Abundance of pests and diseases in Arabica coffee production systems in Uganda - ecological mechanisms and spatial analysis in the face of climate change

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Referent: Prof. Dr. rer. nat. Hans-Michael Poehling
Korreferent: Prof. Dr. rer. hort. Christian Borgemeister
Korreferent: Prof. Dr. rer. hort. Edgar Maiss
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External supervisors / advisers
Dr. Jacques Avelino
Dr. Peter Läderach
Dr. Piet van Asten
Dr. Laurence Jassogne

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Abstract

Coffee production worldwide is threatened by a range of coffee pests and diseases (CPaD). Integrated management options require an understanding of the bioecology of CPaD and the prevalent interdependencies within the agroecological context. The comparison of different shading systems (e.g. shade-grown vs. sun-grown coffee) and the identification of trade-offs for ecosystem services is still a matter of ongoing debates. There is little quantitative knowledge of field-level investigation on shade effects and its ecological mechanisms across environmental and shading system gradients. Considering the increasingly evident effects of progressive climate change on CPaD, the need to examine the balance of shade effects under different environmental conditions becomes apparent. With the example of the coffee growing region of Mt Elgon, Uganda, this project aimed at addressing the complexity of shading effects on economically relevant CPaD using environmental and production system gradients. The approach was designed in an interdisciplinary manner, to involve the broader context of coffee agroforestry systems. The first two chapters of this thesis dealt with general aspects of coffee smallholder farming. The diversity of existing coffee production systems was characterized along an altitudinal gradient. A typology of production systems based on indicators related to the vegetation structure was generated and classified as coffee open canopy, coffee-banana inter-cropping, and densely shaded coffee systems. The typology served as the basis for comparison across the environmental and production system gradients. In the second chapter, farmers' knowledge on CPaD and the role of shade trees was contrasted with expert knowledge and field observations. Discrepancies regarding CPaD symptomatology, management and response to shade were revealed. Tackling institutional obstacles and disentangling shading effects are therefore a priority for the improvement of plant health management. The last two chapters focused more specifically on biophysical aspects of Coffee Leaf Rust (CLR, *Hemileia vastatrix*) and White Coffee Stem Borer (WCSB, *Monochamus leuconotus*). The effects of environment and production system on CLR abundance were spatio-temporally variable and either directly, interactive or indirectly mediated by microclimate. The development of white coffee stem borer was controlled by the bimodal rainfall, and by altitude and shade through their effect on minimum temperature. The findings emphasize the enormous importance of micro-environments for the ecology of CPaD, not least because of its implications in the context of climate change.

Key words: Coffee agroforestry system, interdisciplinary research, microclimate, climate change, *Hemileia vastatrix*, *Monochamus leuconotus*.

Zusammenfassung

Weltweit wird der Kaffeeanbau durch Kaffeeschädlinge- und Krankheiten (KKS) bedroht. Integrierte Pflanzenschutzmanahmen setzten ein umfassendes Verständnis der Bioökologie von KKS und vorherrschenden Wechselbeziehungen im agroökologischen Kontext voraus. Der Vergleich von Schattierungssystemen (z. B. Kaffeeanbau mit oder ohne Schattenbäume) bezüglich Kosten-Nutzen-Abwägungen für Ökosystemdienstleistungen wird noch immer diskutiert. Es gibt wenige quantitative, auf Feldstudien basierende Erkenntnisse über Schatteneffekte und deren ökologische Mechanismen entlang von Umweltgradienten und verschiedenen Schattierungssystemen. In Anbetracht der Auswirkungen des Klimawandels auf KKS wird deutlich, dass verschiedene Systeme unter diversen Umweltbedingungen analysiert werden müssen. Am Beispiel der Anbauregion Mt Elgon in Uganda zielte dieses Projekt darauf ab die Komplexität der Schattierungseffekte auf wirtschaftlich relevante KKS durch den Einsatz von Umwelt- und Produktionssystemgradienten zu untersuchen. Der Forschungsansatz wurde interdisziplinär konzipiert, um den breiteren Kontext von Kaffee-Agroforstsystemen zu beleuchten. Die ersten Kapitel befassten sich mit allgemeinen Aspekten von kleinbäuerlichen Produktionssystemen. Diese wurden entlang eines Höhengradienten basierend auf Vegetationsstrukturindikatoren in drei Systeme klassifiziert: (1) unbeschattet, (2) beschattet durch Bananen und (3) beschattet durch Schattenbäume. Die Klassifizierung diente als Vergleichsbasis entlang der Umwelt- und Produktionssystemgradienten. Im zweiten Kapitel wurden Kenntnisse der Landwirte bezüglich der KKS und der Rolle von Schattenbäumen mit Fachwissen und Feldbeobachtungen verglichen. Es wurden Diskrepanzen bezüglich der Symptomatik, der Pflanzenschutzmaßnahmen und der Rolle von Schattenbäumen festgestellt. Die Bewältigung von institutionellen Hürden und die Aufklärung der Schatteneffekte sind daher eine Priorität für die Verbesserung des Pflanzenschutzmanagements. Die letzten Kapitel konzentrierten sich auf biophysikalischen Aspekte von *Hemileia vastatrix*, (CLR) und *Monochamus leuconotus* (WCSB). Die Beziehung zwischen CLR / WCSB und der Produktionssituation auf verschiedenen räumlichen Skalen wurde analysiert und potenzielle ökologische Mechanismen der Schattierung diskutiert. Die Auswirkungen von Umwelt und Produktionssystem auf die CLR-Abundanz waren räumlich-zeitlich variabel und entweder direkt, interaktiv oder indirekt durch mikroklimatische Verhältnisse vermittelt. Die Entwicklung von WCSB wurde durch die bimodale Niederschlagsverteilung, und durch Höhe und Schatten über ihre Wirkung auf die minimale Temperatur beeinflusst. Die Ergebnisse heben die Bedeutung von Mikro-Umwelten für die Ökologie von KKS hervor, nicht zuletzt wegen ihrer Implikationen in Bezug auf den Klimawandel.

Schlüsselwörter: Kaffee-Agroforstsysteme, interdisziplinäre Forschung, Mikroklima, Klimawandel, *Hemileia vastatrix*, *Monochamus leuconotus*.

Contents

List of Abbreviations

AIC	Akaike Information Criterion
CB	Coffee-Banana System
CBD	Coffee Berry Disease
CLR	Coffee Leaf Rust
CO	Coffee-Open System
CPaD	Coffee Pests and Diseases
CT	Coffee-Tree System
DP	Dew Point Temperature (°C)
DTR	Diurnal Temperature Range (°C)
FPK	Farmers Perception and Knowledge
GLM	Generalized Linear Model
GLMM	Generalized Linear Mixed Model
GAM	Generalized Additive Model
HCPC	Hierarchical Clustering on Principal Components
LMM	Linear Mixed Model
masl	Metres Above Sea Level
MCA	Multiple Correspondence Analysis
piecewiseSEM	Piecewise Structural Equation Model
RH	Relative Humidity (%)
RH.95	Number of hours with RH $>$ 95 %
Temp	Temperature (°C)
WCSB	African White Coffee Stem Borer

List of Figures

List of Tables

1 General Introduction

1.1 Institutional and thematic background

The presented PhD project was conducted within the framework of the BMZ (Federal Ministry for Economic Cooperation and Development) funded project entitled "Trade-offs and synergies in climate change adaptation and mitigation in coffee and cocoa systems", a collaboration between the International Institute for Tropical Agriculture (IITA), the International Center for Tropical Agriculture (CIAT) and the University of Göttingen, Germany (i.a.). The overall goal of the project was the adaptation of vulnerable Arabica coffee and cocoa-based farming systems to climate change that combine improving farmer income and system resilience with contributing to climate change adaptation and mitigation. The project target region for coffee was in the East of Uganda. One of the project outputs was an inventory of the existing diversity of coffee production systems characterized along climate and intensification/shading gradients, in terms of different ecosystem services such as coffee yield quantity and quality, pest and disease control and climate change adaptation and mitigation. Those topics were covered by different PhD candidates, and the characterisation of existing coffee production systems served as starting point and common basis for each doctoral study. The here presented doctoral thesis deals with subtopics related to coffee pests and diseases.

1.2 Context, justification and objectives

1.2.1 Importance of coffee

Coffee (*Coffea arabica L.* and *C. canephora* Pierre ex A. Froehner), is one of the most valuable export products in the world trade and plays an essential role in the economic and social environment in more than 80 countries across the tropics (Vega, 2006). For several of Africa's economies and rural populations such as Uganda, Ethiopia or Tanzania, coffee is of particular importance (Taye (2010); Jaramillo et al. (2011)). In Uganda for instance, nearby a quarter of the country's export earnings of 2008/2009 was contributed by the export of coffee, generating employment and income for approximately 1.3 million households (Worldbank (2011)). Coffee is mainly produced by smallholder farmers who are dependent on the commodity as their main income, and often tend to lack resources allocated to adequate crop management (Waller et al. (2007)). The commercial production is based on Robusta and Arabica coffee, whereby the latter is regarded as the higher-quality species, accounting for approximately 70% of the total production (Worldbank (2011)). The coffee sector has to deal with a high degree of production volatility, caused not only by price risks, but also by a range of other unmanaged risks caused by insufficient crop management, weather events (drought, erratic rainfall) or coffee pests and diseases (CPaD). Especially in countries where resources for research and extension are lacking, the coffee sector is highly vulnerable and insufficiently prepared in order to counteract potential losses due to CPaD (Worldbank (2011)).

1.2.2 Coffee production systems, shade management and plant health

Shade trees and its effects on coffee production is a complex issue, which has been discussed a lot in terms of productivity or quality (Muschler (2001); Vaast et al. (2006); Bosselmann et al. (2009), i.a.), different aspects of ecology (Tscharntke et al. (2011); Jha et al. (2011); De Beenhouwer et al. (2013); Jha et al. (2014); Cerda et al. (2017), i.a.) and plant health (Staver et al. (2001); Soto-Pinto et al. (2002); Perfecto and Vandermeer (2006); Armbrecht and Gallego (2007); Avelino et al. (2011); López-Bravo et al. (2012), i.a.). Shade effects are controversially in relation to the pathogen and pest systems: On the one hand, there are pests or pathogens benefiting from high shade intensities (López-Bravo et al. (2012); Jonsson et al. (2014), i.a.), while others are negatively hindered (Armbrecht and Gallego (2007); Pardee and Philpott (2011), i.a.). On the other hand, different diseases or pests with distinct responses to shade can occur at the same time and location (Staver et al. (2001)). Furthermore, the positive or negative effects of shaded systems can be variable for an individual CPaD, depending on the biophysical context (i.e. the biotic and abiotic surrounding of an organism (HSIE (n.a.))) and spatiotemporal scale (Muschler (2001); Vaast et al. (2006); Van Kanten and Vaast (2006); Cerda et al. (2017), i.a.). Due to the multi-sided effects of shade not only on pests and diseases, but also on other relevant, above-mentioned components of the coffee production systems, it is difficult to define the right shade level or production system in order to minimize damages from CPaD, while maintaining productivity and complying with ecological and social claims. Most studies focused on the effect of few factors on a single CPaD at a specific site. But in spite of the many studies on shade effects on coffee production and sustainability, there is surprisingly little quantitative knowledge of field-level investigation on shade effects and its ecological mechanisms across environmental and production system gradients. However, in the last years there has been a trend to conduct studies which include environmental, management intensity or socio-economic gradients analysing the effects of multiple factors on one or a set of response variables (Fig. 1).

The need to examine these issues becomes more apparent considering the increasingly evident effects of progressive climate change. Pests and diseases threatening coffee production under current climate are likely to be aggravated by the effects of climate change and variability and could bring about serious implications for the coffee sector (Baker and Hagger, 2007). Recent outbreaks and increased incidences of pests and diseases across coffee growing regions of Latin America, East Africa and Asia seem to confirm this hypothesis (Baker and Haggar (2007); Gichimu (2008); Jaramillo et al. (2009, 2011); Kutywayo et al. (2013); Avelino et al. (2015); Mccook and Vandermeer (2015)). The use of shade trees in coffee farming systems is often proposed as an option for adaptation and mitigation to climate change and the control of CPaD (Schroth et al. (2000); Verchot et al. (2007); Lin (2010); Avelino et al. (2011)). However, beneficial and detrimental shade effects on coffee sustainability and resulting trade-offs between pest or disease control, crop productivity, adaption and mitigation to climate change

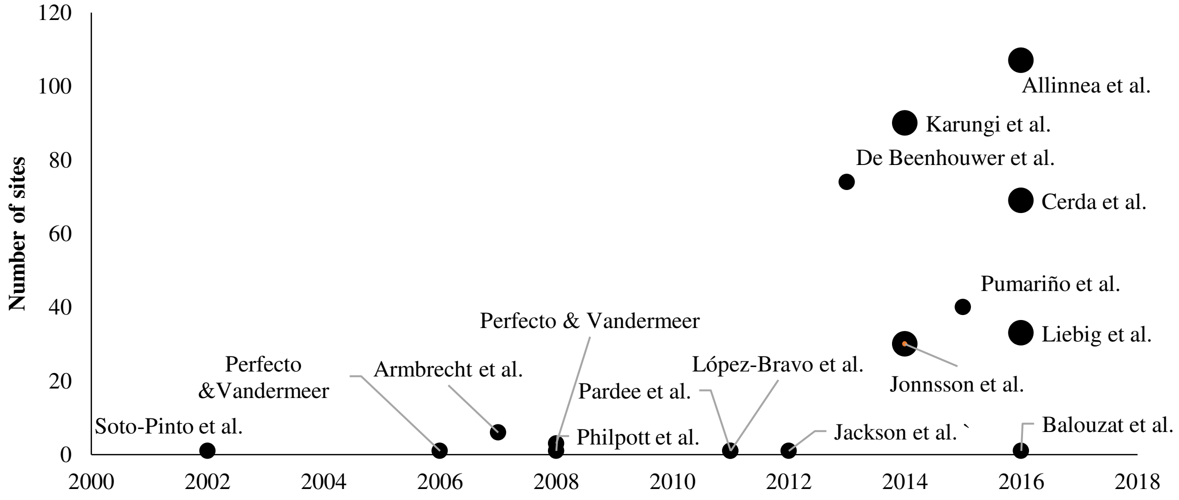

Figure 1: Literature review about studies on shade effects on CPaD Larger points show studies including an environmental gradient. References: Soto-Pinto et al. (2002); Perfecto and Vandermeer (2006); Armbrecht and Gallego (2007); Philpott et al. (2008); Perfecto and Vandermeer (2008); Pardee and Philpott (2011); López-Bravo et al. (2012); Liere et al. (2012); Jonsson et al. (2014); De Beenhouwer et al. (2013); Karungi et al. (2015); Pumariño et al. (2015); Balouzat et al. (2016); Liebig et al. (2016); Cerda et al. (2017); Allinne et al. (2016)

and livelihood benefits have to be taken into account (Rahn et al. (2014)). The balance of shade effects on coffee sustainability is unsure and needs to be investigated under different environmental conditions and in the context of climate change.

1.2.3 Study organisms

Coffee pests and diseases pose a danger to coffee production and can affect farmer livelihoods or even the entire economy of regions or countries (Rutherford and Phiri (2006)). In the past three decades, CPaD incidences and resulting damages have increased considerably. First of all, intensification strategies of coffee production such as the use of coffee varieties with higher yields under full sun exposure and higher inputs of agrochemicals have led to a reduction of shade levels, which in turn resulted in unexpected pest and disease problems (Staver et al. (2001)). Moreover, increased pesticides applications generated secondary pest problems, caused by organisms usually not of economically importance (Guharay et al. (2000)). For the Ugandan coffee supply chain, CPaD are one of the main constraints for coffee production (Worldbank (2011)).

The present study focused on three CPaD, which A) were considered as the economically most important ones based on literature as well as reports of coffee producers of the respective study region, and B) have been shown to be responsive to different environmental and shading conditions.

1. The White Coffee Stem Borer (WCSB, *Monochamus leuconotus* (Pascoe) [Coleoptera: Cerambycidae]), which is the second most important pest of Arabica coffee in Uganda (Egonyu et al, 2015, Jonsson et al, 2014).
2. The Coffee Berry Disease (CBD, *Colletotrichum kahawae* (Bridge and Waller) [Ascomycota: Glomerellales]), which is the first, and
3. Coffee Leaf Rust (CLR, *Hemileia vastatrix* (Berkeley and Broome) [Basidiomycota: Uredinales]), which is the second most devastating fungal disease of Arabica Coffee in Uganda (Matovu et al. (2013)).

A detailed description for each CPaD, including the geographic distribution, symptoms or damages, epidemiology or life cycle and control options is provided in the appendix (Fig. 20, 21, 22, 23).

1.2.4 Objectives

The specific objectives are:

1. To create typologies of coffee production systems, in order to assess the diversity of existing coffee production/shading systems characterized along and altitudinal gradient. (Chap. 2)
2. To asses farmers' and experts' perception and knowledge on CPaD occurrence and impact and its management. More specifically:
    (a) To examine and relate farmers' perception and knowledge on CPaD to topographic variables (represented as the altitudinal gradient) as well as the vegetation structure of the production systems
    (b) To contrast obtained results with perceptions and knowledge from scientists and extension agents
    (c) To validate results with own field observations,

    in order to identify gaps in knowledge and information flow and to discuss potential causes for constraints facing farmers and scientists. (Chap. 3)
3. To understand relationships between pest and disease abundance and production situation and driving ecological mechanisms from the local to regional scale.
    (a) *For WCSB:* (i) To characterize the spatiotemporal development of WCSB, explore associations to environmental and diverse shade-related indicators and discuss the underlying ecological mechanism of shading effects emphasizing the role of microclimatic modifications. (ii) To analyse and map the spatial pattern of WCSB to discuss spatially relevant factors related to pest abundance (Chap. 4)

(b) *For CLR:* (i) To characterize spatiotemporal variations in microclimatic indicators and CLR and (ii) to infer direct, indirect and interactive effects of components of the environment and production system on microclimatic indicators and CLR, in order to discuss the underlying ecological mechanism of shading effects emphasizing the role of microclimatic modifications. (Chap. 5)

The general purpose of the proposed project is to contribute to the overall goal of finding sustainable strategies to adapt coffee production systems to climate change, combining both, the improvement of farmers livelihoods and production system resilience, and the promotion of climate smart agricultural practices, including the identification and analysis of potential trade-offs. For this purpose, controversies concerning the effects of different production or shading systems on the three selected CPaD at different scales are to be clarified, in order to reduce productions risks and to sustainably mitigate potential losses.

1.2.5 Remarks on the content and structure

The first two objectives (Chap. 2 and 3) link to the overall project aims (Sec. 1.1) and provide the contextual framework for objectives 3a and b [Chap. 4 and 5]. A flow chart showing the objectives and related research questions is provided in Fig.2. The data collection and analysis for Chap. 2 was carried out jointly with the working group of the overall project. This dataset served as basis for a joint publication, which was lead by another doctoral student. Besides the typology of existing coffee production systems, it dealt with topics related to the sustainability of coffee agroecosystems. Those additional topics were out of scope for the content of this PhD, therefore only the abstract and relevant sections were included in the main body of the thesis. The full manuscript is attached in Appendix A.1. Chap. 4 and 5 dedicate on CLR and WCSB, respectively, while for CBD, no separate chapter was prepared. For CBD, less plots were sampled because it was only abundant at higher altitudes. The number of sampled plots at high altitudes however could not be increased because of the already laborious monitoring for CBD. No sophisticated statistical analysis could be applied, but data of the first season were analysed with a simpler approach in Chap. 3. In Chap. 6, a general discussion of all chapters is given. Chap. 3 to 5 each include an exhaustive discussion of the major findings, placed into the general context of the current research. Therefore, the general discussion will focus on assembling and referring the key findings of the individual chapters back to the research questions posed in this introduction. Chap. 2 to 5 were prepared as independent research papers, therefore there are some contentual repetitions. The overall thesis formatting has been unified for the entire document.

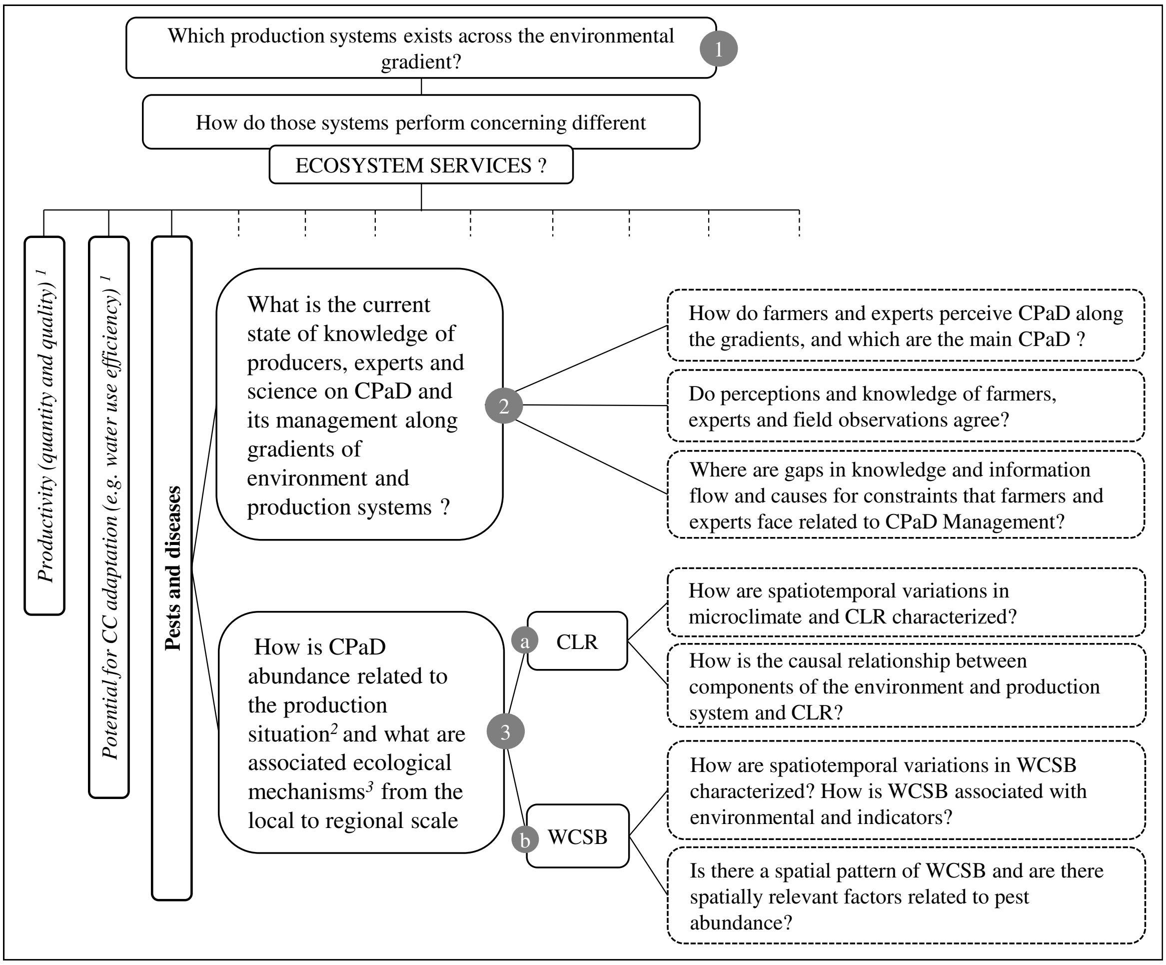

Figure 2: Objectives and research questions [1] Subtopics of other doctoral candidates. [2] Production situation = the combination of technical, social, ecological and economic factors (Rabbinge and De Wit (1989)). [3] The ecological mechanisms of shade analysed in this study mostly related to microclimatic modifications. Boxes with solid lines show general objectives / research questions, and boxes with dashed lines show specific objectives / research questions

2 Sustainable intensification of coffee agroecosystems in the face of climate change along the slopes of Mt Elgon, Uganda

Rahn Eric[1, 2, 3] , Ghazoul Jaboury[1], Liebig Theresa[2, 3,6], van Asten Piet[3], Jassogne Laurence[3], Vaast Philippe[4,5], Garcia Claude[1,5] and Läderach Peter[2].

