 2001), which can lower management costs. A study in Ethiopia showed that coffee plants grown under shade trees produced larger, heavier and better quality coffee beans than unshaded coffee (Bote and Struik 2011). In the same study, shaded coffee exhibited greater biochemical and physiological potential for high dry matter production, enabling the coffee to maintain high yields in the long term.

Our results demonstrated that all four farmer categories perceived that coffee grown under shade is more likely to be attacked by pests and diseases than unshaded coffee. This can be attributed to poor management of shade trees in coffee plantations, as the majority of the farmers were not pruning the trees that were shading their coffee. In contrast to this, the use of 35 to 65% shade has been reported to reduce the incidence of disease-causing fungi such as *Cercospora coffeicola* and *Planococcus citri*, without reducing yields (Staver et al. 2001).

8.5.4 Gender roles in coffee production and marketing

Results from this study showed that men are perceived to be more involved than women in marketing of coffee and in decision making on where to plant trees on the farm. Women are more active in coffee management, which mainly involves weeding of coffee gardens. Gender inequalities at household level considerably affect women's participation in coffee production and marketing. Culturally embedded male-controlled conditions usually restrict women's ability to take autonomous choices and to control resources (Meier 2016), creating barriers to exploit their economic opportunities and personal capabilities. Women generally have limited powers in coffee production decision-making because land traditionally belongs to men. Even where women own land, tenure insecurity has been reported to lower women's agricultural productivity, especially in Africa (Goldstein and Udry 2008; Banana et al. 2012).

Studies have demonstrated that gender integration and increased women participation can be enhanced where they are affiliated with local institutions such as farmer groups, community based organisations and farmer cooperatives (Goldstein and Udry 2008; Lyon et al. 2010; Ruben and Fort 2011). Women belonging to such institutions can attend capacity-building seminars, have greater access to network benefits such as access loans from micro-finance institutions and gain greater control over farming practices (Lyon et al. 2010). When equipped with better information and related resources, women may be in a better position to participate effectively in the production and marketing of coffee and in on-farm decision-making.

8.5.5 Perceived practice characteristics influencing agroforestry technology adoption

The perceived practice characteristics investigated in this study were relative advantage, compatibility, observability, complexity and trialability. Results indicate that perceived high levels of relative advantage and compatibility with existing farming systems were the most important in influencing adoption behavior of smallholder farmers. A related study on adoption of agricultural best management practices conducted in two Indiana water sheds found relative advantage, compatibility and observability as the most important characteristics (Reimer et al. 2012).

Relative advantage is the degree to which an innovation is perceived as being better than any technology it can replace (Rogers 2003). Though traditionally interpreted in terms of financial advantage (such as farm costs and yield) to the farm business (McCann et al 2006), relative advantage can also consist of other types of positive impacts resulting from adoption.

Additional benefits can include an increase in social prestige, time-savings, reduction of discomfort, and immediacy of the rewards from the innovation. Relative advantage is dependent upon a farmer's unique set of interests influenced by economic, social and cultural (norms, beliefs) context within which the innovation will be applied (Pannell et al. 2006). Relative advantage has been reported to be one of the most important motivations for adoption (Reimer et al. 2012). Farmers are therefore likely to vary in their perception of a given practice's relative advantage.

Compatibility is the degree to which an innovation is perceived as consistent with the existing values, past experiences, and needs of potential adopters (Rogers 2003). Our results are congruent with other studies that have found that one of the main criteria for tolerating and planting shade trees is compatibilities with crop production (Soto-Pinto et al. 2007; Anglaaere et al. 2011; Valencia et al. 2015). A number of studies have found that farmers select shade trees based on their compatibility with crops by assessing traits such as crown shape, shade production, deciduousness, foliage density, root system attributes, and allelopathic effects (Albertin and Nair 2004; Souza et al. 2010; Cerdán et al. 2012). Therefore, perceived compatibility of an agroforestry practice with already existing farming systems can be an important adoption incentive particularly among those with marginal land parcels susceptible to erosion and among those who practice mixed farming.

Observability has been reported to have two components: 1) practice observability, being able to see the actual practice in place, and 2) benefit observability, the ability to see the benefits accruing from the practice (Reimer et al. 2012). Agricultural innovations whose advantages are observable are more likely to be adopted by farmers. The ability to observe practice benefits from trusted information sources or through their own experimentation may influence farmers' adoption decisions. Therefore, agroforestry practices whose results are observable to potential adopters are more likely to be adopted. Besides observability being an attribute through which farmers are motivated to adopt new practices, other farmers use practices observed from fellow farmers on grounds that such practices had been taken through a series of modifications and adaptations to suit their local context, a process that farmers perceived to save both time and costs of experimentation. The high variability in farmer responses in this study may be an indication that there is limited co-learning among farmers, a scenario that could adversely affect agricultural technology adoption among farmers in the Mt. Elgon region in the longer term.

8.6 Conclusion

Understanding the perceptions and knowledge of smallholder farmers regarding integration of trees on farms is essential to minimizing the barriers to integrating trees on farm. Farmers' perceptions and knowledge of tree management and their impact on farm differed among the farmer categories studied. The study has demonstrated that farmers are likely to incorporate knowledge that promotes practices with a relative advantage that are compatible to existing farming systems. Research and development interventions implemented by the T4FS project in scaling up locally adopted agroforestry practices could have played a key role in positively influencing farmer perceptions and knowledge of the impact of trees on farm. Such interventions should be extended to other areas for wider adoption to enhance household food security. However, there is need to develop appropriate pruning regimes for mature trees already existing in farmers' coffee plantations that can also be applied to young trees being promoted by the T4FS project. Managing these trees will prolong the period of crop cultivation and control the negative effects of over shading. The study also provides insights into how gender inequalities could be minimized to enhance women participation in coffee production and marketing. There is need for integration of farmers' knowledge and perceptions on agroforestry with information from field experiments involving trees and crops. Knowledge exchange between farmers, scientists and extension agents will enhance promotion of appropriate tree management regimes that provide a ‘diversified food-and-cash crop’ livelihood strategy.

8.7 References

Ajzen I (2011) The theory of planned behaviour: Reactions and reflections. Psychol & Health 26(9): 1113-1127. doi: 10.1080/08870446.2011.613995

Albertin A, Nair P (2004) Farmers' Perspectives on the Role of Shade Trees in Coffee Production Systems: An Assessment from the Nicoya Peninsula, Costa Rica. An Interdiscipl J 32(4): 443-463. doi: 10.1023/B:HUEC.0000043515.84334.76

Ayalew B (2018) Impact of shade on morpho-physiological characteristics of coffee plants, their pests and diseases: A review. . African J Agric Research 13(39): 9. doi: 10.5897/ajar2018.13408

Banana AY, Bukenya M, Arinaitwe E, Birabwa B, Ssekindi S (2012) Gender, tenure and community forests in Uganda. Retrieved from http://www.jstor.org/stable/resrep01908.

Bosselmann AS, Dons K, Oberthur T, Olsen CS, Ræbild A, Usma H (2009) The influence of shade trees on coffee quality in small holder coffee agroforestry systems in Southern Colombia. Agric, Ecosyst & Environ 129(1): 253-260. doi: 10.1016/j.agee.2008.09.004

Bote AD, Struik PC (2011) Effects of shade on growth, production and quality of coffee (Coffea arabica) in Ethiopia. J Horticul & For 3(11): 336-341

Broeckx J, Maertens M, Isabirye M, Vanmaercke M, Namazzi B, Deckers J. . Poesen J (2019) Landslide susceptibility and mobilization rates in the Mount Elgon region. Uganda Landsl 16(3):571–584. https://doi.org/10.1007/s10346-018-1085-y

Buyinza, J., Muthuri, C. W., Downey, A., Njoroge, J., Denton, M. D., & Nuberg, I. K. (2019). Contrasting water use patterns of two important agroforestry tree species in the Mt Elgon region of Uganda. Austr For, 1-9. doi: 10.1080/00049158.2018.1547944

Buyinza J, Nuberg I, Muthuri C, Denton M (2020a) Assessing smallholder farmers' motivation to adopt agroforestry using a multi-group structural equation modeling approach. Agrofor Syst, doi: 10.1007/s10457-020-00541-2

Buyinza J, Nuberg I, Muthuri C, Denton M (2020b) Psychological factors influencing farmers' intention to adopt agroforestry: A structural equation modeling approach. J Sustain For. 39(8), 854-865, doi: 10.1080/10549811.2020.1738948

Buyinza J, Okullo JBL (2015) Threats to Conservation of Vitellaria paradoxa subsp. nilotica (Shea Butter) Tree in Nakasongola district, Central Uganda. Int. Res. J. Environ Sci 4(1): 5

Cardinale JB, Emmett JD, Gonzalez A, Hooper UD, Perrings C, Venail P, . . . Shahid N (2012) Biodiversity loss and its impact on humanity. Nature 486(7401): 59. doi: 10.1038/nature11148

Cerdán CR, Rebolledo MC, Soto G, Rapidel B, Sinclair FL (2012) Local knowledge of impacts of tree cover on ecosystem services in smallholder coffee production systems. Agric Syst 110: 119-130. doi: 10.1016/j.agsy.2012.03.014

Dahlquist R, Whelan M, Winowiecki L, Polidoro B, Candela S, Harvey C, . . . Bosque-Pérez N (2007) Incorporating livelihoods in biodiversity conservation: a case study of cacao agroforestry systems in Talamanca, Costa Rica. Biodiver & Conserv 16(8): 2311-2333. doi: 10.1007/s10531-007-9192-4

DaMatta FM, Ronchi CP, Maestri M, Barros RS (2007) Ecophysiology of coffee growth and production. Brazilian J Plant Physiol 19: 485-510

Fishbein M, Ajzen I (2010) Predicting and Changing Behavior: The Reasoned Action Approach New York: Taylor and Francis

Goldstein M, Udry C (2008) The Profits of Power: Land Rights and Agricultural Investment in Ghana. J Political Econ 116(6): 981-1022. doi: 10.1086/595561

Iiyama M, Derero A, Kelemu K, Muthuri C, Kinuthia R, Ayenkulu E, . . . Sinclair F (2017) Understanding patterns of tree adoption on farms in semi-arid and sub-humid Ethiopia. Intern J incorpor Agrofor Forum 91(2): 271-293. doi: 10.1007/s10457-016-9926-y

Karamage F, Zhang C, Liu T, Maganda A, Isabwe A (2017) Soil Erosion Risk Assessment in Uganda. Forests 8(2): 52. doi: 10.3390/f8020052

Kiptot E, Hebinck P, Franzel S, Richards P (2007) Adopters, testers or pseudo-adopters? Dynamics of the use of improved tree fallows by farmers in western Kenya. Agric Syst 94(2): 509-519. doi: 10.1016/j.agsy.2007.01.002

Meier Zu Selhausen F (2016) What Determines Women's Participation in Collective Action? Evidence from a Western Ugandan Coffee Cooperative. Femin Econ 22(1):130-157. doi: 10.1080/13545701.2015.1088960

Meijer SS, Catacutan D, Ajayi OC, Sileshi GW, Nieuwenhuis M (2015) The role of knowledge, attitudes and perceptions in the uptake of agricultural and agroforestry innovations among smallholder farmers in sub-Saharan Africa. Intern J Agric Sustain 13(1):40-54. doi: 10.1080/14735903.2014.912493

Muthuri, WC (2017) Improving Sustainable Productivity in Systems and Enhanced Livelihoods through adoption of evergreen agriculture in Eastern Africa shortened as 'Trees for Food Security' Project (T4FS). ACIAR Final Reports (No.FR2017/21), 96 pp.

Nasielski J, Furze J, Tan J, Bargaz A, Thevathasan N, Isaac M (2015) Agroforestry promotes soybean yield stability and N 2 -fixation under water stress. Official J Institut National de la Recherche Agron (INRA) 35(4):1541-1549. doi: 10.1007/s13593-015-0330-1

Nakileza BR, Majaliwa MJ, Wandera A, Nantumbwe CM (2017) Enhancing resilience to landslide disaster risks through rehabilitation of slide scars by local communities in Mt Elgon, Uganda. Ja`mba´: J Disaster Risk Studies, 9:1–11

Ndoli, A., Baudron, F., Schuta, A. G. T., Mukuralinda, A., & Gillera, K. E. (2017). Disentangling the positive and negative effects of trees on maize performance in smallholdings of Northern Rwanda. *Field Crop Research*, *213*, 11. doi: 10.1016/j.fcr.2017.07.020

Obua J (2002) Conservation of Shea parklands through Local Resource Management. International Workshop on Processing and Marketing of Shea products in Africa, proceedings, CFC Technical paper 21

Palacios Bucheli VJ, Bokelmann W (2017) Agroforestry systems for biodiversity and ecosystem services: the case of the Sibundoy Valley in the Colombian province of Putumayo. Intern J Biodiv Sci, Ecosyst Services & Manag 13(1):380-397. doi: 10.1080/21513732.2017.1391879

Pauli N, Barrios E, Conacher AJ, Oberthür T (2012) Farmer knowledge of the relationships among soil macrofauna, soil quality and tree species in a smallholder agroforestry system of western Honduras. Farmer knowledge of the relationships among soil macrofauna, soil quality & tree species in a smallholder agrofor syst western Honduras 189:186-198.

Rahn E, Liebig T, Ghazoul J, van Asten P, Läderach P, Vaast . . . . Jassogne L (2018) Opportunities for sustainable intensification of coffee agro-ecosystems along an altitudinal gradient on Mt. Elgon, Uganda. Agric, Ecosyst & Environ 263:31-40. doi: 10.1016/j.agee.2018.04.019

Reimer AP, Weinkauf DK, Prokopy LS (2012) The Influence of Perceptions of Practice Characteristics: An Examination of Agricultural Best Management Practice Adoption in Two Indiana Watersheds. J Rural Studies 28(1):118-128. doi: 10.1016/j.jrurstud.2011.09.005

Rigal C, Vaast P, Xu J (2018) Using farmers' local knowledge of tree provision of ecosystem services to strengthen the emergence of coffee-agroforestry landscapes in southwest China.(Research Article). PLoS ONE, 13(9):e0204046. doi: 10.1371/journal.pone.0204046

Rogers EM (2003) Diffusion of innovations (5th ed.) (5 ed.). New York: Free Press

Ruben R, Fort R (2011) The Impact of Fair Trade Certification for Coffee Farmers in Peru. World Develop doi: 10.1016/j.worlddev.2011.07.030

Segura HR, Barrera JF, Morales H, Nazar A (2004) Farmers’ Perceptions, Knowledge, and Management of Coffee Pests and Diseases and Their Natural Enemies in Chiapas, Mexico. J Econ Entomol 97(5):1491-1499. doi: 10.1603/0022-0493-97.5.1491

Sileshi GW, Akinnifesi FK, Ajayi OC, Muys B (2011) Integration of legume trees in maize-based cropping systems improves rain use efficiency and yield stability under rain-fed agriculture. Agric Water Manag 98(9):1364-1372. doi: 10.1016/j.agwat.2011.04.002

Silva Neto FJD, Morinigo KPG, Guimaraes NDF, Gallo ADS, Souza MDB, Stolf R, Fontanetti A (2018) Shade Trees Spatial Distribution and Its Effect on Grains and Beverage Quality of Shaded Coffee Trees. J Food Quality, 2018:8. doi: 10.1155/2018/7909467

Smethurst PJ, Huth NI, Masikati P, Sileshi GW, Akinnifesi FK, Wilson J, Sinclair F (2017) Accurate crop yield predictions from modelling tree-crop interactions in gliricidia-maize agroforestry. Agric Syst, 155, 70-77. doi: https://doi.org/10.1016/j.agsy.2017.04.008

Soto-Pinto L, Villalvazo-López V, Jiménez-Ferrer G, Ramírez-Marcial N, Montoya G, Sinclair F (2007) The role of local knowledge in determining shade composition of multistrata coffee systems in Chiapas, Mexico. Biodiv & Conserv 16(2):419-436. doi: 10.1007/s10531-005-5436-3