[1]Swiss Federal Institute of Technology (ETH) Zurich, Environmental Systems Science, Switzerland

[2]International Center for Tropical Agriculture (CIAT), Cali, Colombia

[3]International Institute of Tropical Agriculture (IITA), Kampala, Uganda

[4]World Agroforestry Centre (ICRAF), Nairobi, Kenya

[5]Centre de Coopration International en Recherche Agronomique pour le Dveloppement (CIRAD), Montpellier, France

[6]Institute of Horticultural Production Systems - Section Phytomedicine, Leibniz University of Hanover, Hanover, Germany

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Full manuscript attached in Appendix A.1

2.1 Abstract

Coffee (*Coffea arabica*) is a major export crop of East Africa sustaining the livelihoods of millions of smallholder farmers. The viability of coffee in this region is, however, endangered by multiple factors such as climate change, population pressure and coffee price volatility. Sustainable intensification through (shade) inter-cropping is believed to improve farmers livelihoods, facilitate adaptation of coffee production to climate change, and contribute to coffee sector development and biodiversity conservation. Technical guidance on adaptation options is currently weak and requires sound understanding of local contexts. Altitudinal gradients provide a means for analysing coffee production systems in different environmental contexts that co-vary with altitude, and they provide a rough proxy for many of the issues relating to climate. Additionally, management decisions unrelated to environment need to be accounted for. We seek to do this by analysing a range of Arabica coffee systems that differ in vegetation structure across an altitudinal gradient on Mt Elgon, Uganda, to understand (i) if and how farmers adapt their production systems to differing climatic conditions, and (ii) how these different production systems perform. A typology of coffee systems was derived based on the vegetation structure of 144 coffee plots. Coffee systems were compared along an altitudinal gradient (1100–2100 masl). Determinants of farmer adoption of different coffee systems were investigated, highlighting both internal and contextual factors affecting farmers decision-making. Three coffee systems were identified: coffee open canopy, coffee-banana inter-cropping, and densely shaded coffee systems. The climatic gradient had a clear effect on system adoption, with shade trees being used to mitigate higher temperatures and more prolonged drought stress at low altitudes, while inter-cropped banana densities increased at higher altitudes responding to higher rainfall. Although vegetation structure affected coffee yield, differences among systems were not significant. Open canopy systems are mainly used by wealthier farmers who do not depend on inter-crops for food security. Altitude has a strong influence on coffee yield, benefits of shade trees, and soil quality. Socio-ecological constraints, such as farm and household size, and access to forests and markets, play a crucial role in determining what constellation of ecosystem services benefit farmers livelihoods resulting in different sustainable intensification pathways. Our findings reveal inherent trade-offs in socio-ecological conditions, and aligning these is required for achieving the multiple objectives of livelihood improvement, sustainable intensification of coffee production, and biodiversity conservation.

2.2 Material and Methods

2.2.1 Agroecological context of the study area

The study was conducted in three neighbouring Ugandan districts (Bulambuli, Sironko and Kapchorwa) on the slopes of Mt Elgon, the fourth highest (4320 masl) mountain of Africa.

In a first step, the study area was clustered according to the key variables of climate and topography (annual temperature, annual rainfall, altitude, slope inclination, slope aspect) (Fig. 3). The three resulting clusters differed mainly in their altitude and consequently variables correlated to altitude such as temperature and rainfall. An altitudinal gradient with three ranges was derived (1100–1400 masl, 1400–1700 masl, 1700–2100 masl). The study area comprised a total area of 210 km^2 (Fig. 3). The soils are classified as inorganic clays of high plasticity (Mugagga et al. (2012)) and the underlying geology is dominated by basaltic parent rocks (Schlüter (2008)). The area of Mt Elgon receives an approximately bimodal pattern of rainfall with the wettest periods in March/April and October/November, a pronounced dry period from December to February and a period of less intense rain around July to August (Fig. 4). The wet season is prolonged on higher altitudes compared to lowlands. Mean annual rainfall ranges from 1200 mm at low altitudes to 1400 mm at mid altitudes and 1800 mm at high altitudes. The mean annual temperatures are 23°C , 21°C and 18°C , respectively (Hijmans et al. (2005)). The Mt Elgon region has experienced an increase in monthly temperatures in the range of 0.4°C to 1.2 °C during the 2001-2011 period compared to the 1961-1990 period. Intensive rainfall has resulted in numerous landslides on the mountain slopes and floods on the foothill with hundreds of deaths. Increased drought periods are particularly a problem in the northern drier region and areas of low altitude causing stress to crops and scarcity of domestic water availability (Mbogga, 2012).

The area is dominated by agricultural activities with crops grown such as Arabica coffee, bananas, beans, peas, ground nuts, maize, vegetables, sweet and Irish potato, avocado, mango i.a.. Coffee is grown under varying levels of shade provided by different shade-tree species and bananas (*Musa* spp.), and under sun-exposed conditions. Arabica production is mainly based on introduced varieties, such as Bugisu local (Nyasa land), SL 14, SL 28 and KP423 (Musoli et al. (1993)).

2.2.2 Selection of participating farmers for Participatory Rural Appraisals and the classification of existing coffee production systems

The selection of farmers per altitude range followed a stratified random sampling using the ”RAND” function of Excel (Microsoft Excel 2013). For each altitude range and within the three districts where coffee is grown, the existing sub counties were listed in spread sheets, random numbers were generated and assigned to each name. The lists were sorted according to the random number and the first 2 names selected, resulting in a total of 6 sub counties for the three altitude ranges. Within the selected sub counties, the same procedure was repeated for the selection of parishes and farmers. Finally, a total of 300 coffee farmers (50 per sub county) were invited for Participatory Rural Appraisals (PRA). They were conducted (April 2014) in order to introduce the project's objectives and activities to the participating communities and to acquire perceptions of coffee yield limiting factors in general and of

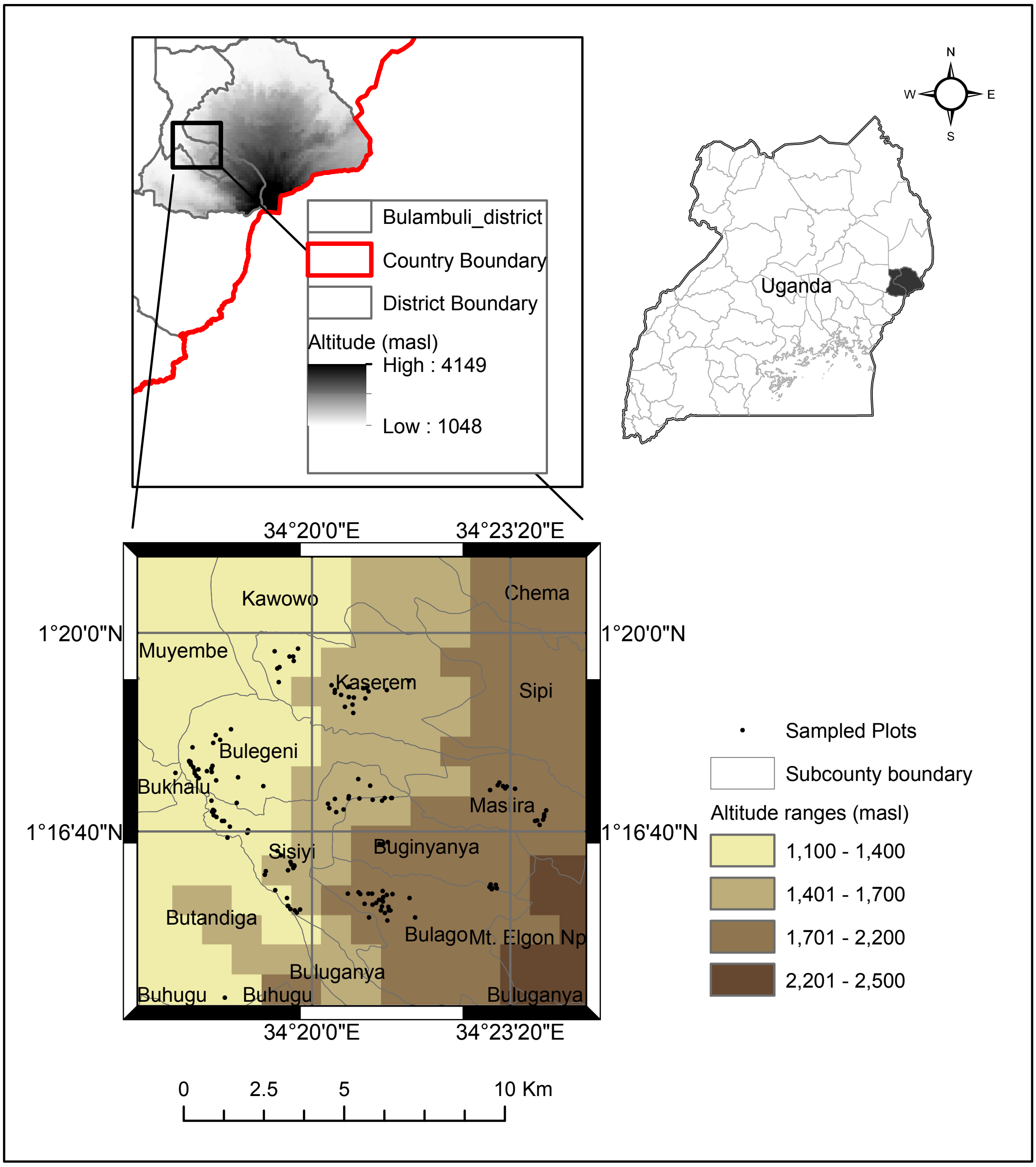

Figure 3: Study area. Location of the study area within the Ugandan Mt Elgon area and the districts of the study area (Bulambuli, Kapchorwa and Sironko) with indicated sub counties and three altitude ranges determined by means of a cluster analysis

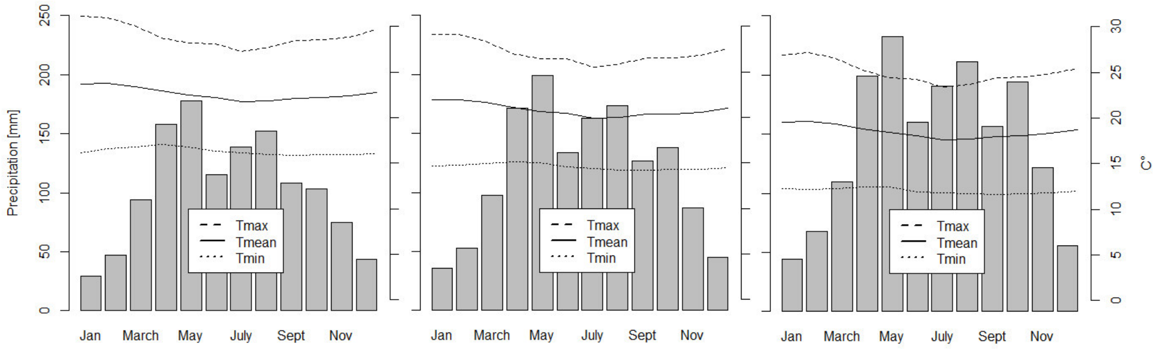

Figure 4: Climate diagrams for Mt Elgon area. From left to right: Climate diagrams of low (1100–1400 masl), mid (1400–1700 masl), and high altitude (1700–2100 masl) based on WorldClim database (Hijmans et al. (2005))

production constraints due to pests and diseases. PRAs were organized in the six selected sub counties. Applied tools included rankings, seasonal calenders and focus group discussions (FAO (1999)) (Appendix 24).

For the classification of existing coffee production systems, a subset of 150 farmers of the previous PRA list was selected following the sampling procedure described above (random selection stratified by altitude). One plot for each of the selected farms was chosen to collect plot scale descriptors of vegetation structure relevant for deriving coffee production system typologies. Plots were selected according to a set of criteria: 1) A maximum of 1 km distance from the homestead, 2) a minimum of 80 coffee bushes per plot and 3) the age of coffee bushes must be above 4 years. Data from six farmers had to be rejected because of unreliable data, resulting in 144 farmers (44-54 per altitude range).

2.2.3 Data collection

In April/May 2014, vegetation structure was measured on the 144 selected plots. The altitude and plot boundary coordinates were recorded using Garmin eTrex GPS. Plot size was calculated based on plot boundary coordinates. The number of coffee bushes, banana mats and stems, and shade trees were counted on the entire plot and densities (in number per hectare) were calculated. Shade tree species were identified and the number of species per plot recorded. The canopy closure as an indicator for average plot shade was estimated using a Forestry Suppliers spherical crown densiometer (convex model A) according to (Lemmon (1957)) at four positions within the plot. A composite soil sample of the topsoil (0-30cm) was taken from each plot and analysed for organic matter, soil pH, total nitrogen, available phosphorus, and exchangeable potassium using standard methods (Okalebo et al. (1993)). The slope was measured using Suunto Tandem Global Compass/Clinometer. Soil erosion was evaluated visually. Data on age of the coffee bushes, yield, coffee management, perceived oc-

Table 1: Typology coffee shading systems based on K-means clustering

	CO, n = 54		**CB, n = 44**		**CT, n = 46**	
	Mean	*SE*	*Mean*	*SE*	*Mean*	*SE*
Coffee density (coffee ha^{-}1)	2255^a	125	2094^a	127	2095^a	112
Banana density (bananas ha^{-}1)	29^a	17	1496^b	105	278^c	82
Shade tree density (trees ha^{-}1)	63^a	6	49^a	6	144^b	16
Shade tree species richness	2.8^a	0.2	2.7^a	0.2	6^b	0.4
Canopy closure (%)	21^a	1.4	28^b	1.4	48^c	2

SE = Standard error. Means within rows with different letters indicate significant differences (one-way ANOVA, p<.05). Clustering was based on a total of 144 plots, which were sampled in May 2014. In 2015, 22 additional plots were included and classified retrospectively. CB = Coffee-Banana System, CO = Coffee-Open System, CT=Coffee-Tree System.

currence and impact of coffee pests and diseases, and livelihood characteristics were obtained through structured farmer interviews during farm visits.

2.2.4 Data analysis

Data analysis was done using R statistics (R Core Team, 2014). The typology of coffee production systems was based on variables related to vegetation structure. Variables included were shade tree and banana densities per unit area, shade tree species diversity and canopy closure. K-means clustering was performed with standardized data in order to minimize the effect of scale differences. The variables were compared between the resulting coffee systems using the one-way ANOVA (with Tukeys post hoc test).

2.3 Results

Three distinct coffee production systems were identified, namely a sparsely shaded open canopy coffee system (CO), a coffee system with high banana densities (CB) and a highly tree shaded coffee system (CT) (Table 1).

Vegetation structure of the coffee systems showed a relationship with altitude. Banana density was higher on mid and high altitude compared to low altitude (one-way ANOVA with Tukey post-hoc test, p<.05), while shade tree density, shade tree species richness and canopy cover were higher on low altitude compared to mid and high altitude (one-way ANOVA with Tukey post-hoc test, p<.05). Due to these spatial differences in banana and shade tree densities a significant association between the coffee production typologies and altitude range was found (X^2, p < .001). The majority of plots assigned to the CT system were found at lower altitudes between 1000–1400 masl, while more CB and CO systems were present at mid to high altitudes between 1400–2200 masl. Only few CB systems were found on low altitude.

3 Towards a collaborative research: A case study on linking science to farmers perceptions and knowledge on *Arabica* coffee pests and diseases and its management

Theresa Liebig[1, 2, 3], Laurence Jassogne[2], Eric Rahn[1, 2, 4], Peter Läderach[1], Hans-Michael Poehling[3], Patrick Kucel[5], Piet Van Asten[2] and Jacques Avelino[6,7,8,9]

[1] International Center for Tropical Agriculture (CIAT), Cali, Colombia
[2] International Institute of Tropical Agriculture (IITA), Kampala, Uganda
[3] Institute of Horticultural Production Systems - Section Phytomedicine, Leibniz University of Hanover, Hanover, Germany
[4] Department of Environmental Systems Science, Swiss Federal Institute of Technology (ETH), Zurich, Switzerland
[5] National Coffee Research Institute (NaCORRI), National Agricultural Research Organisation (NARO), Mukono, Uganda
[6] Centre for International Cooperation in Agricultural Research for Development (CIRAD), UPR Bioagresseurs, Montpellier, France
[7] Department of Research and Development, Tropical Agricultural Research and Higher Education Center (CATIE), Turrialba, Costa Rica
[8] Inter-American Institute for Cooperation on Agriculture (IICA), San Jos, Costa Rica
[9] Regional Cooperative Program for Technological Development and Modernization of Coffee Production (PROMECAFE), Guatemala City, Guatemala

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3.1 Abstract

The scientific community has recognized the importance of integrating farmer's perceptions and knowledge (FPK) for the development of sustainable pest and disease management strategies. However, the knowledge gap between indigenous and scientific knowledge still contributes to misidentification of plant health constraints and poor adoption of management solutions. This is particularly the case in the context of smallholder farming in developing countries. In this paper, we present a case study on coffee production in Uganda, a sector depending mostly on smallholder farming facing a simultaneous and increasing number of socio-ecological pressures. The objectives of this study were (i) to examine and relate FPK on Arabica Coffee Pests and Diseases (CPaD) to altitude and the vegetation structure of the production systems; (ii) to contrast results with perceptions from experts and (iii) to compare results with field observations, in order to identify constraints for improving the information flow between scientists and farmers. Data were acquired by means of interviews and workshops. One hundred and fifty farmer households managing coffee either at sun exposure, under shade trees or inter-cropped with bananas and spread across an altitudinal gradient were selected. Field sampling of the two most important CPaD was conducted on a subset of 34 plots. The study revealed the following findings: (i) Perceptions on CPaD with respect to their distribution across altitudes and perceived impact are partially concordant among farmers, experts and field observations (ii) There are discrepancies among farmers and experts regarding management practices and the development of CPaD issues of the previous years. (iii) Field observations comparing CPaD in different altitudes and production systems indicate ambiguity of the role of shade trees. According to the locality-specific variability in CPaD pressure as well as in FPK, the importance of developing spatially variable and relevant CPaD control practices is proposed.

3.2 Introduction

Natural and social scientists have emphasized the need to incorporate farmers' perceptions and knowledge (FPK) into research programs in order to establish and successfully implement sustainable pest and disease management strategies (Bentley and Thiele (1999); Norton et al. (1999); Heong et al. (2002); Van Asten et al. (2009)). Particularly in countries where smallholder farming faces multiple socio-ecological challenges, the potential impact of newly developed management technologies is supposed to be narrowed if farmers are not involved into the design of agricultural research (Röling et al. (2004)). The scientific community has therefore acknowledged that the lack of understanding what farmers know and how they make decisions may reduce the chances of success of integrated pest and disease programmes (Heong (1985); Morse and Buhler (1997)).

Several perception studies, mainly examining farmers knowledge and applied management practices on crop pests and diseases at a certain location have been conducted for annual crops such as rice (Rubia et al. (1996); Norton et al. (1999); Joshi et al. (2000); Price (2001)), maize (Songa et al. (2002); Wyckhuys and O'Neil (2007)), cotton (Ochou et al. (1998)), legumes (Bottenberg (1995); Trutmann et al. (1996)), millet (Tanzubil and Yakubu (1997); Youm and Owusu (1998)), cassava (Manu-Aduening et al. (2007)) and diverse vegetables (Chitere and Omolo (1993); Norton et al. (1999); Obopile et al. (2008); Adam et al. (2015)). Similar documentation for perennial and tropical fruits and agroforestry trees or shrubs is scarce (Van Mele et al. (2001); Nyeko et al. (2002); Segura et al. (2004); Cerdán et al. (2012); Valencia et al. (2015)).

Perception studies regarding pests and diseases of coffee (*Coffea arabica* and *C. canephora*) are rare, despite its high relevance for the economy of developing counties (Talbot (2004)). The role of coffee becomes evident considering its social, economic and environmental importance across multiple scales, from the household to the global level. In most coffee producing countries, a large proportion of production depends on smallholder farming and is exposed to simultaneous and interdependent challenges of social, ecological and economic nature (Leichenko and O'Brien (2002)). One of those challenges is climate change, faced by coffee farmers worldwide. Arabica coffee will be significantly affected by climate change and variability. On the one hand, increased temperature causes the loss of suitable Arabica growing areas resulting from a shift of respective areas from lower to higher altitudes. On the other hand, regular vegetative and reproductive growing cycle processes of the plant and related biotic constraints such as pests and diseases are affected by more variable seasonal patterns (Läderach et al. (2010, 2011); Davis et al. (2012); Jassogne et al. (2013); Avelino et al. (2015); Bunn et al. (2015); Craparo et al. (2015); Mccook and Vandermeer (2015); Ovalle-Rivera et al. (2015)). CPaD which are already troublesome under the current climate are likely to be aggravated by the effects of climate change and variability. They could entail serious implications for the coffee sector. Recent outbreaks and increased incidences of CPaD have already been reported around the world Baker and Haggar (2007); Gichimu (2008); Jaramillo et al. (2009, 2011); Kutywayo et al. (2013); Avelino et al. (2015); Mccook and Vandermeer (2015). In coffee based production systems, shade trees are often proposed as an option for both, pest and disease management and adaptation to climate change (Schroth et al. (2000); Verchot et al. (2007); Lin (2010); Avelino et al. (2011)). Trees associated with coffee limit extreme temperatures, reduce solar radiation and buffer fluctuations in air temperature and humidity in the plantations (Vaast et al. (2006); Siles et al. (2010b); Avelino et al. (2011); López-Bravo et al. (2012)). Nevertheless, beneficial and detrimental shade effects result in trade-offs between climate change mitigation, adaptation and livelihood benefits at different scales which have to be investigated (Rahn et al. (2014)).

The few studies focusing on farmers perceptions and local knowledge of CPaD revealed that farmers have a detailed knowledge of shade trees and its impact on environmental services, including CPaD (Cerdán et al. (2012)). These authors concluded that agricultural projects could fail to meet expectations if local knowledge is not well understood. Furthermore, Segura et al. (2004) have found that a knowledge gap between research institutions and farmers concerning their main crop health problems explains the low adoption of existing pest management technologies. The ignorance of scientists regarding farmers knowledge and priorities as well as their socio-economic background has been an important contributing factor to this gap.

Coffee is grown in a range of varying agroecological conditions. Accordingly, FPK is connected to specific localities with related ecological context (Bellon (1995); Jansen (1998); Mahiri (1998)). Including the environmental as well as the production system components is therefore crucial (Wyckhuys and O'Neil (2007)). Understanding how farmers perceive and manage CPaD under different production situations and across spatial scales allows for giving relevant spatially explicit recommendations.

In this paper we present a case study on Arabica coffee in Uganda. The objectives of this study are (i) to examine and relate FPK on CPaD to topographic variables as well as the vegetation structure of the production systems; (ii) to contrast obtained results with perceptions and knowledge from scientists and extension agents and (iii) to validate results with field observations, in order to identify gaps in knowledge and information flow and to discuss potential causes for constraints facing farmers and scientists in the face of climate change.

3.3 Material and Methods

3.3.1 Methodological framework of the study

A summary of the methodological framework for the comparison between FPK, expert knowledge and field observations is shown in Fig. 5.