Souza HN, Cardoso IM, Fernandes JM, Garcia FCP, Bonfim VR, Santos AC, . . . Mendonca ES (2010) Selection of native trees for intercropping with coffee in the Atlantic Rainforest biome.(Report). Agrofor Syst 80(1):1. doi: 10.1007/s10457-010-9340-9

Staver C, Guharay F, Monterroso D, Muschler R (2001) Designing pest-suppressive multistrata perennial crop systems: shade-grown coffee in Central America. Int. J. incorpor Agrofor Forum 53(2):151-170. doi: 10.1023/A:1013372403359

Valencia V, West P, Sterling EJ, García - Barrios L, Naeem S (2015) The use of farmers' knowledge in coffee agroforestry management: implications for the conservation of tree biodiversity. Ecosphere 6(7):1-17. doi: 10.1890/ES14-00428.1

Vedeld P, Cavanagh C, Petursson J, Nakakaawa C, Moll R, Sjaastad E (2016) The Political Economy of Conservation at Mount Elgon, Uganda: Between Local Deprivation, Regional Sustainability, and Global Public Goods. Conserv & Society 14(3):183-194. doi: 10.4103/0972-4923.191155

Supplementary Table 1 Demographic characteristics of the different farmer categories

Variable	**Farmers actively participating in T4FS project from phase 1 (%)**	**Farmers neighbouring those actively participating in T4FS project (%)**	**Farmers actively participating in T4FS project phase 2 (%)**	**Farmers who have never participated in T4FS project and living far from project farmers (%)**	**Total (%)**
Sex					
Male	57	52	56	51	57.0
Female	43	48	44	49	43.0
Age (years)					
18-30	12	20	21	26	19.8
31-50	60	57	57	51	56.3
>50	28	23	22	23	24.0
Level of education					
None	0	4	5	12	5.3
Primary	60	60	72	65	64.3
Secondary	15	15	18	16	23.8
Tertiary	13	9	3	2	6.8
Household size					
≤3 members	5	13	10	10	9.5
4-7 members	55	45	45	56	50.2
8-11 members	33	34	35	27	32.3
>11 members	7	8	10	7	8.0
Male active farm workers					
≤3 males	73	82	80	83	79.5
4-7 males	27	17	19	17	20.0
8-11 males	0	0	1	0	0.3
>11 males	0	1	0	0	0.3
Female active farm workers					
≤3 females	77	87	82	81	81.8
4-7 females	21	12	17	18	17.0
8-11 females	0	1	1	1	0.8
>11 females	2	0	0	0	0.5
Size of land					
≤2 acres	43	57	49	37	46.5
3-5 acres	48	34	40	49	42.8
6-8 acres	6	4	9	12	7.8
>8 acres	3	5	2	2	3.0

Supplementary Table 2 Analysis of variance output on farmers' perceptions on the likelihood of the agroforestry practices to serve their purpose across the four farmer categories

Likelihood of the agroforestry practice to serve its purpose		Sum of Squares	df	Mean Square	F	Sig.
How likely scattered trees practice is serving its purpose * Respondent category	Between Groups	53.721	3	17.907	15.042	.000
	Within Groups	467.856	393	1.190		
	Total	521.577	396			
How likely Boundary planting practice is serving its purpose * Respondent category	Between Groups	15.047	3	5.016	.747	.525
	Within Groups	2659.390	396	6.716		
	Total	2674.438	399			
How likely Woodlots practice is serving its purpose * Respondent category	Between Groups	42.798	3	14.266	11.126	.000
	Within Groups	239.778	187	1.282		
	Total	282.576	190			
How likely River bank restoration practice is serving its purpose * Respondent category	Between Groups	30.988	3	10.329	7.087	.000
	Within Groups	139.922	96	1.458		
	Total	170.910	99			
How likely Erosion control using vegetation strips practice is serving its purpose * Respondent category	Between Groups	16.768	3	5.589	6.858	.000
	Within Groups	131.208	161	.815		
	Total	147.976	164			
How likely Fodder banks practice is serving its purpose * Respondent category	Between Groups	20.923	3	6.974	7.010	.000
	Within Groups	109.437	110	.995		
	Total	130.360	113			

Supplementary Table 3 Analysis of variance output on farmers' perceptions on impact of trees on coffee and gender roles in coffee production across farmer categories

Comparing coffee grown under shade with coffee grown in full sun		**Sum of Squares**	**Df**	**Mean Square**	**F**	**Sig.**
Coffee grown under shade is more likely to be attacked by pests and diseases	Between Groups	3.482	3	1.161	.560	.641
	Within Groups	816.206	394	2.072		
	Total	819.688	397			
Coffee grown under shade in a garden produces more yields than one in open	Between Groups	4.347	3	1.449	2.650	.049
	Within Groups	216.590	396	.547		
	Total	220.938	399			
Coffee under shade is larger and heavier than unshaded coffee	Between Groups	6.210	3	2.070	4.062	.007
	Within Groups	201.780	396	.510		
	Total	207.990	399			
Coffee beans under shade take longer to mature and ripen than those on unshaded coffee	Between Groups	10.740	3	3.580	3.357	.019
	Within Groups	422.300	396	1.066		
	Total	433.040	399			
Coffee processed from coffee beans grown under shade tastes better than unshaded coffee	Between Groups	19.100	3	6.367	7.115	.000
	Within Groups	354.340	396	.895		
	Total	373.440	399			
Comparing women and men's roles in coffee planting, management and marketing						
Women are generally more involved than men in planting of coffee	Between Groups	1.047	3	.349	.177	.912
	Within Groups	783.150	396	1.978		
	Total	784.198	399			
Women are generally more involved than men in managing coffee plants	Between Groups	127.820	3	42.607	13.345	.000
	Within Groups	1264.340	396	3.193		
	Total	1392.160	399			
Men are generally more involved than women in marketing coffee	Between Groups	2.127	3	.709	.873	.455
	Within Groups	321.670	396	.812		
	Total	323.798	399			
Men decide when and where to plant trees on our farm	Between Groups	5.067	3	1.689	1.787	.149
	Within Groups	374.230	396	.945		
	Total	379.297	399			

Chapter 9: Why farmers are hesitant to adopt what appears good on the basis of science: Understanding farmers' perceptions of biophysical research

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9.1 Statement of Authorship

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Principal Author

Name of Principal Author (Candidate)	Joel Buyinza		
Contribution to the Paper	Data collection and analysis, theoretical foundation, writing manuscript, conceptual framework development, acted as the first and corresponding author		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	27/05/2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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9.2 Abstract

This study conducted a series of extension events that were followed by farmer interviews involving 394 farmers who had participated in an initial household survey in 2018, involving four farmer categories: 1] those actively participating in the Trees for Food Security (T4FS) project from phase 1 (2014); 2] farmers neighbouring those actively participating in the T4FS project from phase 1; 3] farmers actively participating in the T4FS project from phase 2 (2017) and; 4] farmers living distant and unaware of the T4FS project. The study drew upon knowledge generated from biophysical experiments on tree water use, shade tree planting and management in smallholder coffee-bean agroforestry systems to assess farmers' perceptions and willingness to adopt practices emanating from the study following exposure to the research outputs. The main form of extension used was through display and viewing of posters and a translated power point presentation of the research outputs on impact of tree canopy pruning on tree and coffee plant water use and productivity of coffee and common beans. We present the key messages obtained by the participants from the extension activities conducted, their preferred crop and management combinations, perceptions towards the research outputs and willingness to adopt the practices recommended by the study. We contend that smallholder farmers are hesitant to adopt innovations due to an underlying culture of financial expectancy leading to 'pseudo adoption', underutilization of existing social networks during research and extension, period of exposure to a technology, and limitations in measuring and predicting adoption. We align the four farmer categories to the Process of Agricultural Utilisation Framework (PAUF) criteria, leading to a better understanding of the impact of research and development projects and agroforestry tree planting and management adoption pathways among smallholder farmers, especially in the context of developing countries.

Key words: *participatory extension, agroforestry, adoption*

9.3 Introduction

Agricultural innovations are seen as an important route out of abject poverty in smallholder farmers in developing countries. Researchers have traditionally been tasked with the development of improved agricultural technologies and their dissemination to extension officers and farmers. However, low adoption continues to hold large productivity, sustainability and resilience consequences for majority of farmers (BenYishay & Mobarak, 2019; Glover et al., 2019). There are many reasons for non-adoption of credible agricultural scientific research innovations in developing countries across the globe. Studies in Africa have revealed that farmers' lack of information on agricultural research outputs is not reflective of a lack of interest in obtaining research information, but the unavailability and inaccessibility of learning opportunities (Brown, et al., 2018; Mubofu & Elia, 2017). In cases where learning opportunities exist, the large heterogeneity of African smallholder farmers has further slowed down knowledge diffusion (Aker, 2011) and widened the information gaps. Deeper analyses have further revealed an underlying culture of financial expectancy (Brown, Llewellyn, et al., 2018) which limits farmer engagement in ongoing research activities, especially by research and development projects.

The low engagement of farmers in agricultural research has further been associated with weak linkages between researchers, extension workers and smallholder farmers (Brown, Nuberg, et al., 2018). A lack of interest among farmers to seek well-researched information (Acheampong et al., 2017; Owolade & Arimi, 2012) further slows down diffusion of knowledge of new technologies and practices. While many countries hire agricultural extension agents to communicate with farmers about new technologies, a large academic literature has established that integrating social networks is a key determinant of adoption (Beaman et al., 2015; BenYishay & Mobarak, 2019; Young, 2009). Existing social networks in a community are locally trusted channels through which agricultural information can be delivered to other farmers.

Failure to reliably measure and predict adoption has led to over- and under-estimation of adoption levels of agricultural technologies and practices. Recent frameworks including the Process of Agricultural Utilisation Framework (PAUF) proposed by Brown et al., (2017) and a modified smallholder Adoption and Diffusion Outcome Prediction Tool (ADOPT) framework (Llewellyn & Brown, 2020) are major steps towards a better understanding of agricultural technology adoption pathways. Such frameworks can contribute towards obtaining adoption constraints of a farming community. Therefore, adoption is not only related to technology, socio economic and behavioural factors and the research and extension methods applied, but a result of complex interactions between people, technologies and institutions (Kiptot et al., 2007; Takahashi et al., 2019). In this study, the PAUF is applied to four farmer categories at different levels of interaction with an Australian Centre for International Agricultural Research (ACIAR) funded Trees for Food Security (T4FS) Project.

Unlike agricultural crops, agroforestry adoption is a dynamic process involving farmer experimentation that occurs over a long period with almost no immediate benefits (Kiptot et al., 2007). However, even where traditional agroforestry research has successfully been conducted, the outputs may not be suitable or usable to the farmer for reasons not identified in the initial study. For example, while assessment of tree-water use, tree management and associated crop yield data may appear acceptable to the research community and worth promoting (Buyinza et al., 2019; Namirembe et al, 2008), it may not be socially acceptable to the user communities. Therefore, understanding farmer perceptions about shade tree management and its impact on tree water use and crop productivity would help reveal farmers' propensity to adopt tree canopy pruning.

The primary users of agroforestry research, namely farmers, think in a cross-disciplinary perspectives about their enterprises and not simply distinct 'silos' (Galmiche-Tejeda, 2004). Using an interdisciplinary research (IDR) approach is suitable to address such modern requirements in agriculture, given its complex nature that combines social and environmental factors (Morse et al., 2007). Interdisciplinary research is motivated by a general belief that by drawing information from different fields and employing different methodologies, a broad understanding and new perspective on an existing issue can be achieved. In addition, IDR is useful in providing a valuable opportunity for engagement with the user communities of the research, making it socially relevant (Gibson et al., 2018; Lowe & Phillipson, 2006). Low engagement with user communities (for example, farmers) often results in research outcomes that lack sufficient relevancy to the intended user community. Therefore, IDR creates opportunities for participatory research, while encouraging collaboration between researchers and farmers to create linkages between available biophysical and social economic information. Intrinsic to the nature of smallholder agroforestry farming systems in the Mt. Elgon region are the underlying relationships that exist between their human (farmer perceptions, knowledge and attitudes) and agro-ecological components (coffee, trees and common beans). This study therefore draws upon knowledge generated from biophysical experiments to assess changes in perceptions from farmers with different levels of exposure to biophysical information on agroforestry tree planting and management in coffee-bean systems in the Mt. Elgon region of Uganda.

9.3.1 Conceptual framework

The study had an initial phase of in-depth, semi-structured farmer interviews and generation of biophysical information from two selected farms with *Cordia africana* and *Albizia coriaria* trees integrated with coffee and common beans (Figure 1). The biophysical information generally relates to influences on the physical production process associated with farming – the impact of tree management on water use and productivity of coffee and common beans, for the case of this study. Farmer interviews would establish farmers' underlying perceptions and motivations towards adoption of trees in their farming systems [see (Buyinza. et al., 2020a, 2020b, 2021)], while the biophysical experiment assessed the impacts of trees and their management on crop productivity and tree water use [see (Buyinza et al., 2019), Chapter 4 and Chapter 5]. The biophysical experiment assessed water use in selected *C. africana, A. coriaria* and coffee trees and yield of coffee and common beans planted on the same piece of land. *C. africana* and *A. coriaria* trees were subjected to a 50% pruning regime at a 6-month interval over a period of 20 months (July 2018 - February 2020). The information from the biophysical data was then reported to farmers through a series of extension events. The extension events were used to highlight the relevance of the findings to the farmers and assess the appropriateness of the extension methods used to deliver the biophysical information to the farmers. The participants of the extension activities were the same farmers that had participated in the initial farmer survey under the same farmer categories used by Buyinza et al (2020a).

The extension events were then followed by a second phase of interviews (which is the focus of this paper) that would assist in assessing any changes in farmer perceptions towards planting and management of trees on their farms and their willingness to adopt the recommended practices. This process involved revisiting participants of the initial survey and presenting findings from the biophysical experiment so that they could provide additional feedback, comments and opinions on the results. Obtaining feedback and later integrating it with the biophysical information would enable introduction of socially and biophysically appropriate agroforestry interventions into local realities. Farmers did not have to necessarily agree with the findings of the biophysical study. The project was also interested in collecting the views of the dissenting farmers for documentation and further inquiry.

Lastly, all the data and information collected from the second phase of farmer interviews and the biophysical experiment was then used to establish the potential impact of incorporating *Cordia africana* and *Albizia coriaria* on soil water resources and crops productivity. The potential impacts resulting from adoption of biophysical information would be documented for informing policy decisions relating to agroforestry and household food security.