3.3.2 Study area

This study referred to the same area and farms as described in Sec. 2.2.1 and 2.2.2.

3.3.3 Data collection

(i) Farmer survey

A structured interview with a mix of closed-ended and open-ended questions was used to inquire information about farming structures and management practices, the farmers' socio-economic background and perceptions about a selection of nine CPaD (Table 2). For the latter, farmers were asked a sequence of repetitive questions (Table 3) which were reformulated for the different CPaD. Photographs of the organisms and typical symptoms and damages were used during the interviews. All questions referred to the plot that was previously selected for deriving the coffee system typology. The questions were related to the preceding production year.

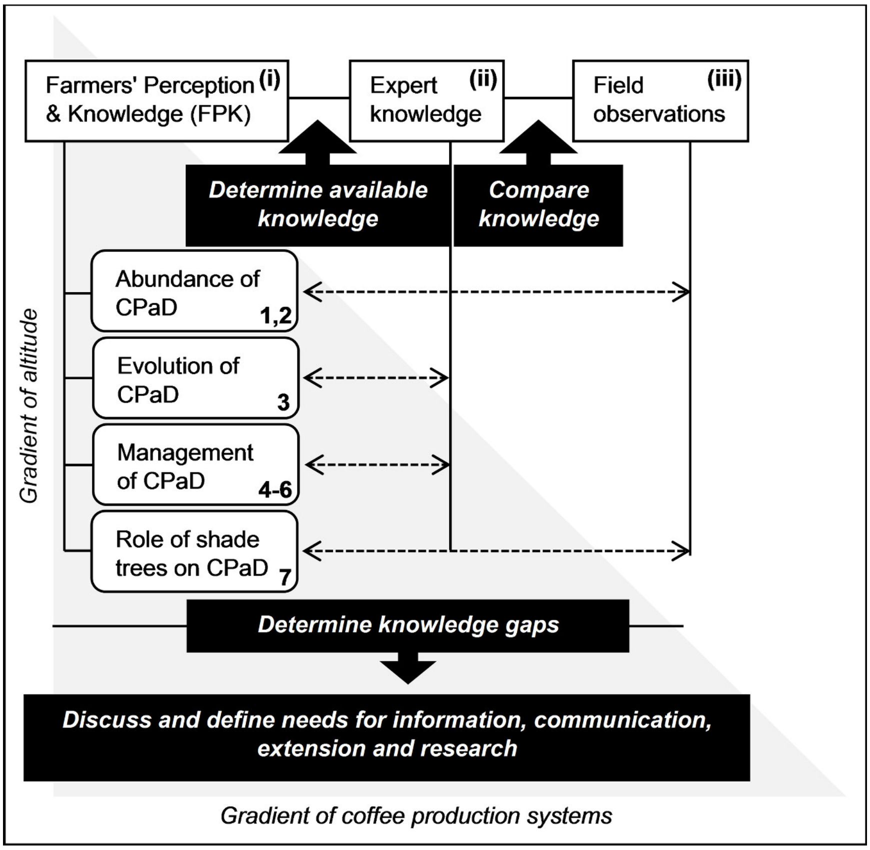

Figure 5: Methodological framework of the study. Comparison between FPK, expert knowledge and field observations with regard to a selection of variables related to CPaD and along a gradient of altitude and production system. Horizontal dashed arrows indicate between which levels (Farmers, Experts, Field) the variables have been compared to. Roman and Arabic numerals correspond to collection and analysis of data as described in the subsequent sections. (i) Farmer survey, (ii) Expert workshop, (iii) Pest and disease field assessments, 1-7 correspond to the sequence of questions asked to farmers shown in Table 3

Table 2: List of CPaD used in interview survey

CPaD	Scientific name	Abbreviation
White coffee stem borer	*Monochamus leuconotus*	WCSB
Coffee berry borer	*Hypothenemus hampei*	CBB
Antestia bug	*Antestiopsis spp.*	AB
Coffee berry moth	*Prophantis adusta*	CBM
Root mealy bug	*Pseudococcus spp.*	RMB
Coffee leaf miner	*Leucoptera coffeella*	CLM
Green scales	*Coccus spp.*	GS
Coffee leaf rust	*Hemileia vastatrix*	CLR
Coffee berry disease	*Colletotrichum kahawae*	CBD

Table 3: List of questions posed to the farmers

No.	Question
1	Is CPaD present in your coffee plots?
2	How severe is CPaD in rainy and dry season? Please score severity (1 = present but not a problem; 2 = minor problem; 3 = intermediate problem; 4 = major problem
3	Has the severity of CPaD changed over the last 5 years?
4	How do you control CPaD?
5	Did you change your control strategies in the last 5 years?
6	Do you think that the applied control strategies are effective?
7	At what time of the day do you apply pesticides?
8	Have you met an extension officer in the last year? If yes, which recommendations did you get?
9	Do you think that shade trees or bananas can influence CBD? If yes, why?

Questions 1 - 7 where asked for each of the 9 CPaD

(ii) Expert workshop

Experts from the Ugandan coffee sector, including entomologists, technicians from the national coffee research institute (NaCORRI) and the academic sector, were invited to a workshop. Experts were asked questions concerning CPaD abundance, management, development over the past five years and the role of shade trees. These questions were derived from an adjusted version of the pests and diseases section of the farmer questionnaire. Subsequently, results of the interviews conducted with the farmers were presented and analysed within an open discussion.

(iii) Pest and disease field assessments

Based on the results obtained through farmers and experts, the two CPaD perceived as the most severe ones (WCSB and CBD) were monitored from June 2014 to February 2015. A subset of 34 plots distributed along the altitudinal gradient was selected out of the 148 farms. Since the interest was to study the effect of the altitude and production system on the most important CPaD, non-probability sampling was used in order to select similar portions of plots assigned to a certain production system and altitude range. Some plots showed no or a very low coffee productivity as a consequence of old coffee bushes or inappropriate management practices. Because the relevance of non-productive coffee for a CPaD assessment is questionable, those plots were excluded from the monitoring. In spite of the assignment of each plot to a certain typology, the within-plot heterogeneity of shade and sun conditions remained quite high. Therefore, sub-plots of each 15 coffee bushes were used in order to capture the specific conditions representative for the respective coffee system. A varying number of sub-plots, depending on the plot size, structure and shape was established. For instance, a small or narrow plot where shaded or sun-exposed patches were confined to a certain area within the plot, only one or two sub-plots were considered. In total, 68 sub-plot were established. Per sub-plot, five coffee bushes for WCSB and three for CBD assessments were marked. A total of 335 coffee bushes were sampled for WCSB assessments. Incidence, i.e. the proportion of infested bushes, was recorded five times: during the minor dry season in June, before the harvest in August, during the rainy season in October, after harvesting in December, and during the dry season in February. The lower trunks, up to 2 m above the collar level of the coffee bushes were examined. The number of bushes showing any signs of stem girdling or boring by WCSB were counted. CBD intensity was assessed as berry loss due to CBD every other week as Mouen Bedimo et al. (2008) have done. Since CBD is practically absent below 1500 masl, it was only monitored in the mid and high altitude range. Therefore, only 129 coffee bushes were sampled. For the analysis, the high altitude range was split into two sub-ranges.

3.3.4 Data analysis

Maps were produced using ArcMap (Version 10.2.2) ESRI (2014). The elevation layer was generated with 90 m resolution from the digital elevation model (DEM) of the shuttle radar topography mission (SRTM) (Reuter et al. (2007)). The administrative borders were derived from the GADM database (Hijmans et al. (2005)). Data analysis was conducted using the R software package (RStudio Version 0.98.983, R Core Team (2014)). All tables and graphs were generated using the ggplot2 (Wickham (2016)), lsmeans (Lenth et al. (2016)) and stargazer (Hlavac (2015)) packages of the R environment.

(i) Farmer survey and (ii) Expert workshop Descriptive statistics were used to analyse the information obtained from farmers and experts. Relations derived from the farmer survey were analysed using non-parametric statistical tests. The relation between perceived impact and altitude range as well as production system was tested using the Kruskal-Wallis test. The relation between occurrence and altitude as well as production system was tested using Fishers' exact test. Further relationships such as the association between pesticide use and the perceived impact of CPaD and the collaboration with an extension officer were analysed using the χ^2 and the Mann-Whitney test.

(iii) Pest and disease field assessments Field data on WCSB incidence and CBD intensity were analysed using generalized linear models (GLM) (Nelder and Wedderburn (1972)). For both models, the two categorical predictors of interest, altitude range and production system, as well as its interactions were included. The proportion of infested coffee bushes by WCSB and the total number of lost berries due to CBD per plot were used as the response variables. A quasi-binomial regression model was used to model WCSB incidence as the predicted odds of coffee bushes infested versus coffee bushes not infested at the plot level. A negative binomial model was fit to the data on CBD intensity as the mean number of lost berries due to CBD per plot. The likelihood ratio test was used to compare the goodness of fit of the full model against the null model. Based on these fitted model parameters, all pairwise comparisons between production systems were performed (analogously to Tukeys HSD).

3.4 Results

Participatory rural appraisals

For all locations along the altitudinal gradient, pests and diseases were ranked as the major constraint for coffee production, followed by low soil fertility, lack of extension services, and changes in weather patterns. For the low altitude, poor flowering and old coffee trees were also mentioned to be the cause of low yields. For the mid altitude, intense mixed cropping, soil erosion and lack of shade trees were named as limiting factors. CPaD (Table 2) common to all altitudes were the WCSB, CBB, AB, and CLR. Additionally, CBD was reported to be an economically important disease for the high and the mid altitudes. Although actual yield losses due to CPaD are difficult to quantify and are a product of interactions between diverse biotic and abiotic factors, the general importance farmers assign to coffee crop health is shown.

3.4.1 (i) Farmers' perceptions and knowledge on coffee pests and diseases

In the following section, FPK on CPaD corresponding to the questions of interest listed in (Table 3) are shown.

The perceived CPaD occurrence and impact (Table 3, questions No. one and two) were analysed by altitude and by production system. Perceived CPaD occurrence in the three different altitude ranges is shown in Fig. 6. The occurrence in % of CBM, CLM, GS and CLR was similar at low and mid altitude but lower at high altitudes. For CBB and RMB highest occurrence was reported at mid altitudes. The occurrence of WCSB was negatively related to altitude, while AB and CBD were positively related to it. The perceived impact of WCSB and CBD appeared to affect coffee productivity most (Table 4). Scores for WCSB were significantly higher at low and mid altitudes, while for CBD highest scores were found at high altitudes (Table 4)). Regarding the different production systems, the occurrence of WCSB and CLR is higher in plots that were assigned to the CT systems (Fisher's exact test, $p = 0.12$, $p = 0.18$ respectively). On the contrary, CBD occurrence is significantly lower in CT systems than in the CB and CO systems (Fisher's exact test, $p < .05$). The perceived impact of WCSB is significantly higher in CT systems (Kruskal-Wallis test, $p < .05$).

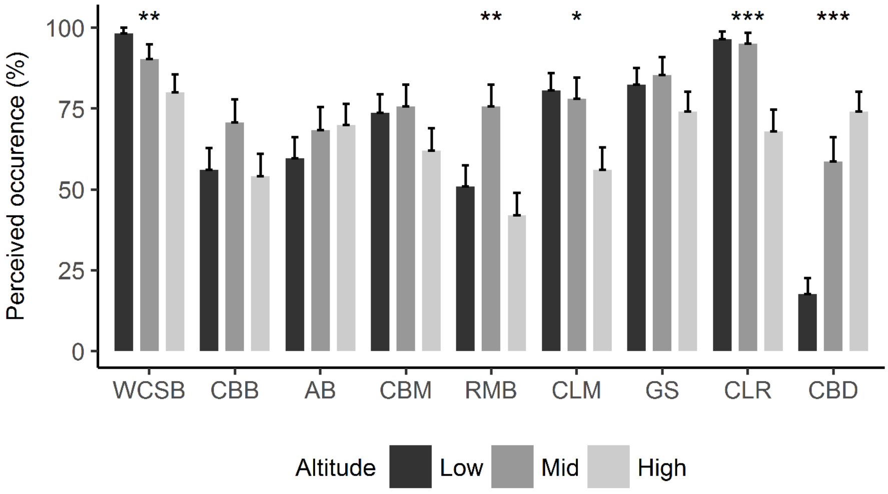

Figure 6: CPaD occurrence perceived by farmers. Proportion of farmers who reported CPaD to be present to farmers where CPaD were not present per altitude range. Low altitude $n = 57$; Mid altitude $n = 41$; High altitude $n = 50$. Fishers' exact test (* significant at $p < 0.05$; ** significant at $p < .001$; *** significant at $p < .0001$

Concerning the development of CPaD issues in the past five years, farmers generally did not perceive a crucial change towards a higher or lower CPaD pressure.

Management practices applied by the interviewed farmers to control CPaD are listed in Table 5. WCSB, perceived as one of the most abundant and severe pests, was controlled by the majority of farmers, either with synthetic insecticides or by cultural methods, such as stumping. The other pests were reported to receive either none or chemical control. The most widely used insecticide was the organophosphate fenitrothion. Almost half of the respondents

Table 4: Comparison of perceived impact scores between altitude ranges

	Perceived severity score													
	Altitude range								**Seasons**					
	1100–1400 masl			*1400–1700 masl*			*1700–2200 masl*			*Dry*		*Rainy*		
CPaD	M	SD	N	M	SD	N	M	SD	N	M	SD	M	SD	N
WSCB	3.09	0.92	56	3.66	1.06	37	3.36	1.26	40	3.85	1.09	3.05	1.35	133
CBB	2.56	1.31	32	2.49	1.12	29	2.51	1.08	27	2.3	1.32	2.65	1.18	88
CLR	2.33	0.57	45	3	0.7	39	2.4	1.14	34	3	1.15	2.4	1.1	128
CBD	2	2.08	10	2.24	1.11	24	2.93	0.55	37	2.07	1.15	3.14	1.29	71
AB	2.76	1.39	34	2.5	0.84	28	2.3	1.23	35	2.46	1.22	2.44	1.04	104
CBM	2.11	1.15	42	2.24	0.88	31	2.59	1.11	31	2.58	1.19	2.32	1.08	81
RMB	2.55	1.46	29	2.22	1	31	2.43	1.51	21	2.55	1.16	2.29	1.09	97
CLM	2.72	1.53	46	2.89	0.97	32	1.82	0.55	28	2.18	1.23	2.07	1.11	117
GS	1.91	1.15	46	3.1	0.73	35	2.83	1.58	36	2.24	1.14	2.04	1.17	106

Impact scores: 1 = present but not a problem; 2 = minor problem; 3 = intermediate problem; 4 = severe problem; 5 = major problem. Mdn = Median, MAD = Median absolute deviation, n = Sub-sample size. Bold labelled rows indicate significant differences between altitude ranges (Kruskal-Wallis test, significant at $p < .1$ and $p < .05$ respectively

did not control diseases, a rather low percentage applied fungicides (mainly copper-based compounds), and a smaller part used insecticides to control CLR and CBD. A relationship was found between the use of pesticides and altitude (Fishers' exact test, $p < .05$). The use of both, fungicides and insecticides, was significantly higher in the high altitude range than compared to mid and low altitudes.

Table 5: Farmers' CPaD management practices

	WCSB	**CBB**	**AB**	**CBM**	**RMB**	**CLM**	**GS**	**CLR**	**CBD**
No control (%)	12	39	35	39	36	51	41	48	49
Insecticides (%)	53	57	60	52	31	44	56	15	17
Fungicides (%)	0	0	0	0	1	1	2	31	20
Cultural (%)	28	1	0	3	28	0	1	4	10
Traditional (%)	7	3	5	6	4	4	0	2	4

Percentages are based on the total number of respondents (n = 148). Traditional practices included plant extracts such as chilli tincture, diverse herbal extracts or manure

More than 90% of all respondents relied on the effectiveness of the used chemical products. However, no significant difference in perceived impact has been found between the farmers who rely on chemical control compared to those who did not.

43% of the respondents have met an extension officer in the past two years. The most frequent recommendation farmers received was the repeated use of chemical insecticides and fungicides. Farmers have not mentioned further details, such as the type of product, its concentration or frequency of application. Accordingly, a significant association between having met an extension officer and the use of chemical products was found (χ^2 test, $p < .1$).

Regarding farmers' perception and knowledge about the role of shade trees for CPaD, the majority of respondents (73%) believed that no relationship, neither positive nor negative exists. Most of the remaining respondents (87%) believed that shade trees promote CPaD, mainly due to their capability to act as alternative hosts for insect pests. Few respondents considered shade trees to be helpful, for instance as hosts for birds and beneficial insects.

3.4.2 (ii) Expert knowledge

Experts from the Ugandan coffee sector evaluated WCSB, CBD and CLR to be the largest constraints to plant health and yield. Furthermore, it has been mentioned that RMB has become a serious pest affecting the region, especially in the dry season. Experts explain that WCSB, CLR and RMB have evolved to a more serious problem in the last 5 years. They suspect that the increasing emergence is related to a change in climatic patterns. Increasing temperatures are supposed to be responsible for the propagation of CLR into higher altitudes, while extended dry spells are considered to favour the life cycle of RMB.

Proposed CPaD control strategies by experts are listed in Table 6. Besides chemical treatment, diverse cultural methods were suggested to be effective. For WCSB for instance, non-conventional methods such as wrapping or smoothing the stem to interfere with the females' oviposition were mentioned to be effective. For CBB, picking up infested berries from the ground and the coffee bushes during and after the harvest was suggested to be an effective cultural method, as well as biological control methods, for instance using the entomopathogenic fungus *Beauveria bassiana*. For CLR and CBD general phytosanitary measures, the use of resistant varieties and the regulation of shade were recommended as further control strategies besides the use of copper-based fungicides.

Experts generally implied interactions between shade regimes and the intensity of CPaD. The incidence of WCSB, CLR, CBD and AB was believed to be favoured by shade trees and bananas, and consequently CT or CB systems. They were said to create a suitable microclimate which is conducive for infestation and infection processes. On the contrary, GS and RMB were observed to be negatively affected by shade and hence to be rather an issue in CO systems. CBB has been reported to be an issue in both, shaded and unshaded systems. No known relation has been mentioned for CLM and CBM.

3.4.3 (iii) Field observations

Table 7 shows the β coefficient, standard error and odds ratio of the quasi-binomial regression model examining the effects of the altitude range and production system on WCSB incidence.

Table 6: CPaD control practices proposed by experts

CPaD	**Control practice**
WCSB	Stem banding, wrapping, stumping, Chemical, stem smoothening
CBB	Chemical, biological, cultural (picking infested berries)
AB	Chemical, cultural (removal of bugs and eggs)
CBM	Chemical, cultural (removal of infested berries)
RMB	Cultural (trapping with legumes), chemical, mineral fertilizer, organic manure
CLM	Chemical, cultural, improve plant nutrition, encourage natural enemies
GS	Cultural (use of mulch to control attendant ants), chemical (stem banding using insecticide)
CLR	Chemical (copper-based), regulation of shade intensity, resistant varieties
CBD	Chemical (copper-based), resistant varieties

A change from high to mid altitude significantly increases the predicted odds for WCSB incidence (OR = 9.3). On average over the three altitude ranges, CT systems exhibit increased odds ratios of infestation. There are combined effects of the two predictors as indicated by the significant interaction term in Table 7. Fig. 7A shows an interaction plot of the predicted WCSB incidence by coffee production systems and altitude ranges. The effect of the CT system on the predicted probability of WCSB incidence is especially pronounced at high altitudes, while no significant effect of production system can be shown at mid altitude ranges.

Table 7: Quasi-binomial model results examining individual and interaction effects of altitude range and production system on WCSB incidence

	Coefficient	**Std. Error**	**Odds Ratio**
Low Altitude	0.499	1.233	1.65
Mid Altitude	2.234^{*}	1.121	9.33
CO	−1.253	1.703	0.29
CT	3.165^{***}	1.108	23.69
Low Altitude x CO	2.557	1.904	12.89
Mid Altitude x CO	0.442	1.861	1.56
Low Altitude x CT	−1.179	1.393	0.30
Mid Altitude x CT	-3.286^{**}	1.309	0.04
Constant	-2.639^{**}	0.999	0.07

*p<.1; **p< .05; ***p<.01. n = 35, Φ (estimated dispersion parameter) = 1.86, Likelihood ratio test: p < .001. Constant refers to the logit mean at high altitude and the CB system (reference level). The remaining coefficients are differences of the given level to the reference level (at logit scale). CB = Coffee-Banana system, CO = Coffee-Open canopy system, CT = Coffee-Tree system.

Table 8 shows the β coefficient and standard error of the negative binomial regression model examining the effect of the altitude range and production system on CBD intensity. The expected log count of berries fallen due to CBD is significantly increased in the CO system (β coefficient = 1.3). Fig. 7B shows the interaction plot of the predicted count of lost berries due to CBD by coffee production system and altitude range. The increasing effect of the CO systems is particularly pronounced at the high altitude range. The effect of the production systems at the high and highest altitude ranges shows similar tendencies.

Table 8: Negative-binomial model results examining individual and interaction effects of altitude range and production system on CBD intensity

	Coefficient	**Std. Error**
Mid Altitude	-0.514	0.479
Highest Altitude	-0.791	0.681
CO	1.289^{***}	0.465
CT	-0.109	0.474
Mid Altitude x CO	-1.659^{***}	0.642
Highest x CO	-0.264	0.826
Mid Altitude x CT	-1.072	0.667
Highest Altitude x CT	-0.314	0.972
Constant	-2.520^{***}	0.364

***p<.01. n = 21, Log Likelihood = -88.754, $\theta = 4.041^{***}$, (1.440) (dispersion parameter of the negative binomial family, std.error in parentheses), Akaike Inf. Crit. = 195.507, Likelihood ratio test: p < .001. Constant is the mean count at log scale at high altitude and CB system. CB = Coffee-Banana System, CO = Coffee-Open System, CT = Coffee-Tree System.

3.5 Discussion

The main purpose of the paper was to draw attention to FPK concerning CPaD and their management as well as the role of the inter-cropped bananas and shade trees. Contrasting FPK with existing scientific knowledge and field observations helps to identify gaps in knowledge and lack of information transfer. Our findings show that CPaD perceptions with respect to their distribution across altitudes and perceived importance are to some extent concordant among farmers, experts and field observations. However, discrepancies among farmers and experts regarding the development of CPaD issues over the previous years as well as CPaD management practices have been unveiled. Furthermore, field observations comparing CPaD in different environments and production systems have shown the role of shade trees to be ambiguous. In the following sections, the comparison between FPK, expert knowledge and field observations corresponding to the questions of interest (Table 3) are discussed with a

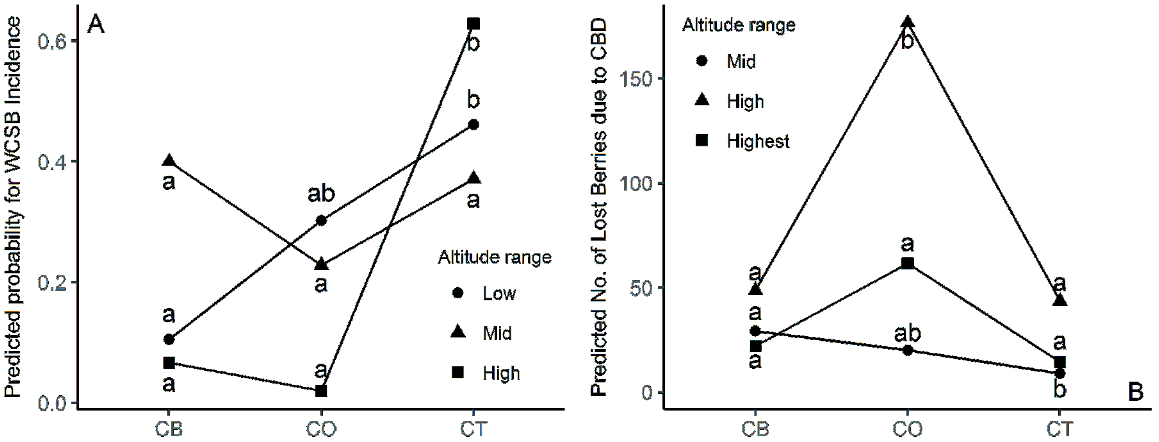

Figure 7: Interaction plots of the least-squares means (back-transformed by inverse-link function to original response scale) based on the fitted models. Effect of coffee production systems on (A) predicted probability of WCSB incidence and (B) predicted number of lost berries due to CBD at different altitude ranges. Production systems with the same letter do not differ significantly (Tukey-type comparisons of glm-parameters, $p < .05$, tested separately for each altitude range). An interaction is given if the difference between coffee systems of one altitude range differs significantly from the difference between coffee systems of another altitude range. CB = Coffee-Banana System, CO = Coffee-Open System, CT = Coffee-Tree System

focus on the two most important CPaD (WCSB and CBD). Identified knowledge gaps as well as challenges facing both, researchers and farmers are discussed in the context of a changing climate.

Occurrence, impact and development of coffee pests and diseases (Table 3, question 1-3)

Farmers perceived WCSB abundance to decrease from low to high altitudes. Similarly, the field sampling showed higher incidences at mid and low altitudes and lower incidence at high altitudes. In fact, WCSB infestation is reported to be an issue of lower altitudes where mild temperatures prevail (Hill (1983)). However, changes in climatic patterns resulted in the extension of coffee growing regions and hence a gradual spread of WCSB into higher elevations up to 1700 masl (Tapley (1960)). Climate trend analysis in Uganda has shown that over the past 25 years, rainfalls have decreased while temperatures have increased (Funk et al. (2012)). WCSB is a serious pest which has been estimated to cause yield losses up to 25 % in other countries such as Zimbabwe (Murphy et al. (2008)). According to farmers' and experts' perceptions as well as field observations, WCSB can be considered as the most serious pest in the Mount Elgon region. Additionally, WCSB infestation levels might aggravate under future climatic conditions. A recent study conducted by Kutywayo et al. (2013) in Zimbabwe estimated the impact of climate change on the potential distribution of WCSB and found that areas suitable for WCSB infestation may considerably increase in the future. Although farmers of our study did not perceive a change in the distribution or infestation levels of WCSB, its spread into higher altitudes was also shown in this study.

Almost a fifth of the farmers located at low altitudes have reported the presence of CBD, most probably due to misidentification or confusion with another disease showing similar symptoms. CBD is known to be particularly severe at high altitudes (> 1600 masl), where higher humidity and cooler temperatures prevail (Griffiths and Waller (1971)). In other African coffee production countries, CBD has been shown to cause yield losses up to 80 % (Wintgens et al. (2004)). Infection levels in the present study did not exceed 30 %. Nevertheless, CBD can be considered as the most severe disease of the higher altitudes of the Mount Elgon region. The field sampling has shown that CBD intensity was highest at altitudes between 1700–1900 masl. In recent years, farmers and experts did not perceive a change in CBD intensity. However, areas located at altitudes above 1900 masl currently providing suboptimal conditions for CBD might become more suitable under future climate conditions.

Coffee pest and disease management strategies and extension service (Table 3, questions 4-6)

The ability to properly identify CPaD, as well as some basic knowledge about pest and disease epidemiology are fundamental requirements to successfully control pests and diseases and increase productivity. This case study has shown that farmers' knowledge about diseases was generally less established than compared to insects, a common issue that has been found in other studies as well (Van Mele et al. (2001)). The consequence of this lack in understanding the differences between diseases and pests is the relatively high percentage of farmers, that erroneously treat fungal diseases with insecticides. The diversity of control strategies adopted by farmers is quite low. Common phytosanitary principles, for instance strip-picking at the end of the harvest season as an important measure to control CBB and CBD (Damon (2000); Rutherford and Phiri (2006)), are rarely followed. Non-conventional strategies which experts mentioned, such as stem-smoothing and stem-wrapping to suppress WCSB (Rutherford and Phiri (2006); Murphy et al. (2008)) are not known or applied by farmers. A recent study found a coffee variety (KP423) which showed resistance to WCSB, while traditional management practices, including stem-smoothing and stem-wrapping were claimed to be ineffective (Egonyu et al. (2015)). The commercial Arabica coffee varieties currently used are susceptible to CBD and CLR (Musoli et al. (1993)). Newly introduced varieties (Catimor NG9257, Elgon CB, Indian selections 5A and 6) which have been tested for CLR resistance in Uganda could be a potential option (Matovu et al. (2013)).

Whether farmers are not aware of existing control practices, or intentionally decide not to adopt them, has yet to be found out. In the presented case study, poor extension service as well as passive cooperatives most likely contribute to the poor information flow between producers and institutions where agricultural knowledge is generated. The fact that at higher located sub counties, a higher pesticide use, but also a generally better understanding of pest and disease biology was found, could be linked to the abundance and proximity to diverse coffee cooperatives, sellers, and an agricultural research and extension institute. It is possible that farmers of higher altitudes are putting a higher priority on coffee production as compared to low altitude. Due to advantageous environmental conditions, high altitude has a positive effect on coffee quality (Decazy et al. (2003); Avelino et al. (2005)). Farmers might obtain higher prices for their coffee, which enables them to invest more in their coffee production. Another driving factor for the high pesticide use could be the high yield loss farmers suffer at high altitudes due to CBD. A higher demand for agrochemical inputs in turn might increase the market for agrochemical suppliers and hence improve the accessibility to products.

Another consequence of the poor extension service is the role which pesticide sellers are assigned to. As the ones being present and accessible on the ground, they are often asked by farmers for advice, a situation which is well known in many developing countries (Heong and Escalada (1997)). A more objective training on pesticide use, promoting not only economic and environmental, but particularly human health benefits, would be preferable. The most frequently used product in this study was fenitrothion, an organophosphate unlicensed in the European Union (Yoshida et al. (1987); EU Pesticides database (2012)). Experts have explained that fenitrothion is not the best choice in terms of health risks, but that it is widely used in the region because of its affordability for resource poor farmers. It is all the more concerning that the majority of the interviewed farmers does not use protection equipment while handling pesticides. Therefore, extension workers have been instructed to discourage the use of fenitrothion and to replace it with less hazardous pesticides. Above all, farmers of the study region reported on fake agrochemical products on the market, causing financial losses and potential health risks (Fishel (2015)).

According to the experts, the lack of common guidelines and recommendations for pest and disease management adapted to a certain region and production system is a further problem. The fact that different institutions exist, each with their own findings and recommendations, causes confusion or even inconsistency among recommended management strategies. It was expressed that there is a need for a functional common platform that synchronizes and merges the information from different sources, develops communication and dissemination material and sends joint extension agents to communicate with farmers and vice versa. A recently launched initiative of the Ugandan coffee sector is a step forward towards the improvement of farmers' technical skills, including pests and diseases management. This cooperation between actors of the public and private coffee sector released comprehensive collection of training material to guide and improve extension work along the national coffee value chain (Café Africa (2014)).

The impact of the production system for coffee pests and diseases (Table 3, question 7)

Farmers and experts perceived the occurrence and impact of WCSB to be higher in CT systems. This agrees with the findings of our sampling as well as with other studies, where WCSB infestation grade was found to be higher in plantations under a high level of shade (Rutherford and Phiri (2006)). The mechanism of the effect of shade trees on WCSB still has to be investigated, however according to the experts and literature it is believed to be based on modifications of microclimatic factors, especially humidity, favouring the beetles' life cycle (Kutywayo et al. (2013); Jonsson et al. (2014)). A recent study conducted in the Mt Elgon region by Jonsson et al. (2014) found that the shading effect is especially pronounced at mid altitudes. In contrast, our results have shown that the conducive effect of shade on WCSB is notably pronounced at high altitudes. On the one hand, these different findings could be explained by the range of included altitudes. While Jonsson et al. (2014) examined a high altitude range of 1717–1840 masl, our study comprised altitudes between 1700–2200 masl. In the highest altitudes where low temperatures prevail, conditions turn unfavourable for WCSB populations. The buffering effect of shading, in particular increased minimum temperatures, could therefore play a significant role, making conditions for the establishment of WCSB favourable or even possible at all. On the other hand, the study areas were located on different slopes of Mt Elgon. The effect of varying rainfall patterns which has been shown to differ between north-eastern and south-western slopes (Hamilton and Perrott (1981)) could also explain the different results.

Regarding CBD intensity, farmers and experts perceptions, as well as field observations revealed that it is lower under shaded conditions (CT Systems). In fact, shade trees have been shown to help controlling CBD. Mouen Bedimo et al. (2008) suggested that shade trees intercept rainfall and therefore decrease the propagules' dispersion. The detailed mechanism still has to be confirmed. Other possible mechanisms could be microclimatic modification of the dew point or the reduction of fruit load under shaded compared to unshaded conditions.

Currently WCSB and CBD seem to be the most threatening biotic constraints for coffee production, not only in the Mt Elgon region, but also in other East African highlands (Murphy et al. (2008); Hindorf and Omondi (2011)). They are both under-researched organisms, where scientific knowledge about the life cycles or epidemiology, as well as knowledge about alternative hosts, natural control agents and the role of shade trees is scarce. Considering the assumption that climate change might cause a shift of suitable coffee growing areas into higher altitudes (Läderach et al. (2008, 2010); Davis et al. (2012)) the situation aggravates. CPaDs are likely to follow the migration of the host to expand their geographic range to the same future suitable coffee growing areas (Rosenzweig et al. (2001)). CBD is already a serious disease in the highlands and might migrate into even higher areas. WCSB is already showing the trend of expanding into higher altitudes (Kutywayo et al. (2013)). Since shaded coffee production systems are strongly considered as an option to adapt to climate change, more research is needed to pinpoint how shade trees influence the dynamics of CPaD. The topic of the sun-shade issue and its relation to different aspects of coffee production, including coffee health, has been subject of many studies (Beer et al. (1998); Muschler (2001); Vaast et al. (2006); DaMatta et al. (2007); Dossa et al. (2008); Bosselmann et al. (2009); Avelino et al. (2011); Teodoro et al. (2010); López-Bravo et al. (2012)). However, the topic remains controversial. Firstly, most studies describe average effects, while interactions between shading and environment, influencing CPaD jointly are almost never taken into account. Secondly, unexpected trade-offs between beneficial and detrimental shade effects might emerge. In the currently most suitable altitude range for Arabica production, WCSB and CBD have shown opposing relations to shade. While WCSB infestation was found to be favoured by shade, CBD intensity resulted to be lowered under shaded conditions. Here, estimating yield losses is the only way to assess production systems in terms of pest and disease regulation (Avelino et al. (2011)). These kind of trade-offs, as well as others related to other components and processes of the coffee production (eco)system have to be taken into account while suggesting sustainable solutions for pest and disease management and climate change adaptation strategies. In practical terms this means that the national coffee sector will need to design and adjust guidelines, recommendations and training material for extension workers and farmers to the variability of site-specific conditions.

3.6 Conclusions

In this case study it was shown that not only the insufficient information transfer within the researcher - extension agent - farmer relationship was responsible for existing knowledge gaps. Furthermore, other institutional and political issues at national level as well as a lack of information that still has to be generated concerning options to manage CPaD in different production situations was responsible for suboptimal management strategies. Gaps in knowledge about CPaD and management at present and in the context of a changing environment exist across different levels. At the farmer level, a basic understanding of CPaD and their identification, as well as existing control strategies are often not well known. A better information flow via extension work, trainings and workshops would assure that pre-existing and newly generated knowledge from science reaches the farmer. Vice versa, at the science level, awareness regarding what technologies are known and accepted by farmers is essential to find out why developed control strategies are not adopted.

A common knowledge gap from farmers to scientists was the role of the production system for CPaD. Further research on mechanisms between shade-trees and CPaD dynamics under varying environmental conditions and resulting trade-offs will be relevant for Uganda and other East African countries. National authorities of the coffee sector play an important role in assigning adequate importance to those issues by providing capacities and promoting relevant research programs. Because the majority of the total coffee export volume of Uganda is Robusta coffee, less research capacities of scientists and extension agents are invested in Arabica coffee. However a significant part of the export value is generated by the production of Arabica coffee. Since it is more sensitive to both, biotic and abiotic constraints, its economic importance for Uganda and the need to also prioritize national research on it becomes evident.

Finally, participatory and integrated pest management strategies have to be designed according to the spatial variability of agroecological conditions as well as rural infrastructures. The presented example of coffee production in Mt Elgon showed that more participatory approaches are needed in order to achieve sustainable agricultural development. Hereby, farmers as the initial and executive body within the coffee value chain have to be involved as an active contributor for the development, implementation and impact assessment of agricultural extension and research programmes.

4 Bioecology of the white coffee stem borer (*Monochamus leuconotus*) in Uganda

Theresa Liebig[1, 2, 3], Régis Babin[4, 5], Fabienne Ribeyre[5], Peter Läderach[1], Piet van Asten[2, 8], Laurence Jassogne[2], Hans-Michael Poehling[3], Christian Cilas[5] and Jacques Avelino[5,6,7]

[1]Climate Change, Agriculture, and Food Security (CCAFS), International Center for Tropical Agriculture (CIAT), AA 6713, Cali, Colombia
[2]Climate Change, Agriculture, and Food Security (CCAFS), International Center for Tropical Agriculture (IITA), Kampala, Uganda
[3]Institute of Horticultural Production Systems - Section Phytomedicine, Leibniz University of Hanover, Hanover, Germany
[4]International Centre of Insect Physiology and Ecology, Nairobi, Kenya
[5]CIRAD, UPR Bioagresseurs, F-34398 Montpellier, France
[6]Department of Research and Development, Tropical Agricultural Research and Higher Education Center (CATIE), Turrialba, Costa Rica
[7]Inter-American Institute for Cooperation on Agriculture (IICA), San José, Costa Rica
[8] Olam International Ltd., Kampala

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4.1 Abstract

The white coffee stem borer (WCSB) *Monochamus leuconotus* is a destructive pest of Arabica coffee in eastern and southern Africa. Documentation on outbreaks, spatio-temporal development and the relation to different environmental conditions and coffee production system is limited. To underpin effective control measures, we studied aspects of local and regional pest drivers in the Mt Elgon region, Uganda. At the local scale, we (i) characterized the temporal development of WCSB and explored associations to environmental and shade-related indicators. During two growing seasons and on 84 coffee plots, we recorded WCSB incidence/infestation and microclimate on an altitudinal gradient and different shading systems. The bimodal rainfall, altitude, and shade affected WCSB development through their effect on minimum temperature. At the landscape level, we (ii) analysed and mapped the spatial pattern of WCSB. Data on WCSB incidence were collected on 180 plots in one year. Pest incidence showed a spatial arrangement varying by districts. A relation to human movement and the landscape context contributing to pest spread are suggested. We verified that the shading effect found in the local context was also expressed at the broader scale. WCSB control measures should be synchronized with the bimodal rainfall patterns, and emphasis should be given to identify and limit pathways of pest spread from highly infested to new areas.

4.2 Introduction

Stem borers of the Cerambycidae family are severe pests of Arabica coffee (Waller et al. (2007), Egonyu et al. (2015)). They have become more important with the banning of dieldrin insecticide and poor management associated with low coffee prices (Waller et al. (2007)). Studies of the bioecology of the important coffee stem borer *Xylotrechus quadripes* in south-east Asia and India underpin recommendations of its sustainable management (Venkatesha and Dinesh (2012); Thapa and Lantinga (2016)). The white coffee stem borer (WCSB, *Monochamus leuconotus*) is similarly destructive on Arabica coffee in Africa (Waller et al. (2007); Jonsson et al. (2014)), but has received less attention. Up to 80% of coffee farms in eastern and southern Africa were infested and suffered crop damage (Kutywayo et al. (2013), Egonyu et al. (2015)).

Early instars of WCSB ring bark the plants, affecting the vascular transport system so that heavily-affected young trees may die (Schoeman et al. (1998); Vega et al. (2006); Rutherford and Phiri (2006)). Because the pest develops inside the trunk, it is difficult to control. There are few economically-effective chemicals, so that management is limited to laborious stem treatments such as manual removal (Vega et al. (2006); Egonyu et al. (2015)). More recently research has sought alternative such as plant resistance (Egonyu et al. (2015)), biological control (Karanja et al. (2010)), and pheromones for trapping systems (Murphy et al. (2008)), but these are in their early stages. Nevertheless, any control method requires understanding of the pests bioecology and its interrelations within the production agroecosystem.

There is some information on the life cycle of WCSB, and its reproductive and feeding behaviour from laboratory and field studies (Knight (1939); Tapley (1960); Gichuhi et al. (2016)). There are only limited data, however, on WCSBs spatiotemporal development, outbreaks, and their relation to environment and shade management. As other insect pests, WCSB is expected to expand its altitude and latitude limits in response to climate change as well as through changed development patterns and inter-generational timing (Porter et al. (1991); Kutywayo et al. (2013); Bjorkman and Niemela (2015)). WCSB responds to shade, with higher infestation in shaded compared to sun-exposed coffee. Depended on altitude, the shade effect is more pronounced at either low (Jonsson et al. (2014)) or high altitudes (Liebig et al. (2016)). The effect is hypothesised to be due to differences in microclimate. The interaction between shading and changed climate in the future is a trade-off in the broader context of adaptation to climate change. In coffee agroecosystems, shade is often seen as an option for an adaptation to future climates (Lin (2007)). It is therefore important to understand if and how shading and other environmental, agronomic and temporal aspects affect WCSB abundance.

We compared WCSB abundance along altitudinal gradients and coffee shading systems, varying in their shade tree diversity and quantity. On the one hand, we use a comparative approach on these gradients to better understand conflicting results of shade effects on pest ecology. Many studies of the past have shown contradictory results on shading effects on coffee pests and diseases because they were site-specific (Avelino et al. (2012); Allinne et al. (2016); Boudrot et al. (2016)). Focusing on a specific site makes decision-making and upscaling of management practices difficult, because the complexity of agroecological systems expands among spatial units (Kogan (1998)). On the other hand, the altitudinal gradient covers a range of environments and moreover allows us to estimate potential responses to climate change (Hodkinson (2005)).

At the local scale, we (i) characterized the temporal development of WCSB and explored associations to environmental (altitude) and shade-related indicators. We discussed the underlying ecological mechanism of shading effects emphasizing the role of microclimatic modifications. At the landscape level, we (ii) analysed and mapped the spatial pattern of WCSB to discuss further, spatially relevant factors related to pest abundance.

4.3 Material and methods

4.3.1 Study area

This study referred to the same area and farms as described in Sec. 2.2.1 and 2.2.2.

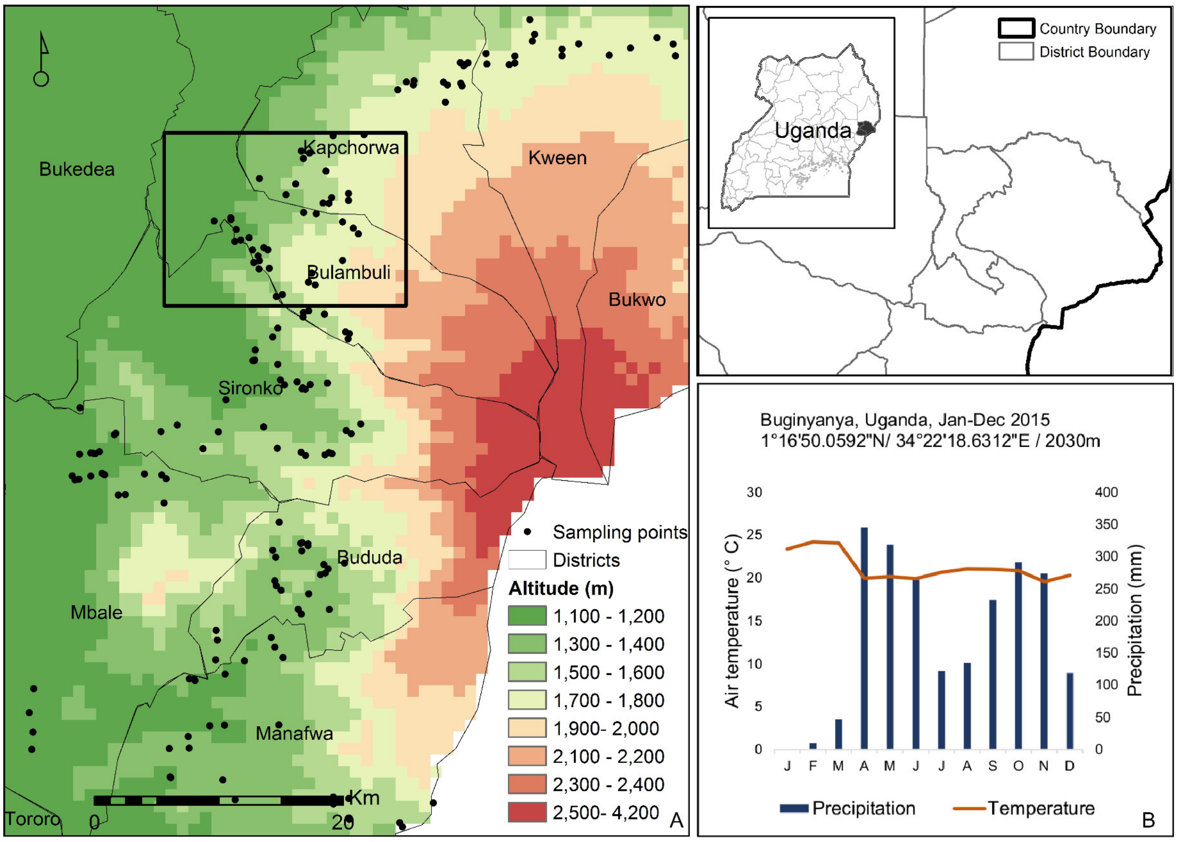

Figure 8: A) Location of the sampled plots within the study area. The squared area contains plots used for assessing the temporal development of WCSB and associations to altitude and shade-related indicators at plot scale (i). Spatial distribution of WCSB at landscape scale (ii) used all the sites shown. B) Monthly mean temperature (mean of daily dry bulb temperature) and accumulated precipitation from January–December 2015

4.3.2 Plot selection and characterization

We selected sites based on a survey made in 2014 (Liebig et al. (2016)). In summary, along the three altitude ranges we created typologies of shading systems using descriptors of the vegetation structure. Table 1 (Sec. 2.3) shows which shade-related descriptors we used and how we characterized them. We collected data from 35 plots in the 2014/2015 and 49 plots in 2015/2016 season to characterize the temporal development of WCSB and its association to altitude and shade-related indicators (i). Plot size ranged between 0.03 –0.5 ha. Farmers usually prune attacked stems during the dry season and stump plots that were heavily attacked. Stumping is a pruning technique leading to the removal of all the foliage by cutting the trunk at 30 cm from the ground. We discarded any plots that were completely stumped in the first season but conserved the ones which were sparingly pruned for the second season. We treated data for each year of the latter as independent (Avelino et al. (2006, 2007)), giving a total of 84 plots. We installed temperature data loggers (iButton DS1923) on a subset of 27 plots (three replicates for each shading system by three altitudes). We installed two screened loggers (Holden et al. (2013)) on each plot at the height of 1.50 m, and set them to record each hour during the 2015/2016 season.