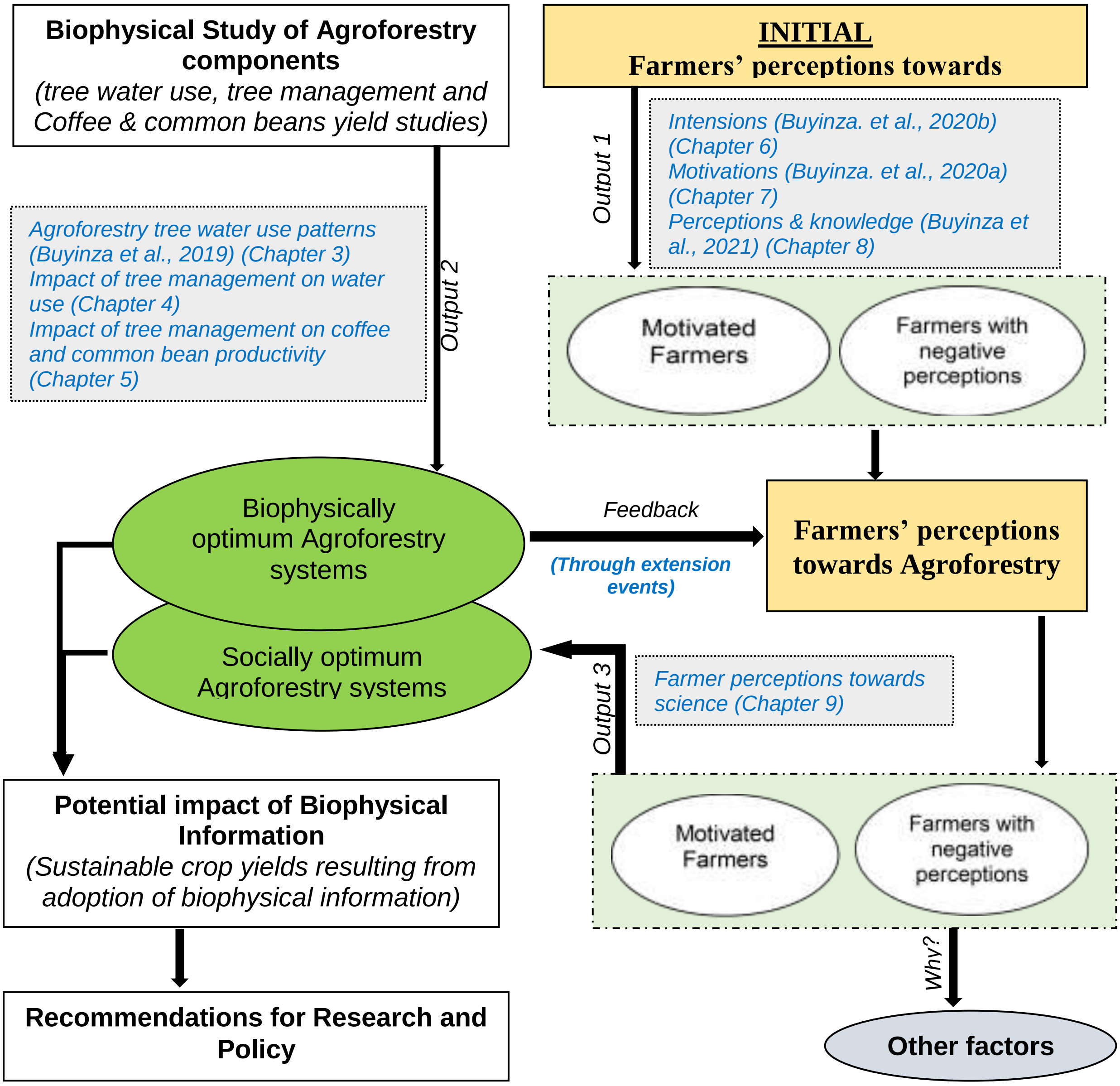


Figure 1: Overall Conceptual framework for the study

9.4 Methods

9.4.1 Study area

This study was conducted in three districts including Manafwa, Bududa and Sironko, located in Mt. Elgon region of Uganda. About 98% of the human population in this region is rural based, with an annual population growth rate of 3.4%. In terms of climate, the average annual rainfall is 1500 mm, with two peak rainy seasons that occur in the months of April–June and August–November.

9.4.2 The Trees for Food Security (T4FS) project in Eastern Africa

These study sites form part of the Trees for Food Security (T4FS) project sites. The T4FS is an Australian Centre for International Agricultural Research (ACIAR) funded project implemented by the World Agroforestry Centre (ICRAF) in partnership with national level stakeholders. The T4FS project aims at improving household food security and smallholder livelihoods through widespread adoption of appropriate locally adapted agroforestry practices in key agricultural landscapes in Ethiopia, Rwanda and Uganda. The project has been reaching out to smallholder farmers in rural regions where an estimated 10 million people are facing acute food security problems since 2012. The second phase of the T4FS project focuses on tree diversity as the cornerstone of smallholder system intensification and integrates tree management with value chain development and sustainable water management. The project is also sustaining food security and livelihood gains for farmers by establishing cross-sector communities of practice and capacity development in locally adaptable agroforestry options that a large number of farmers can adopt.

The T4FS project has established that trees in fields, farm and landscape niches can provide products and services that underpin and improve food security through system intensification and management of interactions amongst components. In Uganda, the T4FS project started in 2014 and is currently in its second phase of implementation in the Manafwa, Bududa and Mbale districts in Eastern Uganda. Agroforestry technologies such as fodder banks, boundary planting, riverbank restoration using trees, scattered trees on-farm, woodlots and use of vegetation strips to control soil erosion are being widely promoted among some of the most vulnerable farming communities in the Mt. Elgon region of Uganda.

9.4.3 Research design

The study used existing records and the local council leadership to trace back the same respondents that had participated in the initial farmer survey in 2018 (May – July) (Buyinza. et al., 2020a, 2020b) for the extension events. The same farmer categories used in 2018 were also maintained. The farmer categories were: 1] those actively participating in the T4FS project from phase 1 (2014); 2] farmers neighbouring those actively participating in the T4FS project from phase 1; 3] farmers actively participating in the T4FS project from phase 2 (2017) and; 4] farmers living distant and unaware of the T4FS project.

9.4.4 Data collection

Conducting extension events

To ensure adherence to the Covid-19 Standard Operating Procedures (SOPs) and Ministry of Health (MoH) guidelines, strategic venues that would accommodate 20-30 people were identified within the communities. Undertaking the extension events close to the communities increased the chances of attaining high participant turn up for the extension events. The participants were also informed about the event a week prior, to give them time to plan for the event. The final reminders were made 2 days to each extension activity through phone calls (for farmers with phones) and verbally through their respective village local council chairpersons. At each venue, copies of two posters were displayed for farmers to view in the first 20 minutes. The posters were entitled (1) A practice for managing agroforestry trees increases coffee and common beans yields and (2) Save water for agriculture by pruning trees (Supplementary figure 1 and 2). The next 20 minutes were then used to go through the posters in the local dialects in 2 separate groups (men and women separately). The groups would then come together for a power point presentation prior to individual farmer assessment and interviews. These activities (poster viewing, poster presentation in local dialects and power point presentations) were conducted to ensure that the participants understood the message being delivered (IIik & Rowe, 2013).

Testing participants' understanding of the information delivered

We got feedback from each participant regarding the key messages and anything new they had learnt from the activities conducted. This would help ascertain participants' understanding of the information delivered.

Assessing changes in farmer perceptions following the extension activities

The study assessed changes in farmers' perceptions after exposure to biophysical information on agroforestry tree planting, water use and management in coffee-bean systems in the Mt. Elgon region. The assessment sought farmers perceptions on planting and management of shade trees, a comparison of coffee growing under pruned and unpruned trees, as well as general opinion on shade tree planting and management, following the perceived practice characteristics (Rogers, 2003). The perceived practice characteristics also known as Rogers' factors of adoption (observability, relative advantage, complexity, trialability and compatibility) were also applied in the initial farmer survey prior to exposure to biophysical information (Buyinza. et al., 2020a, 2020b). A total of 394 farmers participated in the extension events and were interviewed. The high turn-up was achieved through effective mobilization using local council leaders, with an indication that a modest transport facilitation would be provided to ease movement and a snack during each extension event. However, while 4 respondents (among the farmers living distant and unaware of the T4FS project) declined to attend the extension events and could not be interviewed, 2 farmers (among farmers neighbouring those actively participating in the T4FS project) could not be traced in the community, as we were reliably informed they had migrated from the area.

9.4.5 Data analysis

Data from the farmer survey conducted following each extension event was checked for consistency, coded and entered into Statistical Package for Social Scientists (SPSS version 25) software for analysis. Descriptive statistics were used to generate summaries from the data in form of frequency tables and histograms. Analysis of variance was used to determine whether any differences existed in farmers' perceptions of different crop combinations and tree management options considered more beneficial and sustainable to their households.

9.5 Results

9.5.1 Socio economic characteristics of the respondents

Overall, out of the 394 respondents interviewed, 228 (58%) were males with a uniform distribution of male and female respondents across the four farmer categories. Over 50% of the respondents were aged between 31 and 50 years and the majority had only attained primary education (68%); over 60% owned less than 2 acres of land. About 70% of the households had 4-7 family members, and active farm work was mostly done by less than 3 males and females household members.

9.5.2 Assessment of participants' level of understanding the message delivered

Overall, 71% of the respondents understood that pruning could increase coffee and common bean yields, as the key message received from the extension activities, mainly reported by project beneficiaries in both phases 1 and 2 (83 and 86 out of 100 participants respectively) (Table 1). Another key message was that pruned trees use less water than unpruned trees, reported by 59 out of 100 respondents belonging to the farmer actively participating in the T4FS project from phase 1 (2014). The key messages were better understood by farmers directly interacting with the project, probably because the same message had been delivered to them multiple times during project activities. Unlike the farmers neighbouring the project beneficiaries and those living far and unaware of the project, it was not the first time majority of the project beneficiaries were learning about this information. However, 8 participants (distributed across all the farmer categories) understood that beans planted in open fields give very low yields, contrary to the message delivered during extension activities. This may imply that the extension method of displaying posters was not appropriate for them, as they misunderstood the message being displayed.

Table 1: Key messages picked by farmers from the extension activities conducted

Variable	Respondent category				Total
	Farmer actively participating in the T4FS project from phase 1 (2014)	**Farmer neighbouring those actively participating in the T4FS project**	**Farmer actively participating in the T4FS project from phase 2 (2017)**	**Farmer living distant and unaware of T4FS project**	
Pruning can increase coffee and bean yields	21.1 (83)	17.7 (70)	21.8 (86)	9.9 (39)	70.6 (278)
Pruned trees use less water than unpruned trees	15.0 (59)	8.6 (34)	10.2 (40)	12.4 (49)	46.2 (182)
Pruning allows cultivation of beans for a long time	8.7 (34)	7.1 (28)	7.1 (28)	6.9 (27)	29.8 (117)
Pruning allows coffee and beans to access light	10.9 (43)	5.1 (20)	4.1 (16)	6.9 (27)	26.9 (106)
Unshaded coffee uses more water than shaded coffee	5.3 (21)	5.8 (23)	7.1 (28)	1.0 (4)	19.3 (76)
Albizia seems to be the best tree for integrating in coffee	4.3 (17)	2.6 (10)	4.3 (17)	2.6 (10)	13.7 (54)
Pruned branches and leaves add manure to soil	4.1 (16)	2.5 (10)	4.6 (18)	2.3 (9)	13.5 (53)
Pruning increases farm income from sale of coffee and beans	3.6 (14)	4.3 (17)	2.3 (9)	3.0 (12)	13.2 (52)
Shaded coffee can give higher yields than unshaded coffee	1.8 (7)	3.3 (13)	2.0 (8)	5.3 (21)	12.4 (49)
Beans give very low yields in open fields	0.0 (0)	0.0 (0)	1.3 (5)	2.6 (10)	3.9 (15)
It is possible to prune large trees without damaging coffee	1.0 (4)	0.5 (2)	0.5 (2)	1.0 (4)	3.0 (12)
Pruning should be done by a trained person	0.5 (2)	0.5 (2)	0.3 (1)	0.8 (3)	2.0 (8)

Frequency in parenthesis

The participants were asked to give one convincing and most important reason that would encourage them to plant and manage trees in their coffee gardens. The main convincing and important reason was the higher coffee yields from shaded coffee, followed by the prolonged period of intercropping (with common beans) under pruned trees and the higher income from shaded combinations (Table 2). Overall, a total of 184 farmers of the 394 participants (47%)

were convinced that higher coffee yield can be obtained from shaded coffee. This implies that over 50% of the participants were not convinced (by the data presented to them) that higher yields could be obtained from shaded coffee. These farmers are still hesitant to change, as majority of them prune only when there is need for fuelwood and / or poles.

Table 2: The main convincing and important reason that would encourage farmers to plant and prune shade trees on their farms

Variable	Respondent category				Total
	Farmer actively participating in T4FS project from phase 1 (2014)	**Farmer neighbouring those actively participating in T4FS project**	**Farmer actively participating in T4FS project from phase 2 (2017)**	**Farmer living distant and unaware of T4FS project**	
Higher coffee yields from shaded coffee than unshaded coffee	14.4 (56)	10.8 (42)	12.1 (47)	10.0 (39)	47.1 (184)
Pruning prolongs the period of intercropping	4.6 (18)	5.6 (22)	6.4 (25)	5.9 (23)	22.4 (88)
More income from shaded combinations	4.6 (18)	4.3 (17)	4.9 (19)	4.3 (17)	18.2 (71)
Pruning reduces competition for water	0.8 (3)	2.6 (10)	0.5 (2)	1.8 (7)	5.6 (22)
Pruning may control pests and diseases in coffee	0.8 (3)	1.3 (5)	1.5 (6)	1.0 (4)	4.6 (18)
Coffee appears to use more water when under pruned trees	0.5 (2)	0.5 (2)	0.3 (1)	0.8 (5)	2.0 (8)

Frequency in parenthesis

Surprisingly, only 56 out of the 100 farmers actively participating in the T4FS project were convinced that higher coffee yields can be obtained from shaded coffee (Table 2). It is likely because the majority of the farmers who had commenced pruning shade trees (after learning from the experimental sites) were yet to realize yield increases due to the short period of time following pruning, as majority had only pruned once by the time the extension activities were held. Additionally, the farmers needed more time to interact with the experimental sites and the 20-month period of the study may not have been enough to convince them. This may also be responsible for the few participants that were convinced that more income can be generated from shaded combinations, that pruning prolongs the period of intercropping, and that pruning can reduce competition for water and control pests and diseases following reduction of shading effect on coffee. This may also be an indication that farmers may not be convinced to adopt new practices by simply word of mouth, but require other methods of engagement such on-farm demonstrations and social networks.

9.5.3 Farmers' ranking of different crop combinations and tree management options

Farmers' ranking of different crop combinations and tree management options considered more beneficial and sustainable to the household is presented in Table 3 below. Apart from the combination involving pruned Albizia, coffee and beans and the combination involving pruned Cordia, coffee and beans ranked as either first or second most beneficial crop combination, none of the farmers' rankings were consistent with the ranking based on the research results that were presented. Ranking crop combinations involving pruned trees as the most beneficial could be attributed to the additional benefits that can be accrued from pruning. These benefits include additional organic matter from pruned branches and leaves, fuelwood and reduction of negative shading effects that prolongs the period of intercropping below pruned trees.

An analysis of variance further revealed significant differences in farmer opinions on 5 out of the 11 different crop combinations and tree management options ($P<0.05$) (Supplementary Table 1). This is mainly predominant in crop combinations that have common beans as one of the components. It was outstanding that farmers living at distance and unaware of the T4FS project ranked planting of common beans in open field as the third most beneficial option. The point of contention here was that some farmers whose main cash crop was common beans did not perceive any need to integrate trees in their gardens. They would instead prefer to plant common beans in open fields, where the research results indicated the highest yields of common beans would be achieved. The differences in the ranking of the crop combinations among farmer categories and the ranking based on research results could further imply that farmers may not entirely adopt the crop combinations suggested by the project. They could still have other underlying reasons for not adopting the crop combinations as some indicated that they needed to either first try it out or observe from other farmers before adopting them on their farms.

Table 3: Ranking of crop combinations and tree management options considered more beneficial and sustainable to the household

Crop combinations and tree management options	Ranking based on farmer's own perspective* and project results				Ranking based on research results presented
	Farmer actively participating in T4FS project from phase 1 (2014)	Farmer neighbouring those actively participating in T4FS project	Farmer actively participating in T4FS project from phase 2 (2017)	Farmer distant and unaware of T4FS project	
Pruned Albizia + coffee + beans	1	1	1	2	1
Pruned Cordia + coffee + beans	2	2	2	1	2
Coffee only but under pruned Albizia	4	5	4	4	3
Unpruned Albizia + coffee + beans	3	3	3	7	4
Coffee only but under pruned Cordia	5	8	5	11	5
Coffee only but under unpruned Albizia	8	7	11	9	6
Beans + Unshaded coffee	7	10	10	8	6
Unpruned Cordia + coffee + beans	9	11	8	4	8
Coffee only but under unpruned Cordia	10	9	6	10	9
Unshaded coffee only	11	4	7	6	10
Beans in open field	6	6	9	3	11

**Ranking based on farmer's own capability (e.g resources/tools and skills to prune) and perceived need/desire to change from current practice.*

9.5.4 Attitudinal measurable variables on planting and management of shade trees

The attitudinal measurable variables were assessed based on perceived practice characteristics that represent Rogers' factors of adoption (Table 4). Despite the significant difference in opinion ($p<0.05$), the respondents generally agreed that shaded gardens had more general benefits than unshaded gardens (relative advantage) and that tree planting was compatible with existing farm practices at L5.35 and L5.04 respectively on a scale of 1-7 (Table 4). Unlike the neighbours and remote farmers (that were uncertain), those interacting with the project (both Phase 1 and 2 farmers) strongly agreed that a garden shaded with trees has more general benefits than an unshaded garden. This may be attributed to the additional benefits the project beneficiaries had observed in shaded systems while interacting with the T4FS project. All the farmer categories did not find tree planting complex and would not consider that the needed to plant shade trees on a small scale first before planting more extensively. Apart from the remote farmers, other farmer categories would not require previous observation of other farmers planted trees before doing the same (Table 4).