For the spatial analysis (ii), we selected 180 plots (including the plots used for (i)) in the seven coffee-producing districts of Mt Elgon. We allocated each plot to one of the three shade systems and the appropriate altitude class (Table 13, supplementary material).

4.3.3 Data collection

Data on the temporal development of WCSB at plot scale (i) We collected data in two growing seasons from 2014/15 and 2015/16. Plots were heterogeneous in structure and size. Per plot we systematically selected 5–15 bushes representing the shading system of the whole plot. We avoided bushes that were too old (> 30 years) or too young (< 5 years) and those on plot borders to avoid boundary effects. We sampled a total of 767 coffee bushes in both years.

We examined all stems up to two meters above the collar level of each bush for WCSB infestation. Stem borer damage differs depending on the life stage of the insect (Fig. 25, supplementary material). New infestations, visible by the typical ringbarking phase, are characterized by frass (EIs) on the bark surrounding the entry hole. Older damage (barked areas and entry holes) has no frass, while exit holes, from which adults have emerged (EM), all are circular and larger than entry holes. The number of orthotropic stems per marked coffee bush was counted and damages were recorded for each stem.

We monitored four times in 2014/2015 (June, August, October, and December) and eight times in 2015/2016 (February, March/April, May/June, July, September, and November of 2015, and January and February of 2016). We derived two plot-based indices of pest infestation. WCSB incidence was the number of bushes showing any signs of infestation as a proportion of the total number of bushes sampled in each plot. The rate of new infestation was the difference between the number of new entry holes of two consecutive dates as a proportion of the total number of stems and sampled bushes per plot.

Data on the spatial distribution of WCSB at landscape scale (ii) We established transects of 15 coffee bushes, using the same criteria as described above, to score the presence of signs of WCSB. WCSB incidence (the number of bushes showing any signs of infestation as a proportion of the total number of bushes sampled in each plot) was calculated. We sampled in February –April 2016, corresponding to the activity peak of early-instar ringbarking (Fig. 25, supplementary material).

4.3.4 Data analysis

Data on the temporal development of WCSB and associations to altitude and shade-related indicators at plot scale (i) We analysed seasonal development of WCSB graphically, plotting the rate of new infestation against a sampling date. We analysed the effect of altitude and shading on WCSB incidence (maximum annual infestation value per plot) using a generalized linear model with a Poisson error structure. We tested model suitability and goodness of fit with the AIC and likelihood ratio test. We then used post-hoc pairwise comparisons on the interaction terms. We used a three-step procedure to analyse associations between the maximum WCSB incidence, the altitude, and the four descriptors of shading. Because relationships were not linear, we transformed each input variable using hierarchical clustering (Table 14, supplementary material). We then used multiple correspondence analysis as a precursor to profile clustering, using only the first dimensions to stabilize the clustering (Kristensen (2003); Husson et al. (2010)). We extracted monthly means of minimum and maximum temperatures from the hourly data and applied a linear mixed-effects model with the plot ID as the random factor. We assessed goodness of fit with AIC and R^2 for the mixed models.

Data on the spatial distribution of WCSB at landscape scale (ii) We analysed and mapped the spatial pattern of WCSB distribution in the whole Mt Elgon region in a two-step process. We first analysed the spatial autocorrelation among sites. We used semi-variograms to visualize the extent of spatial autocorrelation and how it behaved over distance. We then fitted an empirical variogram using least squares. Next, we modelled the spatial distribution of WCSB in relation to the altitude and geographical coordinates. We used a generalised additive model with a negative binominal error distribution to accommodate the non-linear relationships between the predictors and response variables (Hastie and Tibshirani (1990)). Incorporating the geographic coordinates enabled the model to account for spatial autocorrelation (Dormann et al. (2007); Miller (2010)) and to model WCSB distribution dependent on altitude for each level of the shade systems. We plotted the additive effects of altitude and shade on the predicted WCSB infestation with confidence intervals. We mapped the WCSB predictions for the entire region on a 1-km grid based on altitude and geographic location.

Softwares and packages We used R software (R Core Team , 2016) with RStudio (Version 0.99.903) and following packages for data analysis: ”FactorMineR” (Husson et al. (2016)), ”lsmeans” (Lenth et al. (2016)), ”lme4” (Bates et al. (2014)), ”spdep” (Bivand et al. (2016)), ”geoR” (Ribeiro et al. (2001)), ”mgcv” (Wood (2001)), ”ggplot2” (Wickham (2016)) and ”raster” (Hijmans and van Etten (2014)). We used ArcMap (ESRI, 2014) to produce the maps. We used the 90-meter resolution digital elevation model of the shuttle radar topography mission and the administrative borders from the Data.Ug database (http://maps.data.ug/).

4.4 Results

4.4.1 (i) Temporal development of white coffee stem borer and associations to altitude and shade-related indicators at plot scale

Temporal development of WCSB The temporal pattern of WCSB is shown in Fig. 9. In both seasons, the number of new entry holes increase with time, showing infestation peaks in the periods from December to February of both seasons, and from May of the second season (2015/16). The WCSB incidence was affected by the altitude range, coffee shading system and the interaction between the two predictors (Fig.10). Overall, the WCSB incidence was highest in CT systems, whereat this effect was expressed most at high altitudes (Table 15 of supplementary material).

Associations to altitude and shade-related indicators The multiple correspondence analysis showed a significant association between the used input variables. The leading six components, which explained 66.8 % of the variance, were subsequently used in an hierarchical classification (Fig.11). The two clusters with higher incidences (45 and 46 % of infested bushes on average, respectively) are related to high numbers of shade trees, tree species and canopy closure. The third cluster was from high altitudes. Cluster two with the second lowest mean WCSB incidence shows lowest values on the number of shade trees, the number of shade tree species and canopy closure. The cluster with the lowest WCSB incidences (15 %) had a high density of banana mats. Clusters three and five were, respectively, from high or low altitudes, but the other clusters covered the entire altitudinal range.

Canopy minimum air temperature showed a significant interaction between altitude, shade system and month ($p<.001$), while for the maximum temperature, only the main effects were significant ($p<.001$) (Fig. 12). At high altitudes and consistently over time, CT systems showed significantly higher minimum canopy air temperatures (least-squares mean = 14.7°C) than compared to the other systems (CB = 13.9°C and CO = 13.1°C). For the other altitudes,

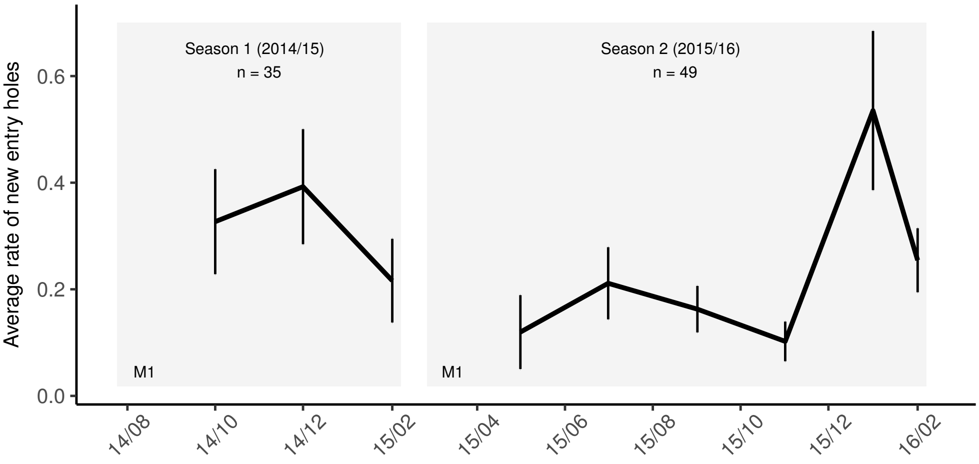

Figure 9: Seasonal development of WCSB. The rate of increase in the number of new entry holes. Means with standard errors starting from the second monitoring date are plotted. M1 refers to the first monitoring date of each season. The mean number of entry holes per plot (relative to the total number of stems/total of sampled bushes) of the first date was 0.85 for the 2014/15 and 0.83 for the 2015/16 season, respectively

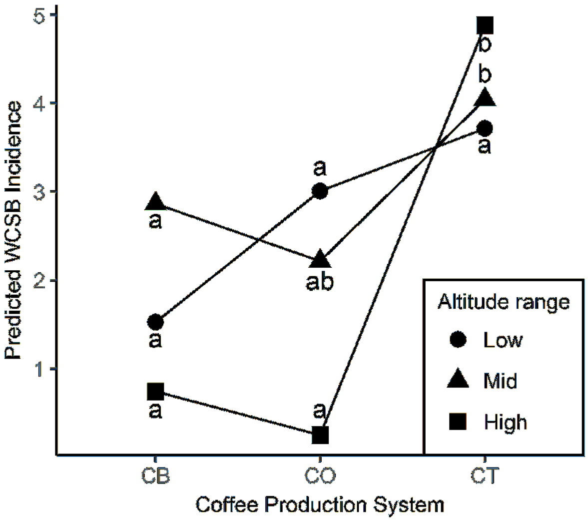

Figure 10: Interaction plot of the least-squares means of predicted probability of WCSB incidence (back-transformed by inverse-link function to the original response scale) based on the fitted GLM model by altitude category and coffee system. Differences between coffee systems are indicated by different letters (Tukey-type comparisons of GLM-parameters, p <.05, tested separately for each altitude category). CB = Coffee-Banana System, CO = Coffee-Open System, CT=Coffee-Tree System. The interaction was very highly significant (p < .001)

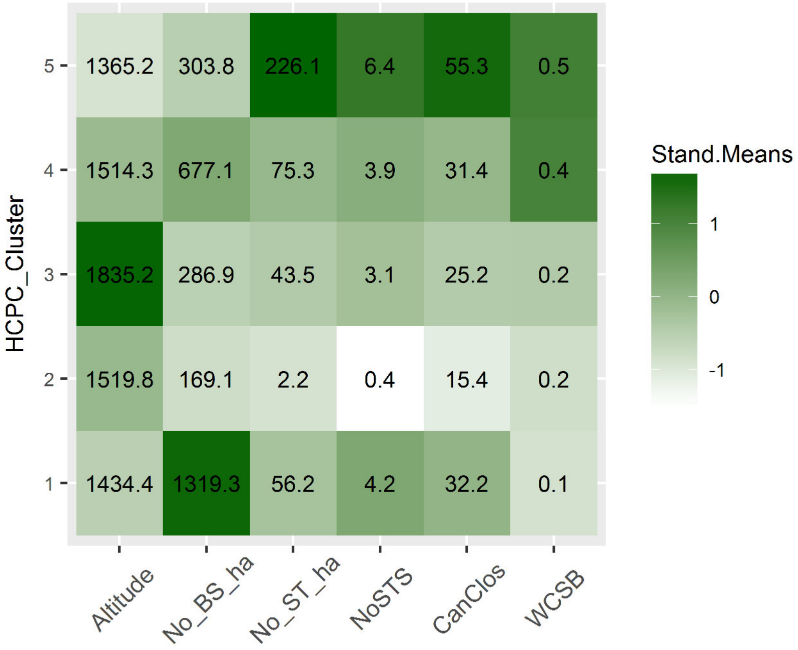

Figure 11: Clusters based on hierarchical classification (mean values within the squares). Shading represent the standardized means. WCSB = WCSB incidence (proportion of infested bushes), CanClos = Canopy closure (%), NoSTS = Shade tree diversity, No_ST_ha = Shade tree density (trees ha^-1), No_BS_ha = Banana density (mats ha^-1)

differences between systems were less pronounced, but more between months. CO systems had the highest maximum canopy air temperatures at all altitudes. (Table 16, supplementary material).

4.4.2 (ii) Spatial distribution of white coffee stem borer at landscape scale

Analysis of spatial autocorrelation There were high incidences of WCSB in the districts of Kapchorwa and Bulambuli, and lower incidences around Kween and Bududa (Fig. 13A), with significant spatial autocorrelation (Moran I coefficient, $p < .05$). The semi-variogram (Fig. 13B) shows nugget effect between degree and range of the spatial autocorrelation, indicating that the spatial structure only explained part of the variability in WCSB incidence. Spatial autocorrelation decreased with distance and reached plateau at approx. 25 –30 km.

Influence of altitude and geographical coordinates on distribution of WCSB Generalized additive models were used to describe the effect of altitude, the geographical location and the coffee shading system on WCSB incidence. The model showed a significant effect of both predictors, altitude and geographical location on WCSB incidence (Table 9). Fig. 14 shows the response curve for WCSB in dependence of altitude for each level of the coffee shading system. There are no differences in WCSB response in the different systems

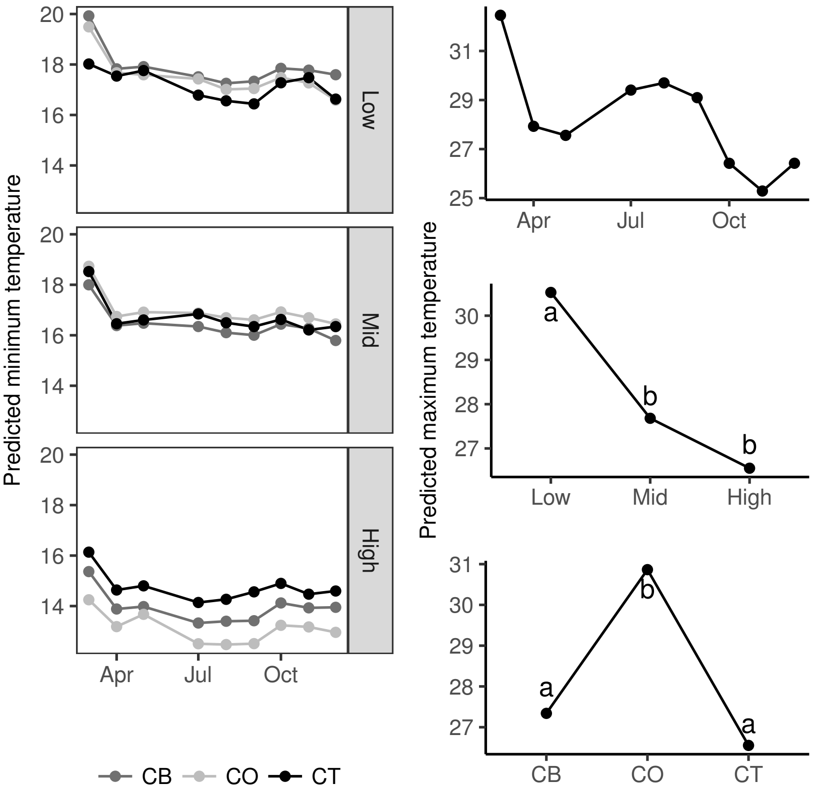

Figure 12: Minimum canopy air temperature (left) showing the second-order interaction between altitude, coffee system and month. CB = Coffee-Banana System, CO = Coffee-Open System, CT=Coffee-Tree System. (p<.001) (Table 17, supplementary material). Maximum canopy air temperature (right) showing the main effects of month of the year, altitude and shade system (p<.001). Differences between altitudes and coffee systems are indicated by different letters (Tukey-type comparisons of GLMM-parameters, p <.05)

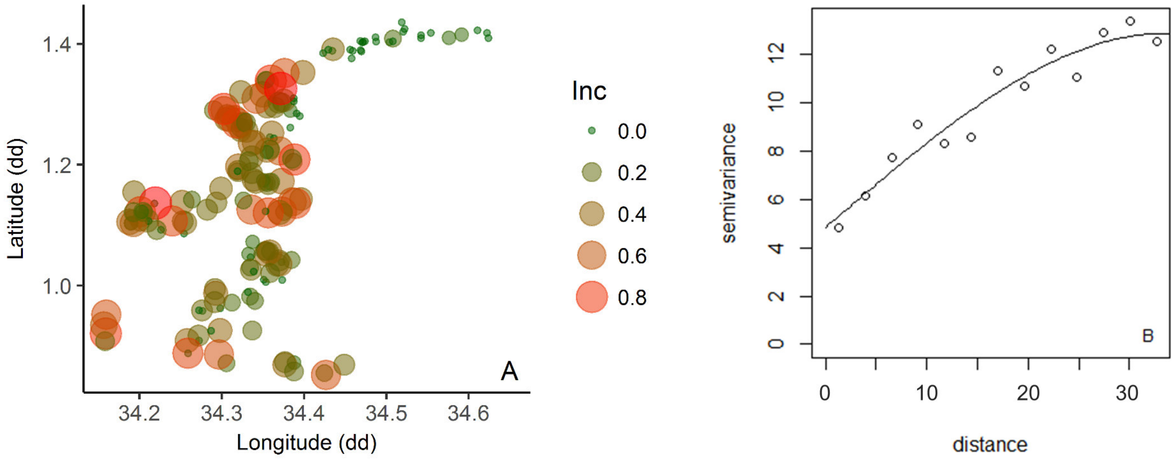

Figure 13: (A) WCSB incidence according to geographic location. (B) Spatial dependency of WCSB incidence. Semi-variance is the mean square deviation, which is plotted against the distance between points

Table 9: Results of generalized additive model showing approximate significance of smooth terms [1]

	edf	Ref.df	Chi.sq	p-value
s(altitude) x CB	3.451	4.269	10.747	0.039474 *
s(altitude) x CO	3.538	4.383	8.962	0.074417 .
s(altitude) x CT	2.318	2.823	5.302	0.099687 .
s(Lat,Long)	9.898	13.203	36.033	0.000721 ***
R-sq.(adj) = 0.305	Deviance explained = 42.3%			n = 179

[1] s()= coefficients for smooth/spline terms. edf = estimated degrees of freedom

below an altitude of around 1700 masl, however above this altitude, the model estimated a slightly higher WCSB response in CT systems, while no differences were estimated for the other systems.

Maps based on the models of altitude and geographic location show that highest infestations are predicted in altitudes below 2000 masl (Fig. 15). We predict high risk in the districts of Kapchorwa and Bulambuli as well as the lowlands of Mbale and Manafwa, and lower risk in Bududa and Kween

4.5 Discussion

We showed that the development of the white coffee stem borer is controlled by the bimodal rainfall, and by altitude and shade through their effect on minimum temperature. Pest incidence showed a spatial arrangement varying according to the districts. A relation to human movement and the landscape context contributing to pest spread are suggested.

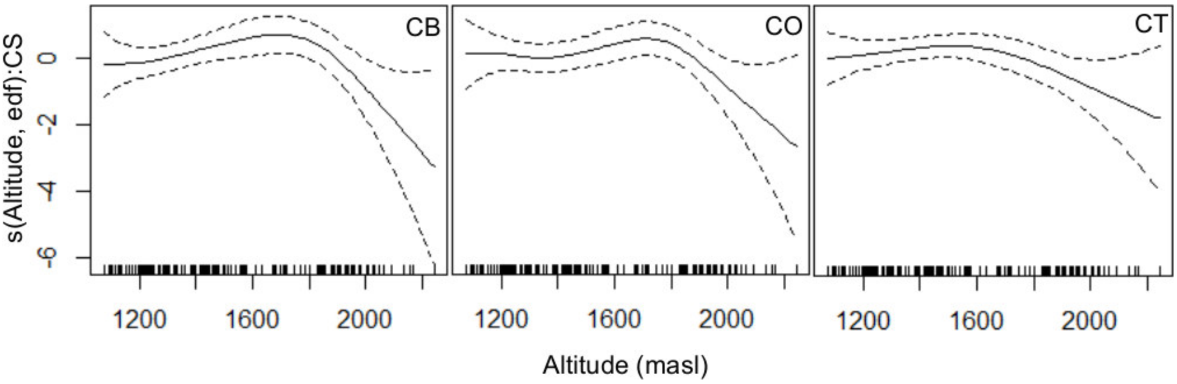

Figure 14: Output of the fitted generalized additive model showing the smooth effect of altitude. Hatch marks on the x-axis indicate the distribution of variable values, dashed lines are the confidence intervals. The y-axis shows the additive effect on the log scale, and for each panel is standardized to a mean value of zero

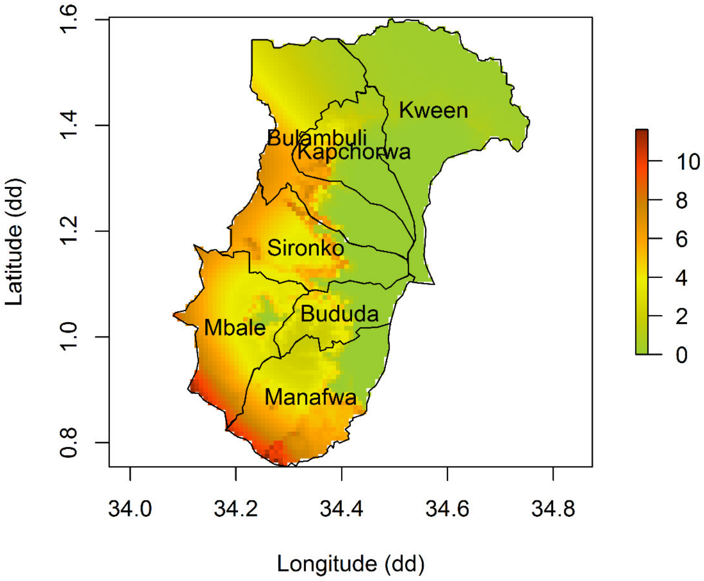

Figure 15: Predicted number of infested coffee bushes per plot (back-transformed data) by geographic location

(i) Temporal development of WCSB and associations to altitude and shade-related indicators at plot scale

Temporal development of WCSB WCSB phenology and its link to the bimodal rainfall pattern agree with former studies (Knight (1939); Tapley (1960)).The peaks can be attributed to the phenological stages where new entry holes were bored (Fig. 25, supplementary material). There were more attacks in the short rains (October/November, 2015/16) than in the long rains (March/April, 2015/16). Growers implement control measures during the post-harvest (dry) season that reduce residual infestation to low levels. Higher infestation at the start of the short rains in October might result from less time spent on pest management during the harvest season (Table 18, supplementary material). Moreover, the duration of the WCSB life cycle varies with latitude and altitude (Waller et al. (2007)), enabling the pest to coordinate its life cycle with conducive environmental conditions (Gichuhi et al. (2016)). Identifying that WCSB adults emerge in synchrony with the rainfall patterns suggests that control measures might be focused at the start of the two rainy seasons. Control options that aim to prevent oviposition such as smoothing the stem bark (the females lay eggs under the bark scales), wrapping, or insecticide banding (De Villiers (1973); Egonyu et al. (2015)) should be synchronised with bimodal rainfall pattern. Once the larvae have penetrated the bark, preventative control options are inefficient. Inadequate timing might be a reason why those methods have remained inconclusive (Murphy et al. (2008); Egonyu et al. (2015)).

Associations between WCSB, altitude and shade-related indicators WCSB infestation is highest in coffee systems with high shade tree density and diversity (Murphy et al. (2008); Jonsson et al. (2014); Liebig et al. (2016)). Poikilotherms depend on ambient temperatures (Bale et al. (2002)), therefore the modification of thermal environment by shade is a possible mechanism. Altitude drives WCSB populations (Waller et al. (2007)), but is only decisive in connection with other factors of the agroecosystem. The interactive effect of altitude and the coffee system on minimum temperatures might be key for WCSB at high altitudes. Where mean atmospheric temperatures are too low (the optimum is 25 °C, (Schoeman et al. (1998); Gichuhi et al. (2016)), increased minimum temperatures in shaded systems (CT) appear to enable WCSB establishment. This could be important for WCSB adults during the reproductive and oviposition phases as well as early larval stages. At lower altitudes with favourable mean atmospheric conditions, minimum temperatures are not a limiting factor. Accordingly, differences in WCSB infestation and minimum temperature between systems are negligible. White coffee stem borer probably prefers shaded habitats to allow it more flexibility to regulate its body temperature. Interactions between the macroclimate and abiotic or biotic factors create a complex thermal landscape. The resulting local microclimate is heterogeneous in space and time, and has a decisive effect on the bioecology of insects (Hodkinson (2005); Sears et al. (2011)). In mountain habitats, the ecological importance of microclimates is more important than habitats at lower altitudes. The variability in radiation, atmospheric pressure and interactions with local factors create habitats for insects, regardless of the mean air temperature (Hodkinson (2005); Mani (2013)).

There are other shading mechanisms possible, such as light level. Females seem to prefer darkness for oviposition, although WCSB is not generally attracted by light (Knight (1939); Schoeman et al. (1998); Gichuhi et al. (2016)). Shade trees are unlikely alternative hosts for WCSB, since only some wild Rubiaceae species are known to host it (Dufpy et al. (1957)).

Management is another possible driving factor for the pest. We found lower infestation in systems shaded by bananas, where coffee is better managed than in the other systems. The intercropped system receives more attention, and women are involved in the process, increasing the labour input. Moreover, bananas are sold, which enables farmers to invest more in agronomic inputs (Van Asten et al. (2011); Jassogne et al. (2013)).

(ii) Spatial distribution of WCSB at landscape scale

Spatial heterogeneity also determines variation in WCSB infestation, indicated by both the spatial autocorrelation and the incidence map, which shows different aggregations at the district level. The effect of altitude is inconsistent. All plots in the Kween district (above 1800 masl), had low infestation as expected (Hill (1983)), but plots in the neighbouring Kapchorwa district at high altitude had high infestation. The area around Bududa and northern Manafwa, at low and mid altitudes had low WCSB infestation. Although altitude does affect WCSB, there must be other factors involved. One potential factor may be the surrounding landscape from which, depending on the species, pests may spill over across both habitats and managed agricultural systems (Tscharntke et al. (2005), Werling and Gratton (2010)). The amount of surrounding land covered by coffee is likely to be important, as it is for other coffee pests (Avelino et al. (2012); Banks et al. (2014)). The flight capacity of WCSB is only up to one mile (Tapley (1960)). It might therefore benefit from connected coffee growing areas because the chances for migration into new coffee fields are increased (Avelino et al. (2012)). Moreover, Kween is relatively new to coffee production, has fewer coffee plots and less infestation than the older district Kapchorwa. Coffee was established in Kapchorwa many decades ago and WCSB infestations are widespread. There is spatial autocorrelation up to 25 –30 km, which might indicate human intervention. Many of the farmers in this study use pruned coffee wood for firewood and construction (Table 4, supplementary material). Any trade in the wood risks spreading pests or diseases to other farms and regions as for WCSB in Malawi and Zimbabwe (Murphy et al. (2008)) and coffee diseases, such as coffee wilt disease (*Gibberella xylarioides*) (Baffes (2006); Belachew (2016)).

4.6 Conclusions

Ecologically relevant microenvironments have been understudied and its relevance understated (Potter et al. (2013); Sunday et al. (2014); Stigter (2015)). The impact of spatial variability and interactions with the local environment on pests and diseases is essential for understanding agricultural systems and the development of IPM strategies (Dormann et al. (2007); Sciarretta and Trematerra (2014)). This is especially relevant for the analysis of potential future climate effects on pest dynamic in tropical mountain areas. GIS techniques to visualize the spatial distribution of pests are useful tools for the implementation of extension services and studies on pest ecology (Nansen et al. (2003); Gonzalez-Redin et al. (2016)). Incorporating cropping system effects in modelling tools to evaluate pest performance in a certain system is a need for future modelling efforts (Colbach (2010); Cerda et al. (2017)). Predicting pest response with globally interpolated climatic data might therefore fail to correctly predict future pest performance (Faye et al. (2014); Rebaudo et al. (2016)).

Based on our findings in this study, we recommend: (i) At the local scale, preventive control actions should be synchronised with the onsets of the rains during the flight periods of adults. During the entire growing season, infested plants should be traced and if necessary eradicated. Infested plant material should not be used for construction or for sale. (ii) At the regional scale, the movement of coffee wood (e.g. selling for firewood or construction) should be strictly controlled to avoid dispersal of WSCB to new areas. Extension agents should emphasize to growers the pathways of pest spread between coffee-growing areas, to limit dispersal from highly-infested to new areas.

5 Direct, indirect and interactive effects in coffee agroecosystems: A case study on the role of microenvironments on Coffee Leaf Rust

Theresa Liebig[1, 2, 3], Fabienne Ribeyre[5], Peter Läderach[1], Piet van Asten[2, 7], Laurence Jassogne[2], Hans-Michael Poehling[3], Jacques Avelino[4,5,6]

[1]Climate Change, Agriculture, and Food Security (CCAFS), International Center for Tropical Agriculture (CIAT), AA 6713, Cali, Colombia
[2]Climate Change, Agriculture, and Food Security (CCAFS), International Center for Tropical Agriculture (IITA), Kampala, Uganda
[3]Institute of Horticultural Production Systems - Section Phytomedicine, Leibniz University of Hanover, Hanover, Germany
[4]CIRAD, UPR Bioagresseurs, F-34398 Montpellier, France
[5]Department of Research and Development, Tropical Agricultural Research and Higher Education Center (CATIE), Turrialba, Costa Rica
[6]Inter-American Institute for Cooperation on Agriculture (IICA), San José, Costa Rica
[7] Olam International Ltd., Kampala

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5.1 Abstract

Shade effects on coffee pests and diseases are ambiguous because they vary depending on the biophysical environment. Using the case study of Coffee Leaf Rust (CLR, *Hemileia vastatrix*) on Arabica coffee we demonstrate relationships between the environment (represented by altitude) and production systems and their effects on disease intensity. In Mt Elgon, Uganda, we (i) identified microclimatic indicators explaining CLR variability and characterized their spatiotemporal variations. We (ii) integrated effects between the environment, production systems, microclimate and CLR into a conceptual framework and formulated a piecewise structural equation model to understand directional relationships. During one growing season, we sampled CLR incidence and microclimate on plots (n = 49) assigned to different production systems and distributed along an altitudinal gradient (1000–2200 masl). We show how altitude and production system affect CLR development through their effect on key microclimatic indicators (diurnal temperature range (DTR), dew point temperature (DP), i.a.). These varied as a function of the environment, production system and season. In systems with high shade density and diversity, humidity related indicators decreased with altitude. These differences were most pronounced during the rainy seasons. DTR was consistently higher in sun exposed systems and increased with altitude. At low altitudes where differences in microclimatic variables between systems were small, differences in CLR incidence were marginal. At mid and high altitudes, highest CLR incidence occurred in the production system showing low DTR and high DP. We conclude that the effects of the environment and production system on CLR abundance are spatio-temporally variable and either direct, interactively or indirectly mediated by the microclimate.

5.2 Introduction

Coffee–agroecosystems are interaction networks consisting of anthropogenic, topographic, meteorological, edaphic and biological components, which vary in space and time (Wagenet (1998); Corwin (2013)). The performance of the coffee system with respect to different ecosystem services is a function of complex space and time-dependent interactions, which can emerge as trade-offs or synergies (Cerda et al. (2017)). Therefore, pest and disease management strategies rely on understanding the complexity of the agroecosystems (Avelino et al. (2006, 2007); Willocquet et al. (2008); Allinne et al. (2016)).

The performance of coffee (e.g. productivity (Beer et al. (1998); DaMatta (2004); Vaast et al. (2006)), quality (Muschler (2001); Bosselmann et al. (2009), biodiversity (Perfecto et al. (2004); Teodoro et al. (2010)), sustainability (Beer et al. (1998); Jha et al. (2011, 2014)) under shaded vs. sun-exposed conditions has been explored in numerous studies. Beneficial shading effects on coffee production through the mitigation of microclimatic extremes have been quantified and are generally well-established (Barradas and Fanjul (1986); Lin (2007); Siles et al. (2010a)). It has also been acknowledged that the extent to which shaded systems are advantageous depends on the biophysical context (Muschler (2001); Oberthür et al. (2011); Cerda et al. (2017)). Since shading effects vary across sites, its impacts on coffee pests and diseases are ambiguous (Schroth et al. (2000); Staver et al. (2001); Soto-Pinto et al. (2002); Avelino et al. (2004, 2006, 2011); López-Bravo et al. (2012); Jonsson et al. (2014)). Few studies were conducted across different temporal and spatial scales or focused on the effect of multiple factors and response variables. With the availability of both spatial data and more sophisticated statistical tools to evaluate networks of causal relationships (Grace (2006); Lefcheck (2016)), recent research addresses the complexity of agroecosystems (Liere et al. (2012); Boreux et al. (2013); Allinne et al. (2016)).

Shading modifies the environment for pests and diseases directly or indirectly via changes in the microclimate, or by creating habitats for beneficial or competitive organisms (Soto-Pinto et al. (2002); Avelino et al. (2004); Pumariño et al. (2015)). Likewise, shade modifies the environment for many other components of the system, e.g. coffee physiology and productivity, soil, water, as well as biodiversity, which in turn may also be related amongst themselves and with pests and diseases (Muschler (2004)). Moreover, these ecological mechanisms of shade are altered by greater spatial factors, such as macroclimatic variations along altitudinal or latitudinal gradients (Staver et al. (2001); Avelino et al. (2011); Cerda et al. (2017)).

The case of Coffee Leaf Rust (CLR, *Hemileia vastatrix*) illustrates how shade can operate in two antithetic pathways: (i) Shade may aggravate the disease due to modifying the microclimate to conditions more favourable for the fungus. ii) Simultaneously, shade may also regulate yield, which in turn could negatively affect the pathogen because attack intensities are more acute when fruit load is high (Avelino et al. (2004, 2006)). CLR has caused tremendous damage for the Arabica coffee sector of the Americas over the past few years (Avelino et al. (2015); Mccook and Vandermeer (2015)). The combination of suboptimal management and meteorological factors were responsible for the heavy outbreaks and this is expected to play a role under future climate conditions (Avelino et al. (2015)). In Africa, CLR is the most devastating disease of Arabica coffee after Coffee Berry Disease (*Colletotrichum kahawae*) (Matovu et al. (2013)). In Uganda, the impact of CLR became apparent in the 1940s when areas of land typically producing Arabica, had to be replaced with Robusta coffee (Musoli et al. (1993); McCook (2006)).

In this study, we infer direct, indirect and interactive effects of the altitude and coffee production system on microclimatic indicators and CLR. We (i) identified microclimatic indicators explaining CLR variability and characterized their spatiotemporal variations. We then (ii) integrated effects between the environment, production systems, microclimate and CLR into a conceptual and statistical framework to understand directional relationships.

5.3 Material and Methods

5.3.1 Study area

This study referred to the same area and farms as described in Sec. 2.2.1 and 2.2.2. The traditional varieties (SL 14, SL 28 and Nyasaland) are highly susceptible to CLR (Musoli2001, Matovu2013).

5.3.2 Plot selection and characterization

We selected sites based on a survey made in 2014 (Liebig et al. (2016)). In summary, along the three altitude ranges we created typologies of shading systems using descriptors of the vegetation structure. Table 1 (Sec. 2.3) shows which shade-related descriptors we used and how we characterized them. Based on those typologies, a total of 49 plots (0.03–0.5 ha) were used for the present study.

5.3.3 Data collection

On each plot, we systematically selected nine coffee bushes on a cross-shaped transect representing the production system of the whole plot. We avoided exhausted, too old (> 30 years) or too young (< 5 years) bushes and those on plot borders to avoid boundary effects. On each coffee bush, six branches in the lower, mid and higher vegetation storey (two per storey) and facing towards different directions were marked. CLR was assessed in approximately six-week intervals from the beginning (March) until the end (December) of the 2015 growing season (seven monitoring dates in total). We installed temperature and relative humidity data loggers (iButtonDS1923) on a subset of 27 plots (three replicates for each system by three altitudes). We installed two screened loggers (Holden et al. (2013)) on each plot at the height of 1.50 m, and set them to record each hour during the 2015/2016 season.

Explanatory and response variables Explanatory variables included the altitude range (representing a set of topographical indicators), and coffee production system. Microclimatic variables served as both response variables as a function of the altitude range and coffee production system, as well as explanatory variables for CLR. Microclimatic variables explaining CLR variability were generated and selected in two steps. First, literature was reviewed to identify microclimatic variables driving CLR epidemics (Table 10). Identified variables (or a related variable if the measurement was not available) were derived from our microclimate recordings, totalling nine microclimatic variables (Table 10). Second, to select time periods for each variable, four-week time intervals for each monitoring date were extracted. The final number of potential CLR driving microclimatic variables totalled 63 (nine variables times seven monitoring dates). CLR incidence, i.e. the number of diseased leaves as a proportion of the total number of healthy leaves, determined by the short internode resulting from the dry season, (Avelino et al. (1991)) per bush was the response variable. Explanatory and response variables are summarized in (Table 11).

5.3.4 Data analysis

(i) Identification of microclimatic indicators and characterization of spatiotemporal variations of microclimate and CLR We identified microclimatic variables and corresponding 4-week time intervals by plotting them against CLR incidence (CLR_{max}). We excluded highly autocorrelated predictors by estimating the correlation coefficients matrix.

The maximum CLR incidence (CLR_{max}) and the selected microclimatic variables were plotted per altitude range and coffee production system to illustrate the spatiotemporal variations. Differences among the altitude and production system gradients, were tested with the method described in the following paragraph.

(ii) Formulation of a piecewise structural equation model (SEM) Based on literature and field observations, we developed a priori conceptual model of the possible underlying relationships between components of the environment, coffee production system, microclimate, coffee productivity and coffee pests and diseases (Fig. 16). Table 11 shows which variables were considered and how they were used in the subsequent analysis.

We used a piecewise structural equation model (SEM) to infer direct and indirect effects of topography and coffee production system on CLR_{max} via microclimatic indicators. SEM is a statistical framework used to understand causalities within complex natural systems (Grace (2006); Shipley (2016)). The hypothetical causal relationships are represented in a graphical model, where each path describes directional relationships between variables. We used piecewise SEM enabling generalized linear models to be fit to different distributions, including those typical for pest and disease data. Individual paths are estimated separately and then combined to a series of equations to estimate direct and indirect effects within the system. (Lefcheck (2016)).

The piecewiseSEM was constructed based on the conceptual model in Fig. 16 and the results of the selection procedure of potential microclimatic variables. First, each response variable (the microclimatic variables and CLR), representing the component models or paths, were fitted as linear or generalized linear models in dependence on individual or combined predictors. For each path, the best model was selected by Akaike information criterion (AIC). Then, the individual models were combined to a list of equations and applied to the piecewise SEM function. Non-significant paths ($p > .05$) were excluded from the overall model. The Shipley's test of d-separation was used to test whether significant paths were missing. The Fisher's C statistic evaluated the overall fit of the piecewise SEM.

Softwares and packages We used R software (R Core Team , 2016) with RStudio (Version 0.99.903) and following packages for data analysis: lsmeans (Lenth et al. (2016)), lme4 (Bates

Table 10: Literature review on microclimatic variables driving CLR epidemics1)

Microclimatic drivers of CLR	**Reference**	**Description**	**Derived variables for selection procedure 2)**
Temperature (Mean, maximum or minimum)	Nutman & Roberts (1963) Rayner (1961) De Jong (1987)	Bimodal relation to spore germination / appressorium formation. Optimum range: 21–25° C. De Jong (1987) reported 16–28°C. Appressorium formation is stimulated by low temperatures	(1) Mean daily, (2) mean nightly[3], (3) maximum, (4) minimum temperature,
Diurnal temperature range (DTR)	López-Bravo et al. (2012) Avelino et al. (2015)	Lower DTR favors CLR infection and reduces the latent period of infection	(5) DTR
Light	Nutman & Roberts (1963) Rayner (1961) Bock (1962)	Light has a retarding but not inhibiting effect on spore germination, which is favored by darkness, but also occurs by day	-
Humidity (RH) and rainfall	Nutman & Roberts (1963) Rayner (1961) Bock (1962) Kushalappa et al. (1983)	The presence and duration of liquid water is essential for germination and infection. Rainfall plays a role in wetting the undersurface of leaves and in spore dispersal	(6) RH, (7) Dew Point (DP), (8) Number of hours with temperatures < DP at night[3,4], (9) Number of hours with RH >95% at night[3,4]
Leaf Wetness	Avelino et al. (2004) López-Bravo et al. (2012) Bebber et al. (2016)	Higher leaf wetness frequency / duration favours CLR intensity	

1) Based on Avelino et al. (2004). 2) For each monitoring date, the mean of the 4-weeks interval (counting backwards from the monitoring date) was extracted. Given a latent period of approximately three weeks (Leguizamon et al. (1985))) and incubation period of four to seven weeks (Rayner (1961)), the four-week interval was considered as reasonable. 3) In East Africa, infection processes occur between 10 p.m. and 8 a.m. (Rayner (1961)), therefore some variables representing the night time hours were extracted. 4) Based on an empirical model (Rowlandson et al. (2015)), leaf wetness duration is equal to the number of hours in which the RH (measured 1.5–2.0 m above the ground) is equal or greater than 90 %

Table 11: Recorded, explanatory and response variables

Available / recorded variables	**Explanatory / response Variables**		**Description**
Topoclimate[1] : Altitude (masl) Slope (°) Slope aspect (°)	Explanatory	Altitude class (Alt.)	Key variables of climate and topography were subjected to a cluster analysis. The determinant variable was altitude, with the remaining variables being correlated. Low: 1100–1400 masl Mid: 1400–1700 masl High: 1700–2200 masl
Vegetation structure: No. of shade trees / ha, No. of shade tree species, No. of banana mats / ha, Canopy Closure (%)	Explanatory	Typology of coffee production system (CS)	CB = Coffee-banana system CO = Coffee-Open canopy system CT = Coffee-Tree system CO system shows lowest, and the CT system highest shade levels.
Microclimate: Temperature (° C), Relative humidity (%)	Explanatry/ Response		Microclimatic indicators [2]
Disease indicator: CLR	Response	Maximum CLR incidence (%) (CLR_{max})[3]	The maximum disease incidence (mean per plot) per season. Monitoring dates: (1) March/April, (2) May/June, (3) July/August, (4) September, (5) October / November (6) January (7) February

1) Topographic variables (altitude, slope and slope aspect) of the study area were generated from a digital elevation model (90m DEM) of the shuttle radar topography mission. 2)Microclimatic indicators resulting from the selection procedure described in the subsequent data analysis section. 3) The maximum incidence of the season was reported to be a good indicator of epidemic intensity (Kushalappa et al. (1980); Silva-Acuña and Zambolim (1999); Avelino et al. (2006))

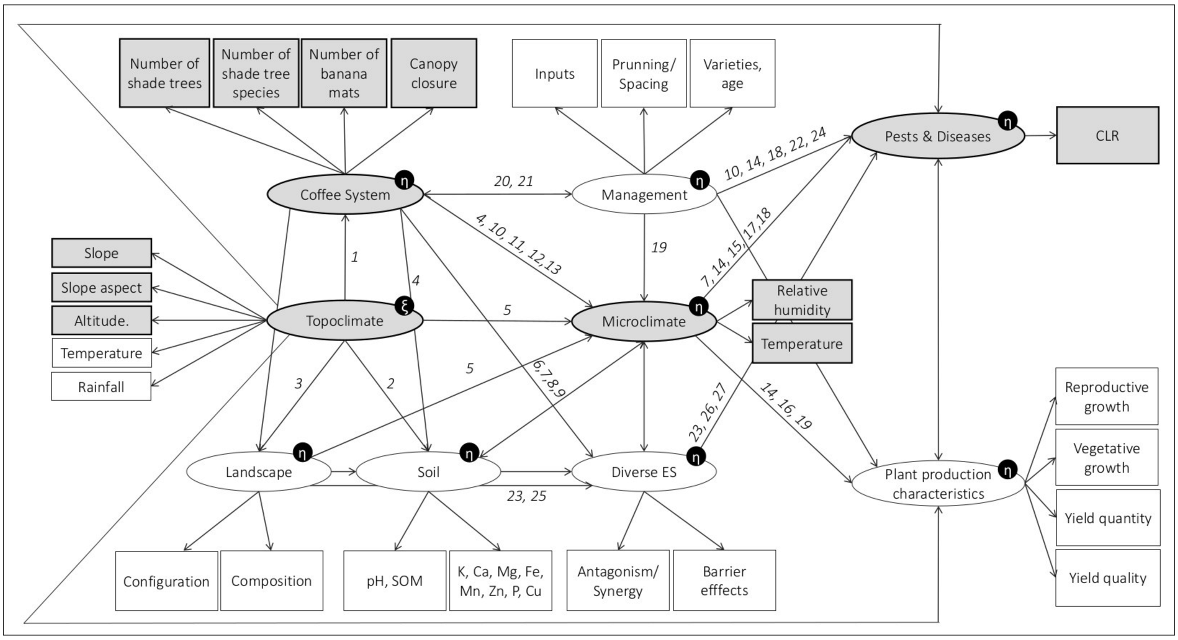

Figure 16: A priori conceptual model of the possible underlying relationships between components of the environment, coffee production system, microclimatic indicators, coffee productivity and coffee pests and diseases. Ovals represent latent constructs (unobserved variables), and boxes manifest (observed) variables. Exogenous constructs (independent variables) are indicated by ξ, and endogenous (dependent variables) by η. Numbers 1–27 refer to literature references (Fig. 19, supplementary material). Arrows indicate the directional relationships between latent constructs, representing individual paths to be modelled in the piecewiseSEM approach. Grey shaded fields show the variables used in the subsequent piecewiseSEM. The indicated sub-system shows the relation between topoclimate and coffee system, both characterized by a set of observed variables, modifying the environment for CPaD either directly and/or indirectly via microclimate

et al. (2014)), ggplot2 (Wickham (2016)) and piecewiseSEM (Lefcheck (2016)) and corrplot (Wei (2013)). We used ArcMap (ESRI, 2014) to produce the maps. We used the 90-m resolution digital elevation model of the shuttle radar topography mission and the administrative borders from the Data.Ug database (http://maps.data.ug/).

5.4 Results

5.4.1 (i) Identification of microclimatic indicators and characterization of spatiotemporal variations of microclimate and CLR

Microclimatic variables and time periods related to CLR$_{max}$ are shown in Table 12. Results of the selection process are shown in detail in Fig.26 and 27 of the supplementary material.

Fig. 17 shows the seasonal patterns of selected microclimatic indicators grouped by altitude range and coffee system. The mean night time temperature (TempN) differed between the three coffee systems in the period between May and September. It was lowest in CT

Table 12: Selected microclimatic variables

Selected microclimatic variables [1]	**Selected time periods** [2]
Night temperature (TempN) [3]	July–Sept.[5]
Dew point temperature (DP) [4]	May–Nov.
Number of night hours with RH >95 % (RH95)[3]	Sept.–Nov.
Diurnal temperature range (DTR) [4]	Sept.–Nov.

1) Variable selection based on literature review (Table 19). 2) Remaining variables and time periods excluding highly correlated predictors. 3) Means per night. 4) Means per day (24 h), 5) Time periods within a variable of microclimate were autocorrelated and hence were combined to one variable for the piecewiseSEM (e.g. dew point temperature of the four time periods were used as the mean dew point temperature for the period between May–November)

at low, in CB at mid, and in CO systems at high altitudes. The diurnal temperature range (DTR) was higher in CO systems in all altitudes, but less pronounced in the low altitude range. The dew point temperature (DP) at low altitude was constantly lower in CO systems over the season. At mid altitude, the mean DP over the season was lower in CT systems, while differences were marginal at high altitudes. The number of night hours with relative humidity > 95 % (RH95) in CO systems was lowest at low altitude and highest at high altitudes, while at mid altitudes it was highest in CB systems.