Table 4: Group-specific descriptive statistics ''mean (standard deviation)'' of attitudinal measurable variables on plating and management of scattered trees on-farm on a scale of 1–7 and Analysis of variance (ANOVA) between different variables and farmer categories (p value)

Statement	Phase 1[a]	Neighbours[a]	Phase 2[a]	Remote[a]	Total	*P* - value
Statements on scattered trees in coffee gardens						
A garden shaded with trees has more general benefits than an unshaded garden *(Relative advantage)*	6.46 (0.58)	4.13 (1.12)	6.24 (0.65)	4.49 (1.36)	5.35 (1.42)	0.000**
Planting trees in the garden is compatible with existing farm practices *(Compatibility)*	5.93 (0.80)	4.02 (1.18)	5.80 (0.74)	4.38 (1.34)	5.04 (1.34)	0.033*
Planting trees for shade is too much trouble for what it is worth *(complexity)*	3.16 (1.27)	2.36 (0.79)	3.10 (1.03)	2.48 (0.97)	2.78 (1.09)	0.060
I am likely to plant trees in my garden after seeing other farmers doing the same *(Observability)*	1.94 (1.10)	2.63 (1.89)	2.73 (0.86)	4.39 (1.52)	2.91 (1.65)	0.050*
I am likely to plant shade trees on a small scale first before planting more *(Trialability)*	2.53 (1.19)	4.50 (1.77)	2.67 (1.06)	4.36 (1.85)	3.50 (1.76)	0.033*
Comparing coffee growing under pruned and unpruned trees						
A garden with pruned trees has more general benefits than one with unpruned trees *(Relative advantage)*	6.07 (0.66)	4.53 (1.13)	5.99 (0.90)	4.81 (1.39)	5.36 (1.25)	0.001**
Pruning trees in coffee would not affect my other farming activities *(Compatibility)*	5.04 (1.36)	3.21 (1.40)	5.35 (1.16)	3.70 (168)	4.34 (1.66)	0.000**
Pruning trees in my coffee garden is too much trouble for what it is worth *(Complexity)*	1.82 (1.13)	5.92 (1.52)	3.96 (1.44)	5.95 (1.39)	4.41 (1.88)	0.000**
I am likely to prune trees in my garden after seeing other farmers doing the same *(Observability)*	3.16 (1.25)	3.06 (1.48)	3.17 (1.29)	5.81 (1.54)	3.55 (1.63)	0.240
I am likely to prune trees on a small scale first before pruning the rest in my garden *(Trialability)*	5.92 (0.89)	4.43 (1.34)	5.95 (0.69)	4.83 (1.10)	5.29 (1.23)	0.000**
I intend to prune trees existing in my coffee garden in the next 5 years *(Intension)*	6.02 (0.64)	5.91 (0.89)	5.95 (0.69)	4.44 (1.42)	5.29 (1.23)	0.000**

[a]*Phase 1= farmers actively participating in the T4FS project from phase 1 (2014); Neighbour= farmers neighbouring those actively participating in the T4FS project from phase 1; Phase 2= farmers actively participating in the T4FS project from phase 2 (2017) and; Remote= farmers living distant and unaware of the T4FS project. N=394; df = 3; *significant at 5% significance level; **significant at 1% significance level.*

In terms of tree canopy pruning, project beneficiaries strongly disagreed that pruning trees was too much trouble for what it is worth, while their neighbours and remote farmers strongly agreed (Table 4). The project beneficiaries did not regard pruning as a complex undertaking probably because they had been trained by the T4FS project on how to prune shade trees in coffee gardens. Unlike other farmer categories, the remote farmers strongly agreed that they needed to first see others prune before doing the same (Table 4). This could imply that the extension activities could not change the perceptions of remote farmers and would want to first observe others pruning trees before they undertook pruning on their farms, an indication that tree pruning is regarded a difficult and risky task to do, as many farmers fear damaging their coffee during pruning. However, all farmer categories exhibited a high intention to prune trees existing in their coffee gardens within the next 5 years.

While the information given during the extension events would encourage majority of the farmers to plant and prune shade trees, a few farmers (23 farmers) would not be encouraged by the information, the majority of whom were non-project beneficiaries (Figure 2). The dissenting farmers reported that their focus was common beans which yield more in open fields while others had too many farm activities to allow time for pruning.

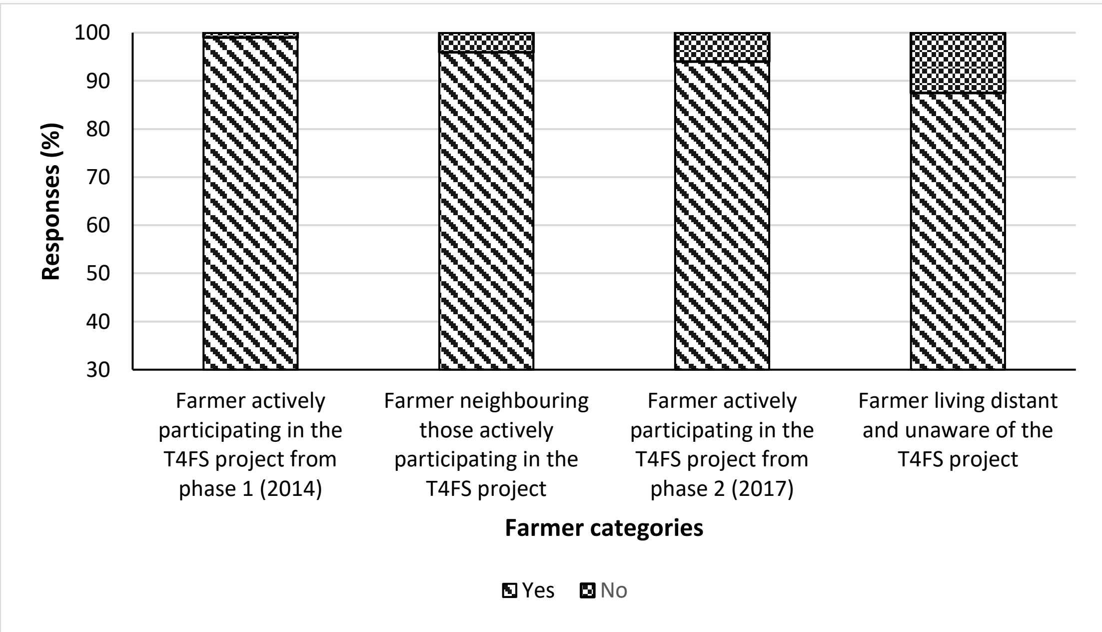


Figure 2: Whether the information given would encourage farmers to plant and prune shade trees

9.6 Discussion

The discussion highlights the history of agricultural extension in Uganda from the colonial government to the present single spine extension system. The section also provides an assessment of farmer perceptions of shaded coffee and management of shade trees following the extension events, the adoption process of smallholder farmers and the impact of development projects on agricultural technology adoption. We finally present the key drivers of agricultural technology adoption among smallholder farmers in the context of developing countries.

9.6.1 Uganda's agricultural extension system

Agricultural extension in Uganda has been changing since its introduction by the colonial government in the late 1800s, with a number of approaches applying regulatory, advisory and educational methods (Hakiza et al., 2004; Mangheni et al., 2003). Semana (1999) identified seven evolutionary phases in agricultural extension in Uganda as (1) Regulatory service: 1920-1956, (2) Advisory Education: 1964-1971, (3) Dormancy: 1972-1981, (4) Recovery: 1982-1999, (5) Educational: 1992-1996, (6) Participatory education: 1997-1998 and (7) Decentralized Education 1997-2001. Following the introduction of contractual extension services between 2001 – 2014 under the National Agricultural Advisory Services (NAADS), the government of Uganda introduced a single spine extension system in 2015 (MAAIF, 2015) in an attempt to further reform the country's agricultural extension system.

A decentralized extension system (1997 – 2001) transferred responsibilities and functions of planning and implementation of agricultural extension services from the mainstream Ministry of Agriculture, Animal Industry and Fisheries (MAAIF) to district local governments. MAAIF was left with the responsibility of planning and policy formulation, regulatory functions, technical backstopping, setting standards and monitoring performance of the agricultural sector, and managing funds of selected projects (Bashaasha et al., 2011). As a result of decentralization, provision of extension services was mainly a responsibility of the district-level government where districts would pay for most of the operational expenses while staff salaries would be paid by the central government (Anderson & Crowder, 2000). Public extension faces several challenges such as weak research and extension, bureaucracy, non-participatory approaches and lack of response to farmers' needs (Buyinza et al., 2015). It was anticipated that the introduction of NAADS would eliminate these bottlenecks through a contractual privatized system, where farmers would pay 50% funding of advisory services within the next 25 years. This would also enhance sustainability of farmer groups and emergence of new farmer organizations (Bekywaso, 2006). In this system the local governments would contract private firms, farmer associations or NGOs to provide extension services (Bashaasha et al., 2011).

Extension through the NAADS system

The NAADS Act of 2001 was designed based on five major components: 1) Advisory and information services to farmers, 2) Technology development and linkages with markets, 3) Quality assurance, 4) Private sector institutional development and 5) Programme management and monitoring (Nahdy, 2002). NAADS was created to empower farmers, especially women, to demand and control agricultural advisory services in the country (Emmanuel, 2012). The expectation of NAADS was that it would operate as a decentralized system that is farmer owned and managed where privately serviced extension would be paid for by farmer-managed public funds (Opondo et al., 2006). NAADS was also expected to enhance farmers' access to quality knowledge and improved technologies through demand-driven as opposed to supply-driven delivery systems. The NAADS approach was centred on use of public funds to support advisory services while exploiting opportunities for inflow of private sector resources and a shift from public to private sector delivery of advisory services. This would in turn empower subsistence farmers to access private extension services and bring control of advisory services and research nearer to the farmers.

In terms of coordination and implementation of extension services, NAADS were posted in each district to run farmer groups and coordinate extension services. NAADS was coordinated through a secretariat and coordinators who oversaw the recruitment and training of Community-Based Facilitators (CBFs) that provided quick follow-up advisory services according to farmers' needs (Benin et al., 2011). The approach was that farmers willing to participate in the program join farmer groups in which they request specific technologies that they intend to implement. Farmers thereafter receive grants within the groups through which they could implement a selected technology and also obtain advisory services. A Technology Development Site (TDS), which was initially financed by the grant, would then become a source of knowledge and skills development by the farmers in the sub county.

A major shortcoming of the NAADS extension system was the lack of integration of a robust research component at the TDS, which would inform improvements in the technologies being implemented. The TDS would also have been designed in such a way that they would provide a platform for knowledge exchange as opposed to knowledge transfer (Buyinza et al., 2020a,b). Several studies have been conducted over NAADS implementation and mixed results of the program performance have been obtained. Benin et al (2011) observed improvement of extension services, farmer empowerment, better access to extension services, improved adoption of new technologies and advisory services in sub counties where NAADS had been implemented. However, they noted that weakness in financial and market sectors were major setbacks in achievement of NAADS objectives adding that NAADS had not fully addressed soil fertility management, livestock productivity and commercialization of agronomic products. A related study conducted in Soroti district in Uganda showed that farmers who were members of Farmer Field Schools and NAADS had higher use of improved soil conservation and pest management methods than non-members (Friis-Hansen et al., 2004). NAADS was also found to be top down, prescriptive, abstract, and required farmers to have high levels of literacy to make sense out of it, and the system also limited the number of enterprises (Obaa et al., 2005).

The Single Spine extension system in Uganda

In 2015, the government of Uganda introduced a pluralistic approach to extension service delivery anchored to the public extension system, referred to as the single spine extension system (MAAIF, 2015, 2016) in an attempt to reform the agricultural extension system. The reforms dubbed as *"Single Spine Extension System"* included transfer of the extension function from the National Agricultural Advisory Services (NAADS) to the mainstream Ministry of Agriculture, Animal Industry and Fisheries (MAAIF), and the creation of a Directorate of Agricultural Extension Services (DAES) in FY 2015/16. The system aims at harmonizing and coordinating all extension service delivery in the country to address the inefficiencies associated with its predecessor systems – the National Agriculture Advisory Services (NAADS) together with the single unified public agricultural extension system. One of the key tenets of the single spine system is to coordinate extension service delivery countrywide both in public and private sectors.

The single spine extension system recognizes the role played by extension managers in ensuring a successful extension system. In this regard, MAAIF developed measurable indicators to evaluate the performance of extension managers based on their roles and responsibilities (Namyenya et al., 2021). However, the new reform of the Single Spine extension service system continues to follow a top-down linear focus on extension that only encourages knowledge transfer.

In Uganda, agroforestry extension has remained a duty of both of foresters and agriculturalists with no clear mandate of which ministry is responsible for agroforestry extension. While forestry falls under the Ministry of Water and Environment, agriculture is under the MAAIF. This has created a debate on which ministry should directly be responsible for agroforestry. NGOs have also played a key role in agroforestry extension in Uganda, mainly targeting smallholder farmers. The main extension approaches used include demonstrations, exchange visits and farmer field school. Efforts have been made to extend agroforestry to a wide range of stakeholders by several agencies such as NARO, which created Zonal Agricultural Research and Development Institutes (ZARDIs), with scientists and technicians responsible for agroforestry. In terms of agroforestry extension financing, apart from government support with free tree seedlings through the Ministry of Water and Environment, limited financial support has been received from the Medium Term Expenditure Framework (MTEF) under the MAAIF.

9.6.2 Farmer perceptions of shaded coffee and management of shade trees following extension activities

This study argues that bridging local and scientific knowledge is fundamental in enhancing agricultural technology adoption among smallholder farmers. Participatory research and extension allows integration of local and scientific knowledge while facilitating dialogue between farmers and agricultural scientists (Bicalho & Peixoto, 2017). In this study, the extension events allowed dialogue between farmers and the researcher on knowledge generated from the biophysical component of the study. Feedback from farmers (in form of perceptions towards the research outputs and willingness to adopt the recommended practices) was later obtained through the farmer survey that followed the extension activities. In the current study, while 83 out of 100 participants belong to phase 1 project beneficiaries understood that pruning can increase coffee and common beans yield (see Table 1), only 56 farmers were fully convinced that higher coffee yields can be obtained from shaded coffee (see Table 2). This is an indication that as much as farmers may understand the message being delivered to them, it may not be convincing enough to adopt new practices by simply word of mouth, but also through other avenues such on-farm demonstrations and social networks. Indeed, several studies have demonstrated that a combination of resource constraints and socio-economic factors (Cedamon et al., 2018; Nahayo et al., 2016; Nyaga et al., 2015) as well as cognitive and psychological factors can influence agricultural technology adoption among smallholder farmers (Buyinza. et al., 2020b; Martínez-García et al., 2013).

Besides the above individual factors, information exchange and peer influences through social networks and general community interactions also provide an important angle from which to understand technology innovation adoption (Bridger & Alter, 2006; Freeman & Qin, 2020). These complex interactions processes are usually important at the early stages of technology adoption (Larsen, 2011) and would enable introduction of socially and biophysically appropriate agroforestry interventions into local realities. Therefore, in addition to the participatory approaches used by this study, knowledge exchange through an interactional approach involving people, technologies and institutions can be a useful approach for enhancing practice adoption in a community.

9.6.3 Understanding the adoption process among smallholder farmers

A better understanding of adoption among smallholder farmers calls for a systematic classification of the adoption process beyond the common binary classification (*i.e.*, adoption and non-adoption). This is because technology/practice adoption is usually proceeded by a period of 'trying' and some degree of adaptation (Mwangi & Kariuki, 2015). Agroforestry adoption is a dynamic process involving farmer experimentation that occurs over a long time period with almost no immediate benefits (Kiptot et al., 2007). The Process of Agricultural Utilisation Framework (PAUF) proposed by Brown et al., (2017) goes beyond the binary classification of adoption to sub - typologies that identify different stages of a technology adoption process in a community. PAUF was initially developed to understand adoption of conservation farming technologies in eastern and southern Africa. In the current study, we apply the PAUF to understand scattered tree planting and management adoption processes and awareness of the impact of agroforestry tree management on tree water use, and yield of coffee and common bean among the four smallholder farmer categories (Table 5).

The farmer categories under the current study generally fit into the PAUF, which frames the adoption process in four phases from exposure to non-trial assessment, trial assessment and utilisation. The four phases are further divided into 10 distinct stages of the adoption process (Brown et al., 2017). While a farmer may not systematically move from stage 1 to 10, aligning the four farmer categories to the PAUF would facilitate a better understanding of the, agroforestry tree planting and management adoption pathways among smallholder farmers.

Table 5: An application of the PAUF to understand scattered tree planting and management adoption process and awareness of the impact of agroforestry tree management on tree water use, and yield of coffee and common bean among the four smallholder farmer categories

Farmer category	**PAUF Adoption phase (1-4) and classification**	**Characteristics of farmer category in relation to PAUF and corresponding PAUF stage (1-10)**
Farmer living distant and unaware of T4FS project	Phase 1 (Exposure)	These farmers have just gone through the process of sensitisation (during extension events) to obtain awareness and familiarity of canopy tree pruning and its impact of tree water use and crop productivity. These farmers would be classified as unaware prior to the extension (stage 1), they are currently aware of the practice but may be unsure of its attributes. PAUF classifies these as 'unfamiliar' at stage 2 of the adoption process.
Farmer neighbouring those actively participating in T4FS project	Phase 2 (Non-trial assessment)	These farmers have no personal experience with the practice as they have only been observing project beneficiaries. The practice could be relevant to some of them, classified as 'interested' (stage 4) and may progress to higher stages when they get involved. Those that are 'not interested' fall in the stage 3 of the adoption process.
Farmer actively participating in T4FS project from phase 2 (2017)	Phase 3 (Trial assessment)	These farmers are recent project beneficiaries undertaking trials in a confined area on their farms, entirely depending on project resources (stage 5). It is still too early for farmer driven adoption (stage 6).
Farmer actively participating in T4FS project from phase 1 (2014)	Phase 4 (Utilisation)	These farmers have been interacting with the project for a long period of time to allow adequate evaluation and implementation of the practice. The dissenting farmers are classified 'disadopters' (stage 7). While some farmers use private resources to undertake the practice (stage 8-10), majority still rely on project support (stage 5).

9.6.4 Impact of development projects on agricultural technology adoption

Applying the PAUF criteria to the current study shows that the farmers actively participating in T4FS project from phase 1 (2014) are in their final stages of the adoption process (Table 5). The feedback following the extension activities also showed a better understanding of the biophysical research outputs (Table 1) and willingness to plant and prune shade trees in their coffee plantations by this farmer category. However, the majority of farmers were still relying on project support (such as free seedlings) at the time of the extension activities. In the African context, agroforestry is strongly promoted via development projects which provide incentives to farmers (Brown et al., 2017) in form of free planting materials, tree nursery inputs and capacity building on planting and management of agroforestry components (Dedefo et al., 2017; Odoi et al., 2019). This is likely to lead to 'pseudo-adoption', where the adoption claimed during implementation of a development project is not a sustained change in practice but due to the temporary influence of the existing project (Brown et al., 2017; Kiptot et al., 2007; Llewellyn & Brown, 2020).

In the current study, there is no guarantee that there will be long-term and farmer-driven adoption of shade tree planting and deliberate tree canopy pruning beyond the Trees for Food Security Project without the short-term incentives to farmers. There is also a likelihood that appears as adoption is in fact trialling of the new practice, rendering it "pseudo adoption" (Woltering et al., 2019) and may mask whether actual long-term adoption is occurring (Llewellyn & Brown, 2020). Furthermore, the farmers could be using the practice as a strategy to access incentives from the project and may discontinue once these benefits are no longer available.

9.6.5 Drivers of agricultural technology adoption among Africa's smallholder farmers

Potential adopters recognizing the relative advantage of the new practice over existing ones. Relative advantage is the degree to which an innovation is perceived as being better than any technology it can replace (Rogers, 2003) and been reported to be one of the most important motivations for adoption (Reimer et al., 2012). In the current study, the PAUF criteria classifies the farmers living distant and unaware of T4FS project as unfamiliar at the exposure phase of the adoption process (Table 5). Such potential adopters often have a greater need for education about the relative advantage of the new practice over the existing practices. For example, explaining that tree canopy pruning would prolong the period of intercropping would trigger mind-set change towards pruning. This is something they had not given much thought to because they have been focussing on higher yields (in short term) and less on sustained yields (over a long period of time). Highlighting the relative advantage of the practice over other existing practices (Lai, 2017; Rogers, 2003) is fundamental in motivating on-farm practice change among smallholder famers (Kuehne et al., 2017; Reimer et al., 2012).

Relative advantage is also a key component of the ADOPT framework for predicting adoption (Kuehne et al., 2017; Llewellyn & Brown, 2020), where a very high mean level of relative advantage is required for a heterogeneous community to become adopters. The current study also assessed relative advantage as one of the attitudinal measurable variables on planting and management of scattered trees on-farm on a scale of 1-7, where a high mean was registered among farmers that were directly interacting with the T4FS project (Table 4). Unlike the neighbours of project beneficiaries and those living far from the project area, farmers interacting with the T4FS project are likely to become adopters, as they perceive a coffee garden shaded with trees (which are regularly pruned) to have more general benefits than unshaded coffee. Farmers are likely to vary in their perception of a given practice's relative advantage due to their unique set of interests influenced by economic, social and cultural (norms, beliefs) context within which the innovation will be applied (Pannell et al., 2006).

Existing community social networks

Farmers often obtain information about new agricultural innovations from extension agents through conventional knowledge transfer extension approaches. However, several studies have established that using social networks during extension can enhance technology adoption (Beaman et al., 2015; BenYishay & Mobarak, 2019; Young, 2009). A related study involving the same farmer categories applied a multi-group structural equation modeling technique to identify differences in farmer motivations to adopting agroforestry practices in the Mt. Elgon region (Buyinza. et al., 2020a). The study found that about 40% of the variation in farmer motivation to integrate trees in their coffee plantations was explained by attitude and perceived behavioural control among farmers actively participating in the T4FS project from phase 1. In the same study, farmer motivation resulting from social pressure was strongest among farmers who had never interacted with the project, who in the absence of project interventions, relied on existing social structures to drive change in their communities.

Other related studies have also demonstrated that farmers are more likely to adopt new practices when most of their neighbours have done so, when they follow the opinion of 'important others' who support practice adoption, and when they are willing to gain social status in their communities (Buyinza et al., 2020b; Dessart et al., 2019). Therefore, adoption behaviour of smallholder farmers is mainly shaped by existing community social norms and beliefs that tend to promote knowledge exchange, as opposed to the conventional knowledge transfer extension approaches. Norms are therefore an inherent part of social systems and can create distinct farming practices, habits and standards within a social group. Researchers and extension agents can act upon the positive attitudes, norms and perceived behavioural controls to guarantee adoption and sustainability of agricultural technologies. Such behavioural factors can enrich economic analyses of farmer decision-making, and inform more realistic and effective smallholder agricultural technology extension policies.

Period and intensity of exposure to the technology

The biggest impacts on agricultural technology adoption and compliance have been reported to come through direct exposure of potential adopters to the new technology and information (Ghasemiesfeh et al., 2013; Young, 2009). This is consistent with a complex contagion model of learning and technology diffusion, where multiple sources of exposure to an innovation are required before an individual adopts the change of behaviour (Beaman et al., 2015; Ghasemiesfeh et al., 2013). In the current study, the farmers interacting with the project had multiple sources of exposure to agroforestry tree planting and the impact of canopy pruning on tree water use and crop productivity through on-farm participatory trials, capacity building trainings and multiple farm visits to the biophysical experiments hosted by fellow farmers. This was not the case with their neighbours and the farmers living far from the project sites. Multiple exposure for a longer period of time (since 2014) further explains the higher mean levels of attitudinal measurable variables on agroforestry tree planting and management compared with other farmer categories (Table 4). However, there have been reported cases where a practice has been widely communicated, yet substantial levels of non-exposure and non-awareness still exist within a population (Brown et al., 2017). This may be attributed to limitations of the extension method being used in the community and limited co-learning among farmers from different cultural backgrounds and locations.

While there could be spill-over social learning by neighbours of project beneficiaries, the responses obtained farmers living far from the project sites were based on the one-day long extension sessions because they had no prior exposure to the information. These farmers' prior beliefs are sufficiently strong (not to adopt shaded coffee and deliberate canopy pruning) that they typically require multiple observations to adjust their priors and induce adoption. With this minimum level of exposure, such farmers can only learn whether to adopt shaded coffee or not but not necessarily how best to plant and manage the trees.

9.7 Conclusion

Low agricultural technology adoption continues to hold large productivity, sustainability and resilience consequences for majority of farmers in developing countries. However, several cases have been reported in Africa where farmers have been hesitant to adopt well-researched innovations (Van Loon et al., 2020; Uguru et al., 2015; Kiptot et al., 2007). This study drew upon knowledge generated from a biophysical experiment to assess changes in farmers' perceptions after exposure to information on agroforestry tree planting and management in coffee-bean systems in the Mt. Elgon region of Uganda. While farmers may understand the information delivered through different knowledge transfer approaches, they may not actually be convinced enough to adopt new practices as other factors may come into play. Although a combination of resource constraints, socio-economic and psychological barriers can be minimized by bridging local and scientific knowledge, a better understanding of the adoption process calls for a systematic classification of the adoption beyond the common binary classification. We applied the Process of Agricultural Utilisation Framework (PAUF) proposed by Brown et al., (2017) to understand scattered tree planting and management adoption process and awareness of the impact of agroforestry tree management on tree water use, and yield of coffee and common bean among the four smallholder farmer categories.

In the African context, agroforestry is strongly promoted via development projects that provide incentives to farmers in form of free planting materials, tree nursery inputs and capacity building on planting and management of agroforestry components. In the current study, there is a likelihood that what appears as adoption is in fact trialling of the new practice, which masks actual long-term adoption. The project beneficiaries could be using the practice as a strategy to access incentives from the project and may discontinue once these benefits are no longer available. We therefore suggest that adoption information exchange and peer influences through social networks and general community interactions (e.g through farmer-to-farmer extension approaches) provide an important angle from which to understand technology innovation adoption. These complex interactions processes are usually important at the early stages of technology adoption and would facilitate introduction of socially and biophysically appropriate agroforestry interventions into local realities. The study has generally demonstrated that adoption is not merely related to the technology, socio economic and behavioural factors, and the research and extension methods applied, but also a result of complex interactions between people, technologies and institutions.

9.8 References

Acheampong, L. D., Nsiah Frimpong, B., Adu-Appiah, A., Asante, B. O., & Asante, M. D. (2017). Assessing the information seeking behaviour and utilization of rice farmers in the Ejisu-Juaben municipality of Ashanti Region of Ghana. *Agriculture & Food Security, 6*(1), 38. doi: 10.1186/s40066-017-0114-8

Aker, J. C. (2011). Dial "A" for agriculture: a review of information and communication technologies for agricultural extension in developing countries. *Agricultural economics, 42*(6), 631-647. doi: 10.1111/j.1574-0862.2011.00545.x

Anderson, J., & Crowder, V. (2000). The present and future of public sector extension in Africa: Contracting out or contracting in? *Public Administration and Development 373-384*

Bashaasha, B., Mangheni, M. N., & Nkonya, E. (2011). Decentralization and Rural Service Delivery in Uganda. *IFPRI Discussion Paper 01063*. Washington, DC: IFPRI.

Beaman, L., BenYishay, A., Magruder, J., & Mobarak, A. M. (2015). *Can Network Theory Based Targeting Increase Technology Adoption?* , (AEARCTR-0002017).

Benin, S., Nkonya, E., Okecho, G., Randriamamonjy, J., Kato, E., Lubade, G., & Kyotalimye, M. (2011). Returns to spending on agricultural extension: the case of the National Agricultural Advisory Services (NAADS) program of Uganda. *Agricultural economics, 42*(2), 249-267. doi: 10.1111/j.1574-0862.2010.00512.x

BenYishay, A., & Mobarak, A. M. (2019). Social Learning and Incentives for Experimentation and Communication. *The Review of economic studies, 86*(3), 976-1009. doi: 10.1093/restud/rdy039

Bicalho, A. M. S., & Peixoto, R. T. G. (2017). Farmer and scientific knowledge of soil quality: a social ecological soil systems approach. *BELGEO (Leuven), 4*(4). doi: 10.4000/belgeo.20069

Bridger, J. C., & Alter, T. R. (2006). Place, Community Development, and Social Capital. *Community Development, 37*(1), 5-18. doi: 10.1080/15575330609490151

Brown, B., Llewellyn, R., & Nuberg, I. (2018). Why do information gaps persist in African smallholder agriculture? Perspectives from farmers lacking exposure to conservation agriculture. *The Journal of Agricultural Education and Extension, 24*(2), 191-208. doi: 10.1080/1389224X.2018.1429283

Brown, B., Nuberg, I., & Llewellyn, R. (2017). Stepwise frameworks for understanding the utilisation of conservation agriculture in Africa. *Agricultural Systems, 153*, 11-22. doi: 10.1016/j.agsy.2017.01.012

Brown, B., Nuberg, I., & Llewellyn, R. (2018). Research capacity for local innovation: the case of conservation agriculture in Ethiopia, Malawi and Mozambique. *The Journal of Agricultural Education and Extension, 24*(3), 249-262. doi: 10.1080/1389224X.2018.1439758

Buyinza, J., Muthuri, C. W., Downey, A., Njoroge, J., Denton, M. D., & Nuberg, I. K. (2019). Contrasting water use patterns of two important agroforestry tree species in the Mt Elgon region of Uganda. *Australian Forestry*, 1-9. doi: 10.1080/00049158.2018.1547944

Buyinza, J., Nuberg, I. K., Muthuri, C. W., & Denton, M. D. (2020a). Assessing smallholder farmers' motivation to adopt agroforestry using a multi-group structural equation modeling approach. *Agroforestry Systems, 94*(6), 2199-2211. doi: 10.1007/s10457-020-00541-2

Buyinza, J., Nuberg, I. K., Muthuri, C. W., & Denton, M. D. (2021). Farmers' Knowledge and Perceptions of Management and the Impact of Trees on-Farm in the Mt. Elgon Region of Uganda. *Small-scale Forestry*. doi: 10.1007/s11842-021-09488-3

Buyinza., J., Nuberg, I. K., Muthuri, C. W., & Denton, M. D. (2020b). Psychological Factors Influencing Farmers' Intention to Adopt Agroforestry: A Structural Equation Modeling Approach. *Journal of Sustainable Forestry, 39*(8), 854-865. doi: 10.1080/10549811.2020.1738948

Byekwaso, F. (2006). Implementing reforms in Agricultural Advisory Services: Lessons from Uganda. In Nahdy, M.S., Obuo-Ogwal, A.A., Olupot, M. (eds.). Proceedings of the 2nd Networking Symposium on Innovations in Agricultural Advisory Services in Africa (pp. 47-51). Kampala, Uganda.