Fig. 18 shows the CLR disease process of the 2015 / 2016 growing season as a sigmoid-shaped growing curve typical for a polycyclic epidemic. At low and mid altitudes, symptoms appeared approximately two months after the rainy season (June/July), when newly grown leaves were fully developed. An exponential increase in CLR incidence followed across the short dry spell around August/September and the second rain flush in October/November, peaking in the main dry season during December until February. The amount of disease at low and mid altitudes was similarly high, while incidence was lower at high altitudes, where CLR developed after the second rainy season. CLR incidence in the different systems did not differ at low altitudes. At mid and high altitudes, there was a downward gradient of disease incidence from CB to CO and CT systems.

5.4.2 (ii) Formulation of a piecewise structural equation model

The piecewiseSEM was fitted to infer the effects of the selected microclimatic variables, the altitude class and coffee system on the maximum CLR incidence. Each component model, corresponding to the five response variables (the four selected microclimatic variables (Table 12) and CLR_{max}) represented one path. Two (DP (May–Nov.), DTR (Sept.–Oct.) of the four response functions for the microclimatic variables were significant paths ($p<.05$). Finally,

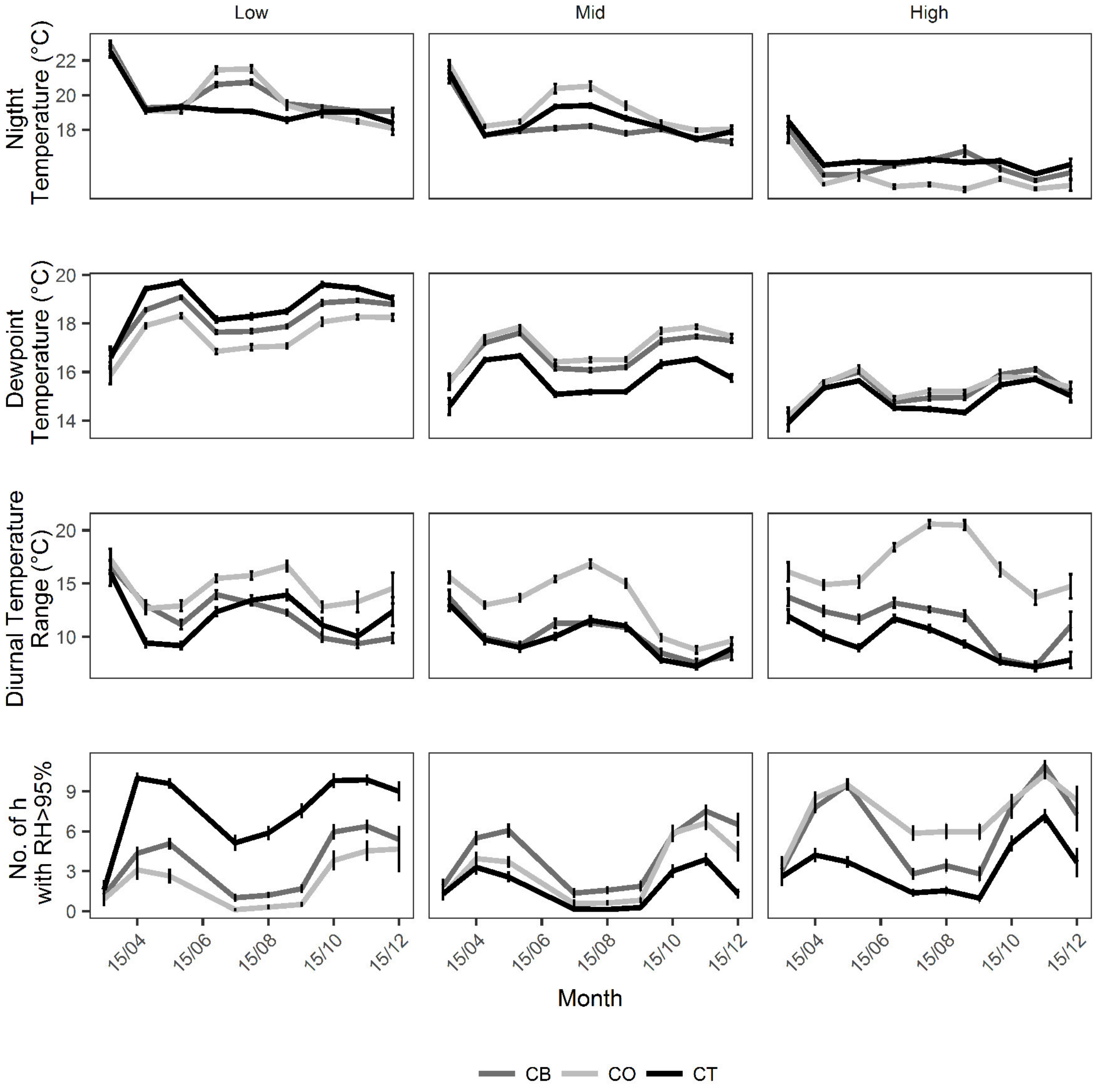

Figure 17: Microclimatic indicators over the 2015 / 2016 growing season. Variables represent monthly means with standard errors. CB = Coffee-Banana system, CO = Coffee-Open canopy system, CT = Coffee-Tree system. Altitude ranges were low (1100–1400 masl), mid (1400–1700 masl) and high (1700–2200 masl). Loggers with missing data were excluded

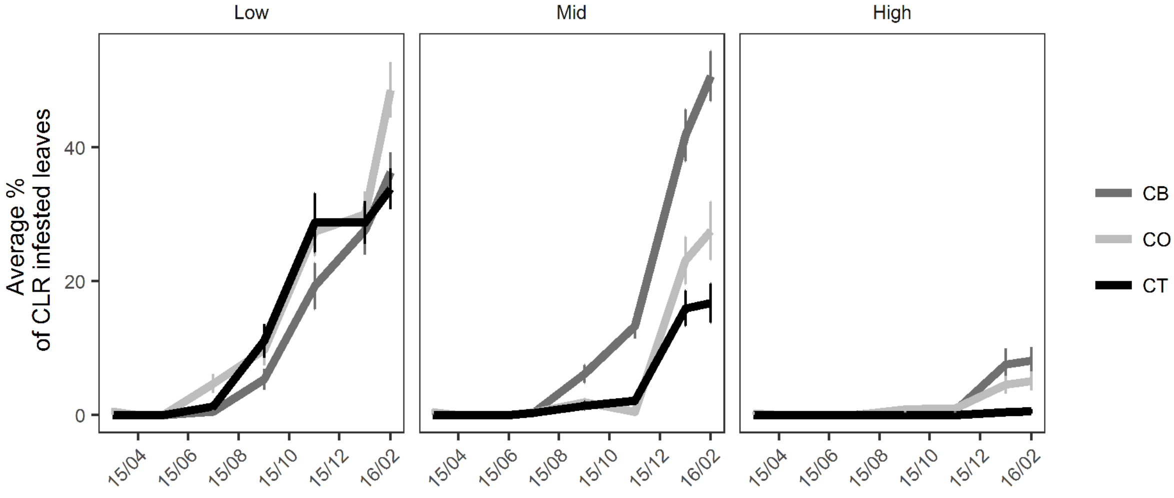

Figure 18: CLR disease process curves of the 2015 / 2016 growing season. The curves represent the average CLR incidence per monitoring date (n = 49), grouped by altitude range and coffee production system. CB = Coffee-Banana system, CO = Coffee-Open canopy system, CT = Coffee-Tree system. Altitude ranges were low (1100–1400 masl), mid (1400–1700 masl) and high (1700–2200 masl)

the list of component models consisted of three equations:

$$\text{(1) CLR}_{max} \sim \text{Alt\_cat x CS} + \text{DP}_{MN} + \text{DTR}_{SO},$$
$$\text{(2) DP}_{MN} \sim \text{Alt\_cat x CS},$$
$$\text{(3) DTR}_{SO} \sim \text{Alt\_cat} + \text{CS}$$

Where CLR$_{max}$ is the maximum disease incidence, Alt_cat the altitude category, CS the coffee production system, DP$_{MN}$ the average dew point temperature of May-Nov and DTR$_{SO}$ the average diurnal temperature range of Sept–Oct. CLR$_{max}$ was fitted as a generalized linear model with a negative binominal distribution, and DP$_{MN}$ and DTR$_{SO}$ as linear models.

The piecewiseSEM ($p > .05$, Fishers C, AIC = 59.01) showed interactive, direct and indirect effects of the altitude classes and coffee systems on CLR$_{max}$ (Fig. 22). CLR$_{max}$ was predicted to be lower in CT systems, (β = - 3.00156, $p < .0001$), but was also determined by an interacting effect of altitude and system. Highest CLR$_{max}$ were predicted in CO systems at low altitude, but in CB systems at mid and high altitudes. DP$_{MN}$ was higher at low and mid, compared to high altitudes ($\beta = 3.1892$, $p < .0001$, $\beta = 1.4821$, $p < .0001$, respectively) and there was a combined effect of altitudes and systems with lowest values in CO systems at low, and in CT systems at mid altitudes ($\beta = 0.6929$, $p < .05$ and $\beta = -0.6220$, $p < .05$). DTR$_{SO}$ was highest in CO systems ($\beta = 3.4354$, $p < .0001$) and lowest at mid altitudes ($\beta = -1.5199$, $p < .05$). The Model showed indirect effects of altitude and coffee systems on CLR$_{max}$, mediated by the microclimatic variables. DTR$_{SO}$ was negatively ($\beta = -0.2731$, $p < .0001$) and DP$_{MN}$ positively ($\beta = 1.5577$, $p < .001$) related to CLR$_{max}$.

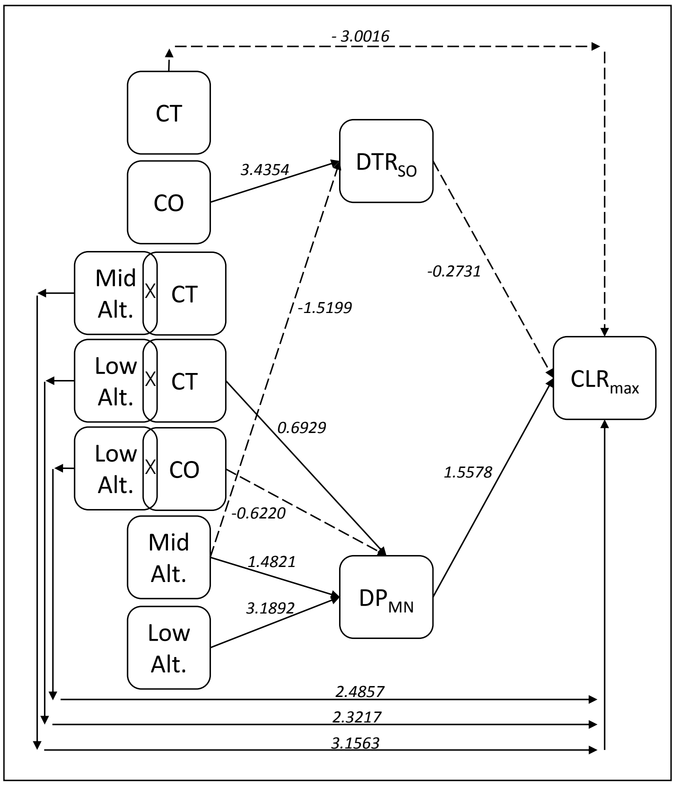

Figure 19: Final path model selected through the piecewise SEM procedure. Solid arrows show positive, dashed arrows negative paths. The standardized coefficient for each path from the individual models are illustrated. Reference categories (not shown) for the coffee production system and altitude range are CB and high altitude. Crosses indicate an interacting effect of two categories. Shipley's test of d-separation was used to estimate the overall fit of the model (χ^2 test on the Fisher's C statistic results in p > .05 if no paths are missing). CT = Coffee-Tree system, CO = Coffee-Open system, Alt. = Altitude range; low (1100–1400 masl), mid (1400–1700 masl), DTR_{SO} = Diurnal Temperature Range (September–October 2015), DP_{MN} = Average Dew Point temperature (May–November 2015), CLR_{max} = the maximum disease incidence

5.5 Discussion and Conclusions

We have shown that the effects of the environment (altitude) and coffee production system (shading) on CLR variability are either direct, interactive or indirectly mediated by key microclimatic indicators. Our case study on CLR illustrates an approach also applicable to other (patho)- systems to describe interactions in agroecosystems.

Literature on microclimatic drivers shows that among others, CLR development is depended on variables related to the presence of liquid water and temperature (Nutman and Roberts (1961); Rayner (1961); Kushalappa and Eskes (1989); De Jong et al. (1987); Avelino et al. (2004); López-Bravo et al. (2012)). The microclimatic indicators we identified as CLR drivers (DP and RH95) relate to dew formation. We also found temperature related variables, especially the DTR, to be decisive for CLR. A lower mean DTR results in shorter latency periods because the temperature is closer to its optimum for infection processes (Rayner (1961); Waller (1982); De Jong et al. (1987); López-Bravo et al. (2012); Avelino et al. (2012)). Night temperatures also affect CLR epidemics. Since germination is favoured by darkness (Nutman and Roberts (1961); Bock (1962)), most infections occur at night if night temperatures are high enough (Rayner (1961)).

It is well established which main factors drive CLR epidemics. However, few studies have investigated how those microclimatic drivers themselves vary in space and time and how this in turn would be related to CLR. We showed that microclimatic indicators varied as a function of the season, altitude and the coffee production system. At higher altitudes, humidity indicators decreased in the systems with highest shade (CT) compared to the lowest shade density and diversity (CB and CO). This contradicts the widely-accepted notion of higher moisture and leaf wetness in shaded versus non-shaded systems (Barradas and Fanjul (1986); Beer et al. (1998); Morais et al. (2006). The consistently highest DTR values of CO systems agreed with reports of existing literature (Barradas and Fanjul (1986); Beer et al. (1998); Morais et al. (2006); Lin (2007)). However, while differences at low altitudes were negligible, they strongly increased with altitude.

The variability of microclimatic variables across altitudinal gradients, production systems and seasons can be explained by processes of surface energy fluxes (Shuttleworth (2012)). Dew formation is driven by the interplay between air moisture, temperature variations and cooling of plant surfaces via radiation (Xiao et al. (2013)). This in turn is influenced by cloudiness, wind speed, soil water content and water vapour pressure and hence by altitude and vegetation cover (Linacre (1982); Dai et al. (1999); Pounds et al. (1999); chao Liu et al. (2006); Zhou et al. (2007); Chen et al. (2013)). Diurnal fluctuations are extreme at high altitudes and under sun-exposed conditions. The reduced atmospheric pressure causes higher maximum and lower minimum temperatures due to rapid insolation and reduced radiation (Linacre (1982); Mani (2013)). Clouds as well as shade tree cover buffer these effects, which on the one hand results in a lower DTR in shaded systems (Dai et al. (1999)), but also reduced night-time radiation (Morais et al. (2006)), and hence less dew formation. In contrast, reduced minimum or night temperatures in unshaded systems increase the nocturnal soil emissivity and hence, dew formation. Those dynamics are furthermore altered by the seasons. Changes in solar radiation, precipitation and cloudiness imply a seasonality in surface energy fluxes and hence microclimate (Dai et al. (1999); Xiao et al. (2013)). Our data also show these seasonal effects. DTR was lowest and DP / RH95 was highest during the rainy seasons (Apr./May and Oct./Nov.), when cloud cover was high.

Differences in microclimatic conditions driven by the environmental and seasonal context influence CLR dynamics. Highest CLR incidence was found at mid altitudes and in CB systems, where DTR was low and DP high. The same reasoning applies for high altitudes, although disease incidence was low due to low mean temperatures. At low altitudes, differences between systems in both microclimatic variability and CLR incidence were minor. Our results agree with findings of other studies, where CLR was reduced at high altitudes in highly diversified systems (Avelino et al. (2006); Cerda et al. (2017)). CLR development was also related to the seasonal changes of microclimate. The microclimate differed between altitude ranges and systems during the rainy seasons. In the first season, this may be less important because leaves that are not fully developed are resistant to infection (Eskes (1982)). In addition, fruit loads, positively related to CLR severity (Avelino et al. (2006)) are low during this time. Leaf susceptibility grows with fruit growth (Kushalappa et al. (1980)), therefore microclimatic conditions during the second rainy season might be decisive. In coffee growing regions with a pronounced dry season such as in our study area, the residual inoculum is minimized by the shedding of diseased leaves and lack of new infections (Bock (1962)). However, in areas without a clear dry season, microclimatic conditions might influence the inter-seasonal survival of rust spores and disease built-up in the subsequent season (Waller (1982)).

The mediated effects of the environment and coffee production system through the local microclimate on CLR are fundamental. They co-occur however, as shown in our conceptual model, with a diversity of other influencing factors. Though not addressed in the present study, they are conceptually incorporated within the piecewiseSEM. The altitude range and the production system are latent constructs, therefore their direct and interacting effects must be mediated through further mechanisms and variables one way or the other.

Our results validate approaches of other studies that showed how production situations (the ecological, technical, social, economic context of agricultural systems (Rabbinge and De Wit (1989)) and crop management are linked to crop health and that they can be considered as proxies for microclimate (Avelino et al. (2004); Savary et al. (2016)). This is not only important for pests and diseases in coffee-based, but also other tropical agroecosystems that form heterogeneous mosaics of small thermal microhabitats (Dangles et al. (2008); Potter et al. (2013); Charbonnier et al. (2014)). The impact of microenvironment on crop health are understudied and their ecological relevance understated (Hodkinson (2005); Faye et al.

(2014); Stigter (2015); Pincebourde and Suppo (2016)). This is especially relevant in the context of adaptation to climate change (Stigter and Ofori (2014a,b,c)).

6 General Discussion

The purpose of the study was to shed light on the complexity of shade effects on three economically important Coffee Pests and Diseases (CPaD), namely Coffee Leaf Rust (CLR), White Coffee Stem Borer (WCSB) and Coffee Berry Disease (CBD) under different environmental conditions. In the long run, a better understanding of the interplay of intrinsic pest and host plant characteristics with an emphasis on the role of microclimatic factors will help to improve the development of CPaD control strategies which sustainably mitigate potential losses, and thereby, improve production system resilience.

This thesis aimed at contributing to this purpose by approaching the issue in an integral manner. To understand the broader context of a system, spatial and temporal as well as socio-economic factors were taken into consideration . The idea to address this complexity using gradients of environmental, production systemic or socio-economic nature, was motivated by conclusions repeated in many studies on the balance of shade effects on coffee sustainability: Shade effects are site-specific, they are dependent on a specific production situation, characterized by the set of environmental, agronomic, socio-economic (including cultural and political) conditions, and are therefore not consistent across scales. Consequently, recommendations on shade management cannot be generalized but must be adapted to local conditions. There is a high diversity of production situations where coffee is grown, and with the example of Mt Elgon, this study gives insight into one out of many coffee growing regions.

In the following, the key findings and conclusions are briefly presented once again by referring back to the research questions posed in the introduction (Sec. 1.2.4 and Fig. 2). In addition, limitations and assumptions, as well as applications and implications of the study are discussed.

6.1 The importance of participatory approaches for agricultural research in smallholder farming systems in the tropics

The diversity of existing coffee production systems along an altitudinal gradient was categorized into three distinct systems, namely a sparsely shaded open canopy coffee system (CO), a coffee system with high banana densities (CB) and a highly tree shaded coffee system (CT) (Chap. 2). The current state of knowledge of producers, experts and science on CPaD and its management showed, that perceptions with respect to CPaD distribution across altitudes and perceived importance are to some extent concordant among farmers and experts. They agreed on WCSB, CBD and CLR to be the major threats to coffee plant health in the region. On the one hand, this information was used to prioritize the CPaD surveys for the subsequent objectives (Chap. 4 and 5). On the other hand, gaps in knowledge and information flow were identified as causes for constraints that farmers and experts face related to CPaD. Many farmers either did not adopt available control strategies or lacked a comprehensive understanding about pest and disease epidemiology. This showed that ultimately, it is institutional obstacles (the improvement of national extension services, pro-actively acting cooperatives, access to quality (non-fake) products, access to markets) that must be overcome to improve plant health management. The use of information, recommendations and inputs for coffee crop management, often based on scientific work, is limited if it is not available for the producers. But even if knowledge and technologies are available to farmers, the usual one-way information flow from scientists to farmers should be improved. Instead of presuming ignorance from farmers' side, the technology or agricultural practice itself should be questioned, and failures communicated back to extension and science (Chambers (1990)). Clearly, those higher-level, institutional, political and paradigm issues must be addressed first, before agricultural technologies can succeed. Content-wise, this might seem far off the scientific questions posed in this thesis. However it is part of the system and ultimately relates to the overall but central objective of many projects related to the sustainable intensification of agricultural production systems, i.e. the improvement of production system resilience and farmers livelihoods.

Agricultural scientists often view their research discipline through a very narrow window, neglecting the fact that many internal linkages exist within the agroecosystems systems of resource-poor farmers (Pimbert (1994)). In recent years however, there has been a growing number of research projects striving for the implementation of more system oriented approaches. In the presented PhD project, specific questions around the role of shade trees and its effects on three major CPaD were addressed. Those results will feed into the framework of the overall project ("Trade-offs and synergies in climate change adaptation and mitigation in coffee and cocoa systems"), where different aspects of coffee production are analysed to adapt vulnerable coffee systems to climate change and to improve farmer income and system resilience. By including the perspective of producers, socio-economic aspects as part of the system were taken into debate. Like this, other issues and gaps, also important to recognize were identified, and could help to prioritize future studies or interventions that are better directed to the needs of a region and its farmer communities. The chapter concludes by emphasizing that more participatory approaches should be applied in research programs aiming at sustainable agricultural development.

6.2 Microenvironments as a key role in agroecosystem and its importance for climate change

As farmers remarked, CPaD abundance varies dependent on the biophysical and production system context. Finding out how CPaD abundance is related to the production situation at different scales, as well as to discuss underlying ecological mechanisms was the objective of Chap. 4 and 5. Aspects of the production situation referred to the coffee production system, representing a set of indicators related to the vegetation structure of the system, as well as the altitude range, representing a set of topographic and climatic factors. The environmental gradients and longitudinal data collection allowed to consider spatial and temporal scales.

The central ecological mechanism of shading focused on was the modification of microclimate and its potential effects on CPaD.

For WCSB, the potential role of minimum temperatures, modified by the interactions between environmental and production system factors was discussed. Especially at high altitudes, where minimum temperatures were buffered by the vegetation cover, it was suggested to be decisive because pest habitats could establish regardless of the mean atmospheric environmental conditions (Hodkinson (2005); Mani (2013)).

Also for CLR it was shown that the effects of the environment and production system on CLR abundance are spatio-temporally variable and either direct, interactively or indirectly mediated by the microclimate. We highlighted how the identified key microclimatic indicators (diurnal temperature range (DTR), dew point temperature (DP) i.a.) varied in function of the environmental and seasonal context, and how this in turn affected CLR abundance.