Cedamon, E., Nuberg, I., Pandit, B., & Shrestha, K. (2018). Adaptation factors and futures of agroforestry systems in Nepal. *An International Journal incorporating Agroforestry Forum, 92*(5), 1437-1453. doi: 10.1007/s10457-017-0090-9

Dedefo, K., Derero, A., Tesfaye, Y., & Muriuki, J. (2017). Tree nursery and seed procurement characteristics influence on seedling quality in Oromia, Ethiopia. *Forests, Trees and Livelihoods, 26*(2), 96-110. doi: 10.1080/14728028.2016.1221365

Dessart, F. J., Barreiro-Hurlé, J., & van Bavel, R. (2019). Behavioural factors affecting the adoption of sustainable farming practices: a policy-oriented review. *European Review of Agricultural Economics, 46*(3), 417-471. doi: 10.1093/erae/jbz019

Freeman, K., & Qin, H. (2020). The Role of Information and Interaction Processes in the Adoption of Agriculture Inputs in Uganda. *Agronomy, 10*(2), 202.

Friis-Hansen, E., Aben, C., & Kidoid, M. (2004). Smallholder agricultural technology development in Soroti district: Synergy between NAADS and farmer field schools. *Uganda Journal of Agricultural Sciences*, 250-256.

Galmiche-Tejeda, A. (2004). Who is interdisciplinary? Two views, two goals, professionals and farmers. *Interdisciplinary Science Reviews: Interdisciplinarity: lessons from the social sciences, 29*(1), 77-95. doi: 10.1179/030801804225012464

Ghasemiesfeh, G., Ebrahimi, R., & Gao, J. (2013). Complex contagion and the weakness of long ties in social networks: revisited *Electronic Commerce* (pp. 507-524): ACM.

Gibson, C., Stutchbury, T., Ikutegbe, V., & Michielin, N. (2018). Challenge-led interdisciplinary research in practice: Program design, early career research, and a dialogic approach to building unlikely collaborations. *Research Evaluation, 28*(1), 51-62. doi: 10.1093/reseval/rvy039

Glover, D., Sumberg, J., Ton, G., Andersson, J., & Badstue, L. (2019). Rethinking technological change in smallholder agriculture. *Outlook on Agriculture, 48*(3), 169-180. doi: 10.1177/0030727019864978

Hakiza, J., Odogola, W., Mugisha, J., Semana, A., Nalukwago, J., Okoth, J., & Ekwamu, A. (2004). Challenges and Prospects of disseminating technologies through farmer field schools: Lessons learnt based on experience from Uganda. *Journal of Agricultural Sciences*, 163-175.

Ilic, D., & Rowe, N. (2013). What is the evidence that poster presentations are effective in promoting knowledge transfer? A state of the art review. *Health Information & Libraries Journal, 30*(1), 4-12. doi: https://doi.org/10.1111/hir.12015

Kiptot, E., Hebinck, P., Franzel, S., & Richards, P. (2007). Adopters, testers or pseudo-adopters? Dynamics of the use of improved tree fallows by farmers in western Kenya. *Agricultural Systems, 94*(2), 509-519. doi: 10.1016/j.agsy.2007.01.002

Kiptot, E., Hebinck, P., Franzel, S., & Richards, P. (2007). Adopters, testers or pseudo-adopters? Dynamics of the use of improved tree fallows by farmers in western Kenya. *Agricultural Systems, 94*(2), 509-519. doi: 10.1016/j.agsy.2007.01.002

Kuehne, G., Llewellyn, R., Pannell, D. J., Wilkinson, R., Dolling, P., Ouzman, J., & Ewing, M. (2017). Predicting farmer uptake of new agricultural practices: A tool for research, extension and policy. *Agricultural Systems, 156*, 115-125. doi: https://doi.org/10.1016/j.agsy.2017.06.007

Lai, P. C. (2017). The literature review of technology adoption models and theories for the noelty technology. *JISTEM - Journal of Information Systems and Technology Management, 14*(1), 21-38. doi: 10.4301/S1807-17752017000100002

Larsen, G. D. (2011). Understanding the early stages of the innovation diffusion process: awareness, influence and communication networks. *Construction Management and Economics, 29*(10), 987-1002. doi: 10.1080/01446193.2011.619994

Llewellyn, R. S., & Brown, B. (2020). Predicting Adoption of Innovations by Farmers: What is Different in Smallholder Agriculture? *Applied economic perspectives and policy, 42*(1), 100-112. doi: 10.1002/aepp.13012

Lowe, P., & Phillipson, J. (2006). Reflexive Interdisciplinary Research: The Making of a Research Programme on the Rural Economy and Land Use. *Journal of Agricultural Economics, 57*(2), 165-184. doi: 10.1111/j.1477-9552.2006.00045.x

MAAIF, (2016) The National Agricultural Extension Policy. Entebbe, Uganda: Ministry of Agriculture, Animal Industry and Fisheries.

Mangheni, M. M., Mutimba, J., & Biryabaho, F.M. (2003). Responding to the Shift from Public to Private Contractual Agricultural Extension Service Delivery: Educational

Implication of Policy Reforms in Uganda. Proceedings of the AIAEE 19th Annual Conference. Raleigh, North Carolina, USA.

Martínez-García, C. G., Dorward, P., & Rehman, T. (2013). Factors influencing adoption of improved grassland management by small-scale dairy farmers in central Mexico and the implications for future research on smallholder adoption in developing countries. *Livestock Science, 152*(2-3), 228-238. doi: 10.1016/j.livsci.2012.10.007

Morse, W. C., Nielsen-Pincus, M., Force, J. E., & Wulfhorst, J. D. (2007). Bridges and Barriers to Developing and Conducting Interdisciplinary Graduate-Student Team Research. *Ecology and Society, 12*(2), 8. doi: 10.5751/ES-02082-120208

Mubofu, C., & Elia, E. (2017). Disseminating Agricultural Research Information: A case study of farmers in Mlolo, Lupalama and Wenda villages in Iringa district, Tanzania. *University of Dar es Salaam Library Journal*, *12*(2), 17.

Mwangi, M., & Kariuki, S. (2015). Factors Determining Adoption of New Agricultural Technology by Smallholder Farmers in Developing Countries. *Journal of economics and sustainable development, 6*, 208-216.

Nahayo, A., Pan, G., & Joseph, S. (2016). Factors influencing the adoption of soil conservation techniques in Northern Rwanda. *Journal of Plant Nutrition and Soil Science, 179*(3), 367-375. doi: 10.1002/jpln.201500403

Nahdy, S.M., (2002). Decentralisation of Services in Uganda: The Formation of National Agricultural Advisory Services (NAADS). Kampala: Kawanda Agricultural Research Institute.

Namirembe, S., Brook, R. M., & Ong, C. K. (2008). Manipulating phenology and water relations in Senna spectabilis in a water limited environment in Kenya. *Agroforestry Systems, 75*(3), 197. doi: 10.1007/s10457-008-9169-7

Namyenya, A., Zeller, M., Rwamigisa, P. B., & Birner, R (2021). Analysing the performance of agricultural extension managers: a case study from Uganda. *The Journal of Agricultural Education and Extension*, 1-27. doi: 10.1080/1389224X.2021.1932539

Nyaga, J., Barrios, E., Muthuri, C. W., Öborn, I., Matiru, V., & Sinclair, F. L. (2015). Evaluating factors influencing heterogeneity in agroforestry adoption and practices within smallholder farms in Rift Valley, Kenya. *Agriculture, Ecosystems and Environment*, *212*(C), 106-118. doi: 10.1016/j.agee.2015.06.013

Obaa, B., Mutimba, J., & Semana, A.R. (2005). Prioritizing Farmers' Extension Needs in a Publicly Funded Contract System of Extension: A Case Study of Mukono District, Uganda. *Agricultural Research & Extension Network (AgREN). Network Paper*, 147.

Odoi, J., Buyinza, J., & Okia, C. (2019). Tree Seed and Seedling Supply and Distribution System in Uganda. *Small-scale Forestry, 18*(3), 309-321. doi: 10.1007/s11842-019-09420-w

Opondo, C., German, L., Stroud, A., & Engorok, O. (2006). Lessons from Using Participatory Action Research to Enhance Farmer-Led Research and Extension in Southwestern Uganda. *Working Paper 3, 1-14*.

Owolade, E. O., & Arimi, K. (2012). Information-seeking behavior and utilization among snail farmers in Oyo State, Nigeria: Implications for sustainable animal production. *Journal of International Agricultural and Extension Education, 19*(3), 11. doi: 10.5191/jiaee.2012.19304

Pannell, D. J., Marshall, G. R., Barr, N., Curtis, A., Vanclay, F., & Wilkinson, R. (2006). Understanding and promoting adoption of conservation practices by rural landholders. *Understanding and promoting adoption of conservation practices by rural landholders, 46*(11), 1407-1424. doi: 10.1071/EA5037

Reimer, A. P., Weinkauf, D. K., & Prokopy, L. S. (2012). The Influence of Perceptions of Practice Characteristics: An Examination of Agricultural Best Management Practice Adoption in Two Indiana Watersheds. *Journal of Rural Studies, 28*(1), 118-128. doi: 10.1016/j.jrurstud.2011.09.005

Rogers, E. M. (2003). *Diffusion of innovations (5th ed.)* (5 ed.). New York: Free Press.

Semana, A. R. (1999). Agricultural Extension Services at Crossroads: Present dilemma and possible solutions for future in Uganda. Department of Agricultural Extension/Education. Makerere University.

Takahashi, K., Muraoka, R., & Otsuka, K. (2019). Technology adoption, impact, and extension in developing countries' agriculture: A review of the recent literature. *Agricultural economics, 51*(1), 31-45. doi: 10.1111/agec.12539

Uguru, C., Ajayi, S., & Ogbu, O. C. (2015). Strategies for Dealing with Low Adoption of Agricultural Innovations: A Case Study of Farmers in Udenu L.G.A. of Enugu State, Nigeria. *Journal of Education and Practice, 6*, 7-12.

Van Loon, J., Woltering, L., Krupnik, T. J., Baudron, F., Boa, M., & Govaerts, B. (2020). Scaling agricultural mechanization services in smallholder farming systems: Case studies from sub-Saharan Africa, South Asia, and Latin America. *Agricultural Systems, 180*, 102792. doi: https://doi.org/10.1016/j.agsy.2020.102792

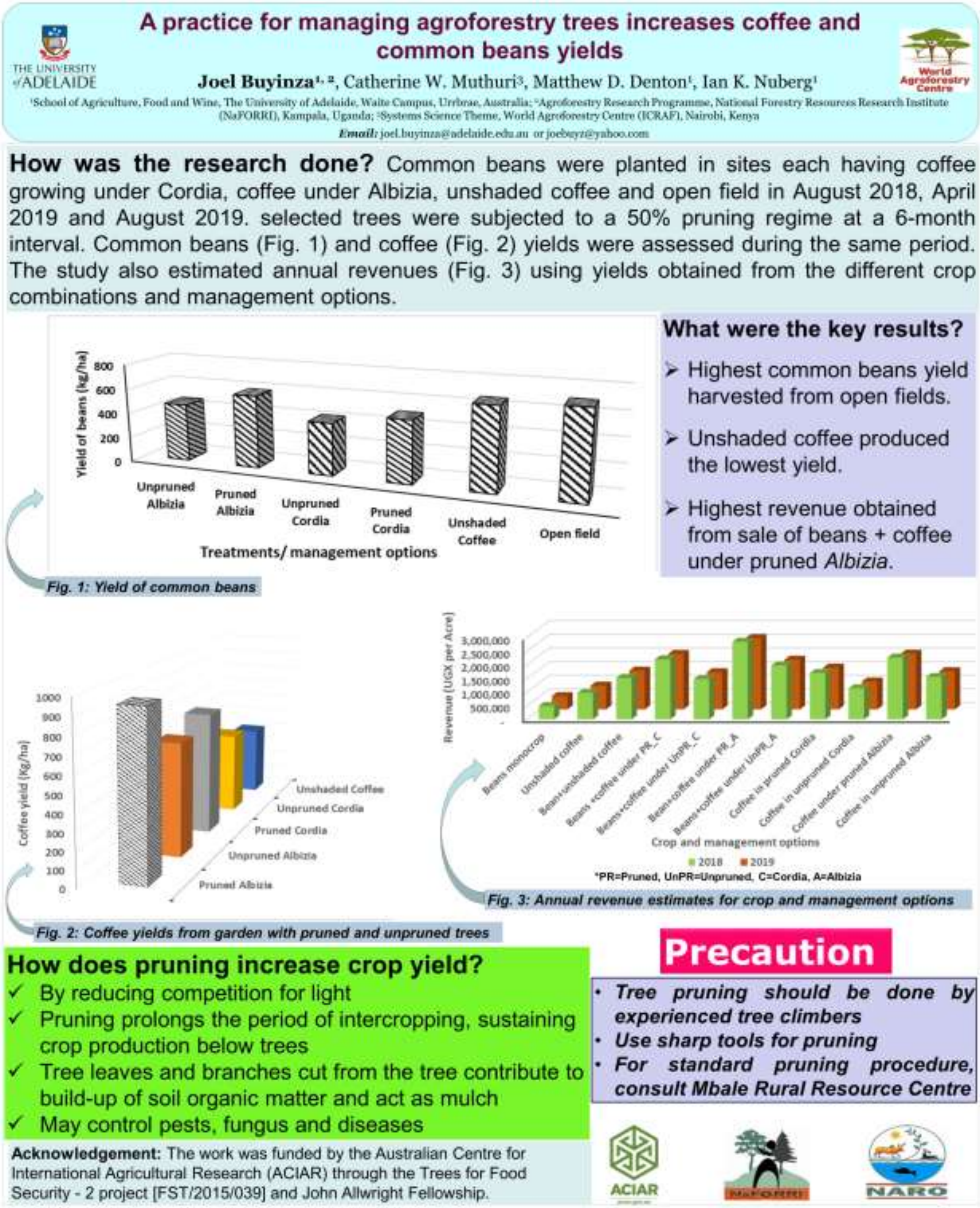
Woltering, L., Fehlenberg, K., Gerard, B., Ubels, J., & Cooley, L. (2019). Scaling – from "reaching many" to sustainable systems change at scale: A critical shift in mindset. *Agricultural Systems, 176*, 102652. doi: 10.1016/j.agsy.2019.102652

Young, H. P. (2009). Innovation diffusion in heterogeneous populations: contagion, social influence, and social learning. *The American economic review, 99*(5), 1899-1924. doi: 10.1257/aer.99.5.1899

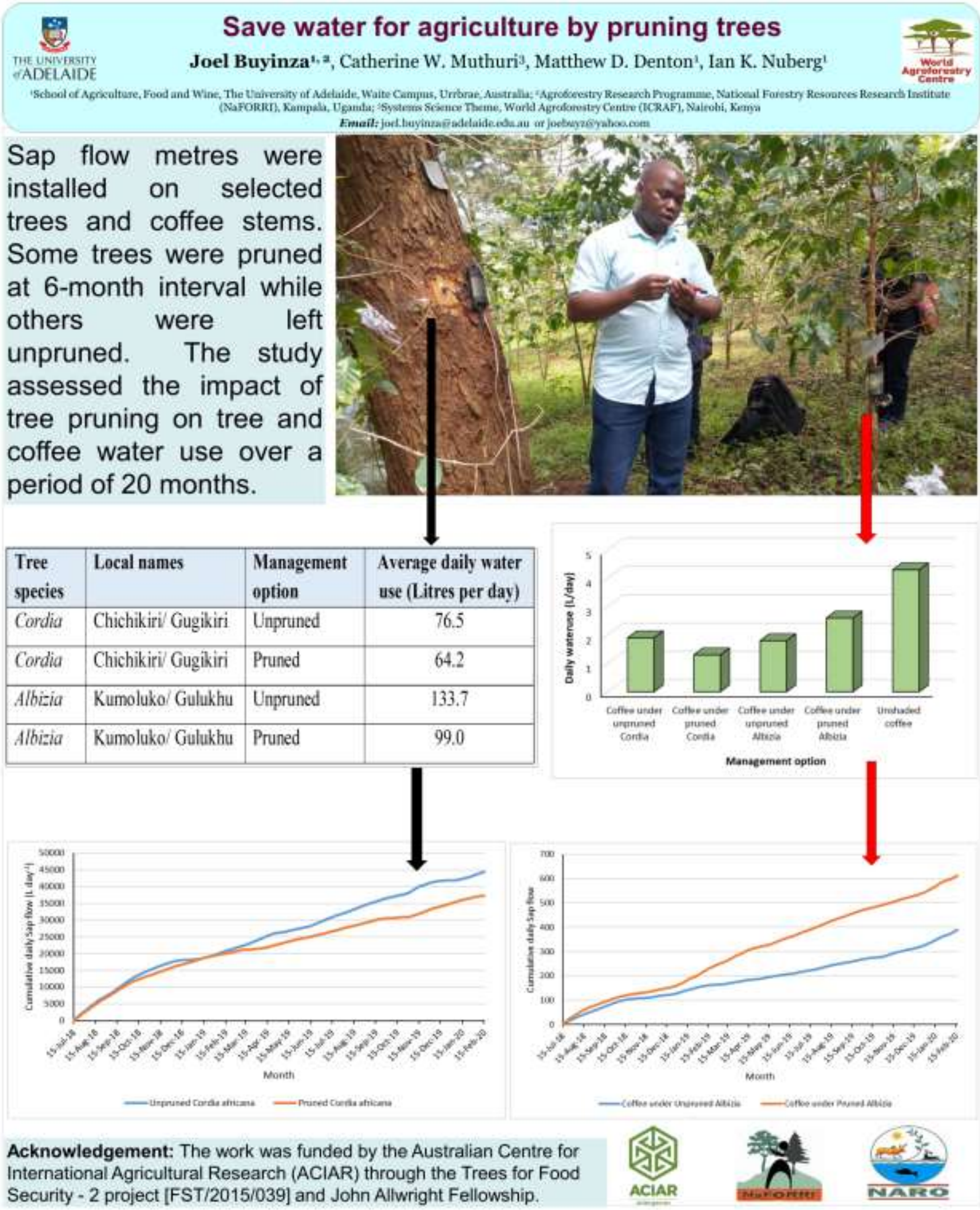
Supplementary Table 1: Analysis of variance on farmer opinion on crop combinations and tree management options

Variables on crop and tree management options		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Unpruned Cordia + coffee + beans	Between Groups	5.795	3	1.932	1.450	0.245
	Within Groups	45.284	34	1.332		
	Total	51.079	37			
Pruned Cordia + coffee + beans	Between Groups	78.405	3	26.135	19.332	0.000**
	Within Groups	454.239	336	1.352		
	Total	532.644	339			
Unpruned Albizia + coffee + beans	Between Groups	21.069	3	7.023	3.386	0.024*
	Within Groups	126.531	61	2.074		
	Total	147.600	64			
Pruned Albizia + coffee + beans	Between Groups	10.935	3	3.645	2.704	0.045*
	Within Groups	465.065	345	1.348		
	Total	476.000	348			
Coffee only but under unpruned Albizia	Between Groups	14.388	3	4.796	3.334	0.024*
	Within Groups	112.210	78	1.439		
	Total	126.598	81			
Coffee only but under pruned Albizia	Between Groups	5.092	3	1.697	1.132	0.336
	Within Groups	500.959	334	1.500		
	Total	506.050	337			
Coffee only but under unpruned Cordia	Between Groups	3.177	3	1.059	.953	0.422
	Within Groups	55.582	50	1.112		
	Total	58.759	53			
Coffee only but under pruned Cordia	Between Groups	4.711	3	1.570	1.252	0.291
	Within Groups	385.192	307	1.255		
	Total	389.904	310			
Unshaded coffee	Between Groups	4.771	3	1.590	.711	0.555
	Within Groups	53.657	24	2.236		
	Total	58.429	27			
Beans in open field	Between Groups	41.668	3	13.889	7.356	0.000**
	Within Groups	417.292	221	1.888		
	Total	458.960	224			
Beans + Unshaded coffee	Between Groups	9.447	3	3.149	1.487	0.221
	Within Groups	281.692	133	2.118		
	Total	291.139	136			

**significant at 5% significance level; **significant at 1% significance level*



Supplementary Figure 1: (1) A poster on impact of pruning on productivity of coffee and common beans (English version)



Supplementary Figure 2: A poster on impact of pruning on tree and coffee water use in smallholder farming systems (English version)

Chapter 10: General discussion, conclusion and policy implications

10.1 Introduction

Agroforestry has been practiced traditionally in the Mt. Elgon region since time immemorial. However, many farmers are motivated to dismantle agroforestry systems in favour of monocultural farming systems. The science needed to improve agroforestry in the Mt Elgon region should focus on tree-crop water interactions because the competition for light and water is one of the main reasons that farmers remove trees in favour of annual crops. Additionally, long-term adoption of agroforestry has been negatively affected by an underlying culture of financial expectancy and highly subsidized extension by research and development programmes, leading to 'pseudo adoption'. I contend that modernised agroforestry practices, informed by science generated in a participatory manner, have the promise of improving household food security, livelihoods and resilience.

This study was aligned to a pragmatic interdisciplinary research approach to embrace the domains of both biophysical science (tree-water use and crop productivity studies) and social science (farmer motivations and perceptions). Farmers' knowledge on agroforestry was integrated with a range of data from biophysical experiments involving trees and crops to understand how farmers generally respond to agricultural research. The four central research questions for this research were: (i) what influences the intentions of smallholder farmers in Mt. Elgon region to plant and retain trees on their farms?; (ii) what factors influence farmers' perceptions of the impact of trees on common bean and coffee productivity?; (iii) what are the impacts of trees and their management on crop productivity and water use across a range of farm contexts?, and; (iv) what is the impact of biophysical information on farmers' perceptions about agroforestry tree management in coffee-bean systems? This study applied an interdisciplinary approach to research within the pragmatic paradigm to obtain the desired practical outcomes and recommendations.

10.2 Outcomes, discussion and conclusions

10.2.1 Agroforestry tree canopy pruning is an important on-farm management decision for controlling competition, increasing crop yields and prolonging the period of intercropping in intensive farming systems

Soil water is often the main resource limiting productivity in smallholder agroforestry systems because most farmers select tree-crop combinations without consideration of avoidance of competition (Namirembe et al., 2008). The aim of Chapter 4 was to assess the impact of tree pruning on water relations in tree-coffee systems on smallholder farms in Eastern Uganda. In this study, tree canopy pruning altered the synchrony in the vegetative phenology of Albizia trees, as leaf cover changes occurred earlier in pruned trees than in unpruned trees following pruning. Pruned Cordia and Albizia trees respectively used 22.8% and 50.1% less water than unpruned trees whose average daily water use was 76.5L day^{-1} and 133.7L day^{-1}. Pruning is therefore a practical measure to control competition for resources in an intensive farming system (Jackson et al., 2000) such as coffee agroforestry, as reported in this study. It increases light availability at crop level, and directly affect tree demand for water and nutrients (Bazié. et al., 2012; Bayala et al., 2004). In this study, canopy pruning reduced the water demand of the tree component and resulted in recharge in the crop-rooting zone. These findings demonstrate that agroforestry tree canopy pruning can regulate water use in smallholder agroforestry systems, the benefits of other tree products notwithstanding. Carefully phased tree canopy pruning can therefore provide an opportunity to reduce the volume of water transpired, and reduce competition for water in coexisting species. Tree pruning and the deciduous nature of Cordia and Albizia trees offer opportunities for regulating water competition in agroforestry systems. The knowledge generated can be used to match smallholder farming systems' water requirements with expected soil water availability, to manage competition for water.

Chapter 5 assessed the impact of tree management on coffee and common bean productivity in smallholder agroforestry systems in Mt Elgon of Uganda. In this study, the hypothesis was that tree canopy pruning would positively influence the relative growth performance and productivity of coffee (*Coffea arabica* L.) and common beans (*Phaseolus vulgaris* L.) growing under *Cordia africana* and *Albizia coriaria* trees. Yields of parchment coffee were highest under pruned Albizia (949 kg/ha), followed by coffee under unpruned Albizia (792kg/ha). Unshaded coffee produced the least yield at 402 kg/ha and 422 kg/ha in the Albizia and Cordia sites respectively. The highest common beans yields (708 and 688 kg/ha) were obtained from common beans planted in open field sites, followed by those grown under unshaded coffee sites. Beans that were planted under unpruned Cordia gave the least yield of 420 kg/ha. The low yields from coffee and common beans under unpruned trees may have resulted from belowground and above ground competition consistently outweighing the benefits of shade. Relatedly, canopy pruning of the shea nut tree (*Vitellaria paradoxa*) in West Africa was reported to reduce belowground competition through reduction of root density in the crop rooting zone, which consequently increased crop production (Bayala et al., 2004). Assessment of the different coffee and common beans yield components and their interactions provided practical information on management interventions that can potentially improve coffee and common beans yields.

10.2.2 Psychological factors are key drivers to the farmers' internal decision-making process in agroforestry technology adoption and can be context specific

The aim of Chapter 6, 7 and 8 was to assess the psychological factors influencing smallholder farmers' intentions to plant and manage trees on their farms, and their perception of the impact of trees and their management on productivity of common beans and coffee. While biophysical characteristics of the farm and farmers' socioeconomic factors have been used to explain technology adoption in Africa, agricultural technology adoption requires that we also understand the psychological factors that can encourage or discourage farmer adoption of technologies. This study demonstrated how the various components of TPB (attitude, subjective norm and perceived behavioural control) influence farmers' intentions to adopt shaded coffee. Our findings show that attitude had a larger influence than perceived behavioural control and subjective norm on farmers' intention to integrate trees in their coffee plantations (Chapter 6).

The TPB collectively explained about 40% of the variance in farmers' intensions to integrate trees in coffee plantations with attitude and perceived behavioural control being the statistically significant predictors (Chapter 7). However, the adoption behaviour of smallholder farmers that had never interacted with the Australian funded Trees for Food Security (T4FS) project was mainly shaped by existing community social norms and beliefs that tend to promote knowledge exchange, as opposed to the conventional knowledge transfer extension approaches. Social norms can influence farmer behaviours through the process of diffusion (Mankad, 2016), where an innovation is communicated through social channels within a social structure (Rogers, 2004). Rural people tend to rely more on indigenous knowledge when engaging in tree planting and less on formal knowledge (Meijer et al., 2015; Ofoegbu and Speranza, 2017). Conventionally, extension has assumed that innovations originate from science and are transferred to farmers who adopt them (Black 2000). However, extension theory and practice has seen a paradigm shift from knowledge transfer approaches to knowledge exchange approaches (Blackstock et al. 2010). The expression of social norms as drivers towards integration of trees in coffee systems among farmers who had never interacted with the project seems to demonstrate this theory.

Chapter 8 specifically evaluated farmers' knowledge and perceptions of management and impact of trees on-farm in the Mt. Elgon region of Uganda. Farmer perceptions and knowledge of the impact of trees on farm and their management varied across the farmer categories studied. This could have implications on agroforestry adoption and scaling up. Smallholder farmers evaluated integration of trees in coffee as more favourable compared with unshaded coffee. Shading has been reported to reduce the quantity of weeds in the plantation (Staver et al., 2001), which can lower management costs. A study in Ethiopia showed that coffee plants grown under shade trees produced larger, heavier and better quality coffee beans than unshaded coffee (Bote and Struik, 2011). This study also demonstrated the importance of context-specific design of research and development projects aiming for local impact.

10.2.3 Effective extension is a function of research visibility over a long period as opposed to the formal short-term interactions between farmers and extension agents

Chapter 9 drew upon knowledge generated from biophysical experiments on tree water use, shade tree planting and management in smallholder coffee-bean agroforestry systems to assess farmers' perceptions and willingness to adopt practices emanating from the study following exposure to the research outputs. This study conducted a series of extension events that were followed by farmer interviews involving 394 farmers who had participated in an initial household survey in 2018 (information in Chapter 6, 7 and 8), involving four farmer categories: 1] those actively participating in the Trees for Food Security (T4FS) project from phase 1 (2014); 2] farmers neighbouring those actively participating in the T4FS project from phase 1; 3] farmers actively participating in the T4FS project from phase 2 (2017) and; 4] farmers living distant and unaware of the T4FS project. The farmer categories under the current study generally fit into the PAUF, which frames the adoption process in four phases from exposure to non-trial assessment, trial assessment and utilisation (Brown et al., 2017). The results have shown that farmers may be hesitant to adopt agroforestry technologies due to an underlying culture of financial expectancy leading to 'pseudo adoption', underutilization of existing social networks during research and extension, an insufficient period of exposure to a technology, and limitations in measuring and predicting adoption.

In the African context, agroforestry is strongly promoted via development projects that provide incentives to farmers (Brown et al., 2017) in the form of free planting materials, tree nursery inputs and capacity building on planting and management of agroforestry components (Odoi et al., 2019; Dedefo et al., 2017). This is likely to lead to 'pseudo-adoption', where the adoption claimed during implementation of a development project is not a sustained change in practice but due to the temporary influence of the existing project (Kiptot et al., 2007; Brown et al., 2017; Llewellyn and Brown, 2020). The study has generally demonstrated that adoption is not merely related to the technology, socio economic and behavioural factors, and the research and extension methods applied, but also a result of complex interactions between people, technologies and institutions. Therefore, effective extension requires more visibility of the research itself and over a long period of time rather than the formal short-term interactions between farmers and extension agents. This is because more visibility of the research over a long period provides a platform for knowledge exchange among researchers, farmers and extension agents. The impacts resulting from successful adoption of biophysical information can be essential for informing policy decisions relating to agroforestry and household food security.

10.2.4 Interdisciplinary research in agriculture is central to addressing global food security challenges by bridging science and development in the long term

Intrinsic to the nature of smallholder agroforestry farming systems in the Mt. Elgon region are the underlying relationships that exist between their human (farmer perceptions, knowledge and attitudes) and agroecological components (coffee, trees and common beans). Thus, to fully understand how these intensive farming systems function, it becomes necessary to integrate both socioeconomic and biophysical aspects of these systems (Chapter 2). Although scientists have repeatedly called for greater integration between the social and biophysical domains (Robertson et al., 2004; Pickett et al., 2005; Farber et al., 2006), the majority tend to dwell in their own "comfort zone" and concentrate on different, disciplinary facets of the same issues. A promising approach to reach a better understanding of smallholder farming systems is to address the social and biophysical bottlenecks to their sustainability. These can be addressed by transforming farmers' knowledge, perceptions and attitudes using information obtained from biophysical studies that relate to the issues hindering sustainable production of smallholder farming systems (Chapter 9).

A significant barrier to addressing farmers' problems is that farmers think in interdisciplinary terms, while researchers are still ruled by disciplinary boundaries. I believe that interdisciplinary research in agriculture must increasingly become the standard rather than the exception because the approaches needed and the implications of agricultural research are by their very nature interdisciplinary. The current and future global complex agricultural sustainability challenges will require disciplinary experts with an interdisciplinary experience. However, while IDR should not be incentivized at the expense of good quality mono-disciplinary agricultural research, one can anticipate that IDR will contribute to better understanding of the complex problems of agriculture. I hope that these efforts will highlight the challenges and opportunities in the current state of affairs and convince scientists in different disciplines to work together in better and more broadly integrated research for sustainable agricultural development, especially in developing countries.

10.3 Highlights of research findings

- The two agroforestry tree species under study (*Cordia africana* and *Albizia coriaria*) show contrasting patterns of seasonal water use across leaf shedding stages characterized by episodes of reverse flow in *A. coriaria* (pruned and unpruned) and pruned Cordia at specific periods of the year.
- Pruning altered the synchrony in the vegetative phenology of Albizia trees, as leaf cover changes occurred earlier in pruned trees than in unpruned trees following pruning.
- Pruned Cordia and Albizia trees, respectively, used 22.8% and 50.1% less water than unpruned trees whose average daily water use was 76.5L day^{-1} and 133.7L day^{-1}.
- While unshaded coffee used more water (up to 4.3 litres of water per day) than shaded coffee, coffee growing under pruned trees used more water than coffee growing under unpruned trees.
- Yields of parchment coffee were highest under pruned Albizia (949 kg/ha), followed by coffee under unpruned Albizia (792kg/ha). Unshaded coffee produced the least yield at 402 kg/ha and 422 kg/ha in the Albizia and Cordia sites respectively.
- The highest yields of common beans (708 and 688 kg/ha) were obtained from common beans planted in open field sites, followed by those grown under unshaded coffee sites. Beans that were planted under unpruned Cordia gave the least yield of 420 kg/ha. The low yields from coffee and common beans under unpruned trees may have resulted from belowground and above ground competition consistently outweighing the benefits of shade.
- The intention of farmers to integrate trees in coffee plantations was mainly driven by their evaluation of the benefits of shaded coffee (attitude) followed by perceptions about their own capability (perceived behavioural control). This renders attitude and

perceived behavioural control as reliable predictors of farmer tree planting behavior, especially in the context of developing countries.

- Following segregation of data into the four farmer categories, about 40% of the variation in farmer motivation to integrate trees in their coffee plantations was explained by ‘attitude’ and ‘perceived behavioural control’ among farmers actively participating in the Trees for Food Security (T4FS) project since 2014. However, the neighbours of participating farmers and farmers who had never interacted with the project were only motivated by ‘attitude’ and ‘social norms’ respectively. Farmer motivation resulting from social pressure was strongest among farmers who had never interacted with the project, and in the absence of project interventions, rely on existing social structures to drive change in their community.
- While 50% of farmers actively participating in the T4FS project from phase 1 indicated that they pruned their tree canopies, tree pruning was mainly driven by the need for fuelwood, rather than the need to reduce tree shade.
- Unlike other farmer categories, the majority of the farmers actively participating in the T4FS project from phase 1 did not perceive planting of trees for shade as being too much trouble for what it is worth (complexity), and that a garden shaded with trees has more general benefits than an unshaded garden (relative advantage). This shows the importance of context-specific design of research and development projects aiming for local impact.
- This study argues that bridging local and scientific knowledge through participatory research and extension is fundamental in enhancing agricultural technology adoption among smallholder farmers.

10.4 Policy implications

The government of Uganda is committed to transforming the agricultural extension system that enhances agricultural production and productivity, value addition, food security, household incomes and export. In 2015, the government of Uganda introduced a single spine extension system (MAAIF, 2015) in an attempt to reform the agricultural extension system. The reforms dubbed as *"Single Spine Extension System"* included transfer of the extension function from the National Agricultural Advisory Services (NAADS) to the mainstream Ministry of Agriculture, Animal Industry and Fisheries (MAAIF), and the creation of a Directorate of Agricultural Extension Services (DAES) in FY 2015/16. However, the new reform of the Single Spine extension service system continues to follow a top-down linear focus on extension, that encourages knowledge transfer. First, this study found that the adoption behaviour of smallholder farmers is mainly shaped by existing community social norms and beliefs that tend to promote knowledge exchange, as opposed to the conventional knowledge transfer extension approaches. Norms are therefore an inherent part of social systems and can create distinct farming practices, habits and standards within a social group. Therefore, government extension systems should make use of the existing social systems and provide an environment that facilitates knowledge exchange.

Secondly, this study argues that bridging local and scientific knowledge through participatory research and extension is fundamental in enhancing agricultural technology adoption among smallholder farmers. Therefore, for effective extension to happen, there must be a lot more visibility of the research itself and over a long period of time rather than the formal short-term interactions between farmers and extension agents. This calls for policy options that facilitate close collaboration among researcher and development agencies, farmers and the extension agents during research and extension engagements.

A significant barrier to addressing farmers' problems is that farmers think in interdisciplinary terms, while researchers are still ruled by disciplinary boundaries. I believe that interdisciplinary research in agriculture must increasingly become the standard rather than the exception because the approaches needed, and the implications of agricultural research are by their very nature interdisciplinary. The current and future global complex agricultural sustainability challenges will require disciplinary experts with an interdisciplinary experience. This will require reforms in the existing education policies and curriculum systems to encourage interdisciplinarity in the education curricula.

10.5 Limitations and future research

10.5.1 Limitations

The final phase of the socioeconomic component of this study was affected by COVID 19 travel and meeting restrictions. The extension events conducted (Chapter 9) to assess farmers' perceptions and willingness to adopt practices emanating from the study following exposure to the research outputs, were delayed by 6 months due to lockdown. The events were adjusted to allow several extension events comprising of fewer participants, while following the Ministry of Health COVID 19 standard operating procedures.

The soil moisture assessment aspects of the biophysical component of the study were conducted 11 months into the experiment due to late acquisition of the instruments (MPKit) from Australia. This delayed rapid sampling of Volumetric Soil Water Content (VSW%). I therefore have soil moisture data covering only the last 9 months of the experiment. The study would also have desired to have more Sapflow Meters for a more robust experimental set up and design but this was not possible due to limited funds.

10.5.2 Future research

The socioeconomic component of this thesis used the Theory of Planned Behavior (TPB) to assess the smallholder farmers' motivation to adopt agroforestry. While this study focused on three psychological constructs – Attitude, Subjective Norms and Perceived Behavioural Control – to understand smallholder farmers' intention toward integration of trees in coffee, other non-psychosocial factors that may influence farmers' behavior were not captured. To this end, future application of the TPB framework should include additional factors such as the role of institutions and environmental concern by farmers. Similarly, future applications of the TPB and multi-group Structural Equation Modeling (SEM) should include additional constructs such as environmental concern by farmers and incentives to farmers for having shaded coffee. This would provide a more comprehensive analysis of the motivations of smallholder farmers to adopt agroforestry practices.

For the biophysical component of this study, further studies are required to analyse the impact of shoot pruning on root behaviour and growth and accompanying isotope studies in these and other agroforestry tree species, to gain a holistic understanding of these processes. In addition, studies quantifying additional benefits resulting from canopy pruning, especially in provision of fuelwood as an important tree product in this region, the mulch and soil nutrient enrichment components are recommended.

Secondly, this study component has demonstrated that deliberately phased agroforestry tree canopy pruning is an important management decision that can potentially reduce competition for growth resources and prolong the period of intercropping in smallholder farming systems. However, it is likely that more tangible benefits of agroforestry tree canopy pruning will be accrued in the long-term, beyond the 20-months of this study. I therefore recommend studies longer than the current study period.

10.6 References

Bayala J, Teklehaimanot Z and Ouedraogo SJ. (2004) Fine root distribution of pruned trees and associated crops in a parkland system in Burkina Faso. *Agroforestry Systems* 60(1): 13-26.

Bazié. H, Bayala J, Zombré G, et al. (2012) Separating competition-related factors limiting crop performance in an agroforestry parkland system in Burkina Faso. *Agroforestry Systems* 84(3): 377-388.

Bote and Struik PC. (2011) Effects of shade on growth, production and quality of coffee (Coffea arabica) in Ethiopia. *Journal of Horticulture and Forestry* 3(11): 336-341.

Brown B, Nuberg I and Llewellyn R. (2017) Stepwise frameworks for understanding the utilisation of conservation agriculture in Africa. *Agricultural Systems* 153: 11-22.

Dedefo K, Derero A, Tesfaye Y, et al. (2017) Tree nursery and seed procurement characteristics influence on seedling quality in Oromia, Ethiopia. *Forests, Trees and Livelihoods* 26(2): 96-110.

Farber S, Costanza R, Childers DL, et al. (2006) Linking Ecology and Economics for Ecosystem Management. *BioScience* 56(2): 121-133.

Jackson NA, Wallace JS and Ong CK. (2000) Tree pruning as a means of controlling water use in an agroforestry system in Kenya. *Forest Ecology and Management* 126(2): 133-148.

Kiptot E, Hebinck P, Franzel S, et al. (2007) Adopters, testers or pseudo-adopters? Dynamics of the use of improved tree fallows by farmers in western Kenya. *Agricultural Systems* 94(2): 509-519.

Llewellyn RS and Brown B. (2020) Predicting Adoption of Innovations by Farmers: What is Different in Smallholder Agriculture? *Applied economic perspectives and policy* 42(1): 100-112.

MAAIF (2015) Framework Implementation Plan For The Agricultural Extension Services. Agricultural Sector Development Plan, 2015/16 – 2019/20. Submitted on June 8, 2015 by the Extension Thematic Team.

Mankad A. (2016) Psychological influences on biosecurity control and farmer decision-making. A review. *Agronomy for Sustainable Development* 36(2): 40.

Meijer SS, Catacutan D, Sileshi GW, et al. (2015) Tree planting by smallholder farmers in Malawi: Using the theory of planned behaviour to examine the relationship between attitudes and behaviour. *Journal of Environmental Psychology* 43: 1-12.

Namirembe S, Brook RM and Ong CK. (2008) Manipulating phenology and water relations in Senna spectabilis in a water limited environment in Kenya. *Agroforestry Systems* 75(3): 197.

Odoi J, Buyinza J and Okia C. (2019) Tree Seed and Seedling Supply and Distribution System in Uganda. *Small-scale Forestry* 18(3): 309-321.

Ofoegbu C and Speranza IC. (2017) Assessing rural peoples' intention to adopt sustainable forest use and management practices in South Africa. *Journal of Sustainable Forestry* 36(7): 729-746.

Pickett STA, Cadenasso ML and Grove JM. (2005) Biocomplexity in Coupled Natural–Human Systems: A Multidimensional Framework. *Ecosystems* 8(3): 225-232.

Robertson GP, Broome JC, Chornesky EA, et al. (2004) Rethinking the Vision for Environmental Research in US Agriculture. *BioScience* 54(1): 61-65.

Staver C, Guharay F, Monterroso D, et al. (2001) Designing pest-suppressive multistrata perennial crop systems: shade-grown coffee in Central America. *An International Journal incorporating Agroforestry Forum* 53(2): 151-170.

APPENDICES

Contrasting water use patterns of two agroforestry tree species in Mt. Elgon region of Uganda: Implication on management

THE UNIVERSITY of ADELAIDE

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Background: Biophysical success in agroforestry is primarily based on selecting tree-crop combinations that exploit spatial and temporal complementarities in resource use. Knowledge of daily tree water use can inform the water requirements of interacting components and best bet management options for farmers, such as pruning to reduce water and light competition.

Methods: 8 SFM1 Sap Flow Meters were installed on stems of four trees each of *Cordia africana* (dbh 38-45cm) & *Albizia coriaria* (dbh 48-63cm). Two *C. africana* (CT2 and CT3) and *A. coriaria* (AT1 and AT3) trees were pruned on 5th October 2018 by removing 50% of the branches. Leaf phenology was also monitored (Fig 1).

Fig. 1: The unsynchronized phenology of *C. africana*; Pictures taken on the same day show CT1 flushing, CT2 &CT3 are fully leafing while CT4 is close to shedding off all leaves

Fig. 2: *A. coriaria* in coffee

Results: The two species show contrasting patterns of seasonal water use characterized by episodes of reverse flows in *A. coriaria* (Fig. 3) in Jan-Feb when they shed their leaves Prior to pruning *C. africana* trees exhibited a uniform trend in daily flow (Fig. 4). However, the trend changed 2 months after pruning when the dry season began. While the unpruned *C. africana* (CT4 & CT1) showed a drastic decline in daily flow from Dec - Jan, pruned trees (CT2 & CT3) maintained a consistent daily flow as the dry period set in.

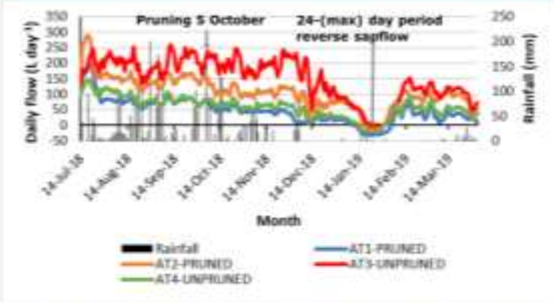

Fig. 3: Daily sap flow in pruned and unpruned *A. coriaria* trees over a 9-month period

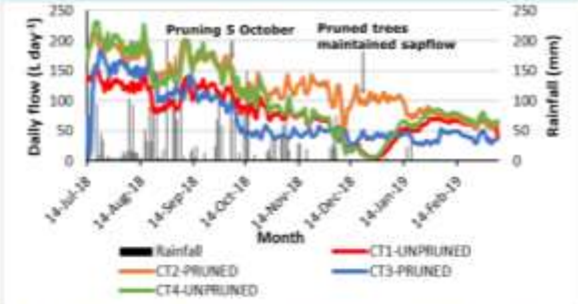

Fig. 4: Daily sap flow in pruned and unpruned *C. africana* trees over a 9-month period

Conclusion: Pruning influenced water use of *C.africiana* but not *A. coriaria*. Although pruning did not reduce the water demand of *C.africiana* trees (with the 50% pruning regime), it will prolong the period of intercropping because of less shade. Synchronised leaf shedding of *A. coriaria* in the dry period makes it more suitable for intercropping because of less water use and shade. Further studies will capitalize on the deciduous nature of these tree species, apply >50% pruning regimes and verify whether pruning results into any recharge in the crop-rooting zone and its potential to impact under canopy crop production.

Acknowledgement: The work was funded by the Australian Centre for International Agricultural Research (ACIAR) through the Trees for Food Security - 2 project [FST/2015/039] and John Allwright Fellowship.

Appendix I: Poster presented at the 4th World Congress on Agroforestry, Montpellier, France, May 2019

Appendix II: Human Research Ethics Committee Approval

THE UNIVERSITY *of* ADELAIDE

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OFFICE OF RESEARCH ETHICS, COMPLIANCE AND INTEGRITY
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06 March 2018

Dr Ian Nuberg
School of Agriculture, Food & Wine-RW

Dear Dr Nuberg

ETHICS APPROVAL No:	H-2018-041
PROJECT TITLE:	Farmers' motivation and biophysical impact of agroforestry using Cordia africana and Albizia coriaria on coffee-bean intercrops in the Mt Elgon region

The ethics application for the above project has been reviewed by the Executive, Human Research Ethics Committee and is deemed to meet the requirements of the *National Statement on Ethical Conduct in Human Research (2007)* involving no more than low risk for research participants.

You are authorised to commence your research on:	06/03/2018
The ethics expiry date for this project is:	31/03/2021

NAMED INVESTIGATORS:

Chief Investigator:	Dr Ian Nuberg
Student - Postgraduate Doctorate by Research (PhD):	Mr Joel Buyinza
Associate Investigator:	Dr Matthew Denton
Associate Investigator:	Professor Catherine Muthuri

CONDITIONS OF APPROVAL: Thank you for the response dated 1.3.18 to the matters raised and the amended application dated 5.3.18.

Ethics approval is granted for three years and is subject to satisfactory annual reporting. The form titled Annual Report on Project Status is to be used when reporting annual progress and project completion and can be downloaded at http://www.adelaide.edu.au/research-services/oreci/human/reporting/. Prior to expiry, ethics approval may be extended for a further period.

Participants in the study are to be given a copy of the information sheet and the signed consent form to retain. It is also a condition of approval that you immediately report anything which might warrant review of ethical approval including:

- serious or unexpected adverse effects on participants,
- previously unforeseen events which might affect continued ethical acceptability of the project,
- proposed changes to the protocol or project investigators; and
- the project is discontinued before the expected date of completion.

Yours sincerely,

Professor Paul Delfabbro
Convenor

Appendix III: Some field photos

One of the study sites with shaded coffee under Albizia coriaria trees

Joel Buyinza and his field assistants during sapflow meter (SFM1) installation on one of the *Albizia coriaria* tree

Sapflow meter being installed on Albizia (Left) and Sapflow meter on coffee (Right)