In a nutshell, the role of microclimatic effects on both studied organisms can be captured in a central statement of this thesis: The significance of microenvironments for the ecology of the regarded CPaD is crucial and therefore, generalized assumptions of shade effects on CLR and WCSB do not hold, not only, but also because of the described spatiotemporal variations in microclimate. This has implications for both, research and practice:

From a scientific point of view, it has been recognized that the impact of microenvironments on small organisms, although of enormous importance, is understudied (Stigter (2008); Sears et al. (2011); Mani (2013); Potter et al. (2013); Faye et al. (2014); Stigter (2015); Pincebourde and Suppo (2016), i.a.), and that there is no common approach to predict patterns of microclimatic diversity (Woods et al. (2015)). This of course is not only important for research in coffee-based, but also other, especially tropical agroforestry systems and landscapes, where traditional systems form a heterogeneous mosaic of small microhabitats (Dangles et al. (2008); Potter et al. (2013); Charbonnier et al. (2014)). Without doubt, and to link it with the main purpose of this and numerous other research initiatives: The importance of microhabitats and its modifications are absolutely central in the context of adaptation to a changing climate (Stigter and Ofori (2014a,b,c)), which (i.a.) will be complicated by the impacts of pest and diseases (Verchot et al. (2007); Syampungani et al. (2010); Schoeneberger et al. (2012), i.a.). Consequently, microclimate changes must be considered in research questions, hypothesis and approaches around climate change adaptation and mitigation, especially if they are of predictive nature.

However, precisely this is often neglected in modelling climate change impacts on pests and diseases (Potter et al. (2013); Faye et al. (2014); Stigter (2015); Woods et al. (2015); Pincebourde and Suppo (2016)). In recent times, more and more scientists claim that there are equivocations about the extent of physical climate change effects on organisms, e.g. about how species ranges will be shifted (Buckley and Kingsolver (2012a)), and that those equivocations or uncertainties will remain central obstacles in predicting when and to which extent it will happen (Woods et al. (2015)). Because those uncertainties are also reasoned by the fact that actual responses of organisms experienced at the local scale are less predictable by global, coarse-scale climatic data, recent research efforts emphasized the relevance of fine-scale climatic data to model responses at a scale that actually reflects the climatic reality of species (Potter et al. (2013); Faye et al. (2014); Pincebourde and Suppo (2016)).

Uncertainties about the predictability of species responses to climate change were the reason why no CPaD response under future climate conditions was predicted in this study. The research questions and the sampling design (across the altitudinal gradient) were conceived to discuss the results particularly with a view on climate change. One of the original objectives was to model WCSB distribution in different shading systems and under future climate conditions. Because of the following reasons, this objective was abandoned / modified.

The two main approaches to model species risk or distribution, referred to as inductive or deductive, were revised. Inductive or correlative models infer a species response from the climatic conditions of the known distribution. They work with presence / absence data as input variables, resulting in an output describing the probability of presence or absence of a species at a certain location. Deductive or mechanistic models use detailed knowledge from the laboratory, e.g. life table data, to infer the relationship between a specific climatic factor (e.g. temperature) and a specific species response (e.g. number of generations per year) (Venette et al. (2010); Eyre et al. (2012)).

An inductive approach such as MAXENT (Phillips et al. (2006)) was ruled out because of following reasons: 1) WCSB is established in virtually all Arabica growing areas of Africa, therefore knowing how probable it is that WCSB appears is irrelevant (see Fig.20). Instead, it is relevant to know about a potential change in infestation degree (e.g. alteration in the number of generations per year due to changes in temperature). 2) The climatic data used to model future scenarios are based on broad-scaled general circulation models, resulting in the same problem of "broad-scaled climatic data vs. experienced fine-scaled microenvironment" described above. 3) Inductive models are increasingly criticised because of their simplicity and high degree of uncertainty (Venette et al. (2010); Buckley and Kingsolver (2012b)).

The use of a mechanistic model was considered as more useful. Models like CLIMEX (Sutherst et al. (2007)) or ILCYM (Tonnang et al. (2013)) incorporate components to model phenologies and are powerful tools for pest and disease risk analysis. However, life table data of different constant temperatures must be available. Such data are not available for WCSB because of its long-life cycle (Gichuhi et al. (2016)).

The faced difficulties for realising this objective reflects a common scientific problem. Within the scientific community, the misuse of models for pest and disease risk analysis is recognized. This has even prompted scientist to develop decision support tools designed to facilitate the decision on whether a modelling exercise is appropriate, given the data availability and the considered species (Eyre et al. (2012)).

For those reasons, the spatial analysis component of the study was modified to a question relating to the present situation, but with relevance for the future as well. The results on the spatial analysis of WCSB around Mt Elgon have important implications. They suggest a solution on how WCSB control could be improved by synchronizing control measures with the rainfall pattern. Moreover, they showed that emphasis should be given to identify and limit pathways of pest spread from highly infested to new areas.

Coming back to the starting point of the discussion on the significance of microenvironments for the ecology of the regarded CPaD and its implications for science and practice: Also from a practical point of view, it is clear that an understanding of the coffee agroecosystems must include microclimatic management and manipulation (Stigter (2015)). Agroforestry systems are a substantial and multi-functional resource providing socio - cultural, economic, and ecological services (Cornell and Miller (2007), i.a.). The implications are evident and relate again to the importance of participatory and site-specific research as discussed before. Scaling processes to achieve impact are non-linear processes, hence the approach of "find out what works (in one place) and do more of the same (elsewhere)" might produce adverse result (Wigboldus et al. (2016)). This transfer of technology paradigm, which since the green revolution has been handled as so called top-down extension, should be adapted to the more diverse and risk-prone cropping systems used in many tropical countries (Chambers (1990)). Here, finding a balance between top-down and bottom-up, or generalized and locality-specific extension will remain difficult for scaling up and scaling out initiatives.

To finalize the discussion on this topic, the following statement by (Stigter (2015)) comes straight to the point of the issue: "The general biases in both agricultural and social sciences combine to conceal microenvironments, understate or exclude them in statistics, and undervalue their importance for livelihoods."

6.3 Challenges of data acquisition and analysis in the context of agricultural research in smallholder farming systems in the tropics

CLR is probably the best researched coffee disease. The intention for this chapter was therefore not primarily to describe relations which are only valid for CLR, but rather to exemplify an approach to analyse a system which cannot be described with a simple "$y \sim x$"-approach. In the following, limitations but also opportunities in the process of data sampling and analysis in the context of highly divers and heterogeneous systems will be discussed.

Data sets of agroecological studies conducted under real conditions are often complex and messy. They might not comply with the assumptions of conventional statistics, and hence require more sophisticated, non-standard tools to be properly analysed (Johnson and Milliken (2004); Bolker et al. (2009, 2012); Lefcheck (2016)). First, as mentioned repeatedly, agroecosystems are complex, and resulting datasets are multi-faceted: They usually follow non-normal distributions and often involve random effects and collinearity (Graham (2003); Bolker et al. (2009)). Despite the availability of non-parametric approaches such as GLMs and GLMMs, those models are difficult to fit and even challenging for statisticians (Bolker et al. (2009)). Furthermore, although those models offer a non-parametric alternative, the assumption of linearity remains to be an issue. Second, because habitat data are so complex, numerous variables with sufficient sample size at different spatial and temporal scales are aimed to be recorded. This requires a high logistical and financial effort (Vaughan and Ormerod (2003)), and datasets might be messy because financial and human resources are lacking. In addition, the involvement of farmers in agricultural research (although desirable) entails risks concerning the quality of the data. Biophysical researchers often have little experience in social science, and inaccurate information might results from misunderstandings between farmers and scientists (Van Asten et al. (2009)).

Many of those obstacles were faced in this project at some point: Since our data originate from field surveys, and hence uncontrolled conditions, they are highly heterogeneous. Although farms were selected in such a way as to minimize factors which would make a comparison difficult (Sec. 2.2.2), heterogeneity due to different environments and management was conserved. Almost all response variables are non-normal and follow binomial, negative binomial or Poisson distributions, which is the norm for pest and disease data (Bolker et al. (2009)). Many of our data were collinear, making the selection process of microclimatic variables for instance quite challenging (Sec. 4). Because of lacking human resources, the sample sizes for CBD were insufficient for a sophisticated analysis including repeated measures or random factors (Sec. 1). Working in an area like Mt Elgon is also a logistical challenge. The data collection was often delayed, especially during the rainy season where the fertile, but very heavy and sticky clay soils up the mountains makes driving almost impossible. Even political events, such as the presidential elections in 2016 had an impact by delaying the samplings. Finally, data acquisition in collaboration with farmers was difficult because the communication was indirectly through translators.

Despite the resulting challenges for data collection and analysis, this data heterogeneity also offered opportunities. First, from an academic perspective, the non-applicability of conventional statistical methods inevitably leads to an exploration of more modern methods, offering innovative and useful alternatives. Tools like piecewiseSEM, which was applied to the CLR data, enable the establishment of internal validity (defined as "the ability of a researcher to argue that observed correlations are causal", (Roe and Just (2009)) and gave qualitative indications on processes within the considered sub-system. For the WCSB analysis, the use of categorical data combined with MCA, an approach considered as useful especially for analysing plant disease and pest data (Savary et al. (1995)), offered a viable alternative. Furthermore, the application of the GAM enabled to model a non-linear relationship between WCSB and altitude. Therefore, this thesis also turned out to include an exhaustive revision of statistical tools and integrated analysis approaches relevant for agroecological studies.

Second, because the agroecological context remained practically undisturbed, the study has ecological validity. Inferences are meaningful for that specific setting because they provide a real reflection of the truth (Roe and Just (2009)). The results and implications related to farmers' perception and spatiotemporal dynamics of CLR and WCSB described in Chap. 3 - 5 provided insightful and important information useful for farmers in the respective growing region. Concrete conclusions as a base for possible decision-making support are compiled in the subsequent section.

6.4 Conclusions and outlook

This study revealed several facts, linkages and gaps related to farmer-scientist knowledge transfer, shading systems and CPaD abundance as well as future research needs. The findings may contribute to sustainable solutions for farmers and extension services in the studied area, but conceptually also for other coffee growing regions.

Farmer-scientist knowledge transfer

- There is potential to strengthen farmers knowledge capacities by improving the extension service system. Based on the identified knowledge gaps, regional or sub county-based training programs should emphasize following topics:
    - CPaD diagnostics to enable farmers to identify and distinguish between CPaD
    - Available CPaD management practices
    - Correct use of pesticides
    - Identification and use of different Arabica varieties with different traits (especially CPaD resistance)
    - Paradigm shift away from the common believes on the role of shade trees (i.e. alternative hosts for CPaD or nutrient competitor of coffee)
- In turn, improving the extension service and communication with farmers could strengthen feedback mechanism on the efficiency of recommended control strategies and CPaD surveillance and improve the understanding about why farmers opt for or against a certain practice.
- There is potential to better approach and target joint issues of farmer communities by the formation of farmer groups or cooperatives. Such groups might improve:
    - Information sharing on coffee crop management practices, CPaD outbreaks, climate events or market prices, among others
    - Information on available certification bodies and active cooperatives in the region
    - Joint problem-solving, e.g. issues with fake pesticides

Shading systems and CPaD abundance

- The shading system to reduce CPaD pressure can be adopted depended on environmental conditions and farmers needs.
    - At low altitudes:
        - The environmental conditions for CLR are currently optimal, and the system effect is neglectable. The use of CLR resistant varieties would be an option, especially if the cup quality (a common trade-off when using rust resistant varieties) is not the priority. Low-land, compared to high-land coffee, is generally of inferior quality
        - WCSB infestation is associated with shade tree density and diversity, however, especially at low altitudes, the removal of trees would rise trade-offs for the mitigation of climate change effects as well as the provision of tree resources from within-farm trees. Therefore, WCSB control must aim at (1) Removal and eradication of heavily infested stems, (2) Preservation of infested stems with manually removal of young larvae, (3) Prevention of new infestations by applying cultural or chemical control methods during the emergences and oviposition periods (shortly after rainy seasons) (4) The limitation of WCSB spread by eradicating pruned infested wood material, (5) The use of systemic insecticide, if accessible and affordable
    - At mid altitudes:
        - Because of the combination of high dew formation and low diurnal temperatures during the rainy seasons, CB systems provided conducive conditions for CLR. Since banana mats grow fast, a proper pruning during the rainy seasons to improve ventilation in the plot and hence reduce dew formation might help to hamper CLR epidemics. Introducing more shade trees might also reduce dew formation, however, could result in better conditions for WCSB
        - For WCSB, the same reasoning as for low altitudes applies
    - At high altitudes:
        - The high CBD pressure in unshaded systems is the major issue at high altitude. Banana systems, which are already adopted by many farmers, are currently the best option because they would reduce CBD and keep WCSB infestation low. However, with climate change and the predicted reduction in diurnal temperature ranges, CLR might get more prevalent at higher altitudes as well and might follow the same inferences as currently at mid altitudes (conducive conditions under CB systems). The use of CBD and / or CLR resistant varieties is an option as well, but might compromise the cup quality, which makes high-land coffee distinguishable

        - ∗ The limitation of further WCSB expansion is of high priority at high altitudes since is not present on many farms yet. This is also important as a preparation to future climate conditions: If minimum temperatures rise as predicted and more shaded systems are adopted, conditions at high altitude might improve for WCSB

Further research topics

- The benefits and trade-offs of various shade tree species as well as their spatial arrangements on different ecosystem services
- More control options must be developed, implying a better understanding about the pests ecology and biology. This thesis established preliminary indications and hypotheses on several topics which need to be further explored:
    - Pathways of WCSB spread across the landscape
    - Food preferences (coffee varieties, age of coffee bushes, wood characteristics)
    - Biological control options and pheromone traps
- The development of CBD and CLR resistant Arabica varieties which do not compromise cup quality
- Common guidelines and tools for data collection to further promote the inclusion of indigenous knowledge into biophysical studies should be developed

Clearly, the central statement and hence ”take-home message” of this thesis is the importance of microenvironments for the development and establishment of the analysed CPaD, and the resulting implications for CPaD management in the present and future. In coffee-based agroforestry systems, shade trees will most likely continue to play an important role, especially under future climate conditions. Research on its benefits and trade-offs must include the perspective of producers. Their actions are, first and foremost, driven by their own necessities at the household scale, and less by global issues or consumer’s demands on sustainability. Ultimately, the best way to achieve positive outputs, outcomes and impacts is by using inputs representing the interests and needs of all stakeholders.

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A Supplementary Material

A.1 Publication manuscript for Chap. 2

Sustainable intensification of coffee agro-ecosystems in the face of climate change along the slopes of Mt. Elgon, Uganda.

Rahn Eric[1,2,3], Liebig Theresa[2,3,6], van Asten Piet[3], Jassogne Laurence[3], Ghazoul Jaboury[1], Vaast Philippe[4,5], Garcia Claude[1,5], Läderach Peter[2].

[1]Swiss Federal Institute of Technology (ETH) Zurich, Environmental Systems Science, Switzerland
[2]International Center for Tropical Agriculture (CIAT), Cali, Colombia
[3]International Institute of Tropical Agriculture (IITA), Kampala, Uganda
[4]World Agroforestry Centre (ICRAF), Nairobi, Kenya
[5]Centre de Coopération International en Recherche Agronomique pour le Développement (CIRAD), Montpellier, France
[6]Leibniz University Hannover, Germany

Corresponding author:
Eric Rahn, eric.rahn@usys.ethz.ch

Highlights:

- Ecosystem-based adaptation allows for sustainable intensification (SI) of coffee systems
- SI improves coffee farmer's livelihoods in East Africa
- Socio-ecological context defines appropriate SI pathway
- SI does not necessarily increase coffee production nor biodiversity conservation

Keywords:
Sustainable intensification, ecosystem-based adaptation, Coffea arabica, shade trees, adoption, Uganda

Abstract

Coffee (*Coffea arabica*) is a major export crop of East Africa sustaining the livelihoods of millions of smallholder farmers. The viability of coffee in this region is, however, endangered by multiple factors such as climate change, population pressure and coffee price volatility. Sustainable intensification through (shade) intercropping is believed to improve farmers' livelihoods, facilitate adaptation of coffee production to climate change, and contribute to coffee sector development and biodiversity conservation. Technical guidance on adaptation options is currently weak and requires sound understanding of local contexts. Altitudinal gradients provide a means for analyzing coffee production systems in different environmental contexts that co-vary with altitude, and they provide a rough proxy for many of the issues relating to climate. Additionally, management decisions unrelated to environment need to be accounted for. We seek to do this by analyzing a range of Arabica coffee systems that differ in vegetation structure across an altitudinal gradient on Mount Elgon, Uganda, to understand (i) if and how farmers adapt their production systems to differing climatic conditions, and (ii) how these different production systems perform. A typology of coffee systems was derived based on the vegetation structure of 146 coffee plots. Coffee systems were compared along an altitudinal gradient (1100 – 2100 m.a.s.l.). Determinants of farmer adoption of different coffee systems were investigated, highlighting both internal and contextual factors affecting farmers' decision-making. Three coffee systems were identified: coffee open canopy, coffee-banana intercropping, and densely shaded coffee systems. The climatic gradient had a clear effect on system adoption, with shade trees being used to mitigate higher temperatures and more prolonged drought stress at low altitudes, while intercropped banana densities increased at higher altitudes responding to higher rainfall. Although vegetation structure affected coffee yield, differences among systems were not significant. Open canopy systems are mainly used by wealthier farmers who do not depend on intercrops for food security. Altitude has a strong influence on coffee yield, benefits of shade trees, and soil quality. Socio-ecological constraints, such as farm and household size, and access to forests and markets, play a crucial role in determining what constellation of ecosystem services benefit farmers' livelihoods resulting in different sustainable intensification pathways. Our findings reveal inherent trade-offs in socio-ecological conditions, and aligning these is required for achieving the multiple objectives of livelihood improvement, sustainable intensification of coffee production, and biodiversity conservation.

1. Introduction

Trees in tropical agricultural systems have gained increased interest due to their climate change mitigation (IPCC 2000) and adaptation potential (Lin 2010; Lasco et al. 2014; Minang et al. 2015). Additionally, there is an increased recognition that tropical biodiversity in rural landscapes can have high conservation value while sustaining rural livelihoods (Perfecto et al. 1996; Schroth et al. 2004; Chazdon et al. 2009; Baudron & Giller 2014). These interests in trees within agricultural areas have been accompanied by a shift in scale of analysis from the plot to the farm to the landscape level (Tittonell et al. 2005; Perfecto & Vandermeer 2010; Sayer et al. 2013). Meanwhile, many diversified coffee and cocoa agroforestry systems are being intensified by removing shade trees and reducing shade tree species richness in pursuit of higher yields and increased profitability (Garcia et al. 2010; Ruf 2011; Jha et al. 2014). This trend is incentivized by the public and private sectors to increase export and value chain earnings in response to increasing global demand (FAO, 2015).

In Sub-Saharan Africa the crop yield gap is particularly high, and coffee has been identified by various national and international agencies as a focus crop for development interventions (e.g. MAAIF 2010, USAID 2011). Next to the challenge of increasing yields in a sustainable way, the coffee sector is confronted with a changing climate that is altering the environmental conditions on which coffee production depends (Jaramillo et al. 2011; Davis et al. 2012; Bunn et al. 2015; Craparo et al. 2015; Ovalle et al. 2015). This is putting at risk the livelihoods of coffee farmers and related ecosystem services (Bunn et al. 2015; Magrach & Ghazoul 2015). In East Africa, where the majority of Arabica coffee (*Coffea arabica*) is grown on the African continent, the current suitable climatic range for coffee production is found in highland areas, and often on steep mountain slopes bordering remnant Afromontane rainforest with high biodiversity conservation and ecosystem service values. Climate change is expected to shift the suitable area for coffee production up the slopes. Hence, adaptation to climate change will be required to sustaining coffee production in the area.

The production systems will need to adapt i) to rising mean temperatures and shifts in mean precipitation rates and patterns, and ii) to extreme events. The former are long-term, slow-changing climatic events, while the latter occur rapidly and over a very short time span. Second, there are i) technical adaptation strategies, such as genetic modification of crops, changes in the location of production, irrigation, or the development of agroclimatic forecasting systems, and ii) ecosystem based approaches that improve system resilience (Schroth & Ruf 2014; Vignola et al. 2015; Perfecto & Vandermeer 2015:225).

There is consensus that the potential yield increase should be reached through sustainable intensification (SI), rather than conventional intensification (Tilman et al. 2002). But, various definitions of SI exist and there is considerable debate regarding the means to reach this goal (Kuyper & Struik 2014; Tittonell 2014; Cook et al. 2015). While there are a multitude of pathways towards SI in the context of climate change adaptation, there is sufficient evidence that African smallholders are often unable to benefit from the yield gains offered by improved technology due to small farm size, insufficient inputs of nutrients and organic matter, and limited access to markets (see Tittonel & Giller, 2013; Harris & Orr, 2014). Because of these lacking requirements, an ecosystem-based adaptation approach based on ecological intensification is a promising strategy towards SI and climate change adaptation in the East African smallholder farming context.

The use of shade trees is a popular example of ecosystem-based adaptation and ecological intensification as it helps to ensure the provision of important ecosystem services such as erosion control, pollination, and natural pest control, in addition to buffering microclimate extremes, reducing coffee transpiration and soil evaporation loss and increasing nutrient cycling (Beer et al. 1998; Vaast et al. 2005; Lin 2007, 2010). Diverse agroforestry systems have been shown to increase food security of smallholder farmers and increase or diversify their sources of income (Rice 2011; Schroth & Ruf 2014; Altieri et al. 2015). Coffee yields in intensive non-shaded systems can, however, be higher than in shaded systems, provided that environmental and management conditions are optimal (Beer et al. 1998; DaMatta 2004; Haggar et al. 2011). Trees and their effect on micro-climate can promote pests and diseases and increase light, water and nutrient competition (Beer et al. 1998; Avelino et al. 2011; Cannavo et al. 2011; Lopez-Bravo et al. 2012). Furthermore, coffee planting density can be significantly increased in a monoculture context. A recent study even questioned the benefit of shade trees to buffering microclimate extremes. Shade trees increase the minimum temperature and this is found to have a worse impact on Arabica coffee performance than increasing maximum temperatures (Craparo et al. 2015).

Other considerations are equally important. Managing a diversified agro-ecosystem and engaging in certification schemes that incentivize the adoption of such systems might increase management complexity and the resulting additional workloads might adversely affect other livelihood activities, particularly if the capacities and skills required are not part of local knowledge (Beer et al. 1998; Vellema et al. 2015). Furthermore, provisional services other than coffee such as fruits, timber, and fuelwood might be equally important. Understanding the interaction between all these factors is crucial for enabling SI in the context of climate change. Because these relationships are highly context dependent, adaptive intervention measures are required that allow for addressing system complexity (Giller et al. 2011; Vignola et al. 2015).

In order to gain insights regarding appropriate means towards SI through ecosystem-based adaptation, this study aimed at understanding (i) if and how farmers adapt their production systems to differing climatic conditions, and (ii) how these different production systems performed. We analyzed existing management practices and the related vegetation structure along an altitudinal transect, reflecting differences in mean temperature and precipitation. This was done by i) classifying existing coffee systems at plot level according to vegetation structure, ii) comparing the trade-offs of the identified coffee systems regarding coffee yield and biodiversity, and iii) investigating determinants of adoption of each system.

2. Methods

2.1 Study area

The study was conducted in two districts (Bulambuli and Kapchorwa) of Mt. Elgon, Uganda, an extinct volcano on the border between Uganda and Kenya of 4321 m altitude (Fig. 1). In order to cover a heterogeneous area in terms of environmental conditions, a cluster analysis including key variables of climate and topography (annual temperature, annual rainfall, altitude, slope, slope aspect) was performed (Fig. 1c). The three resulting clusters differed mainly in altitude and consequently the variables correlated with altitude such as temperature and rainfall. The clusters form an altitudinal gradient of < 1400 m.a.s.l., 1400 – 1700 m.a.s.l., and > 1700 m.a.s.l. The selected plots lie within an area of 210 km^2 and border the Afromontane rainforest located above 2200 m.a.s.l, protected as Mount Elgon National Park. Local farming communities depend heavily on this forest for construction materials, stems used as crop-supports, and biomass for charcoal making and firewood. (Sassen et al. 2013, 2015; Sassen & Sheil 2013).

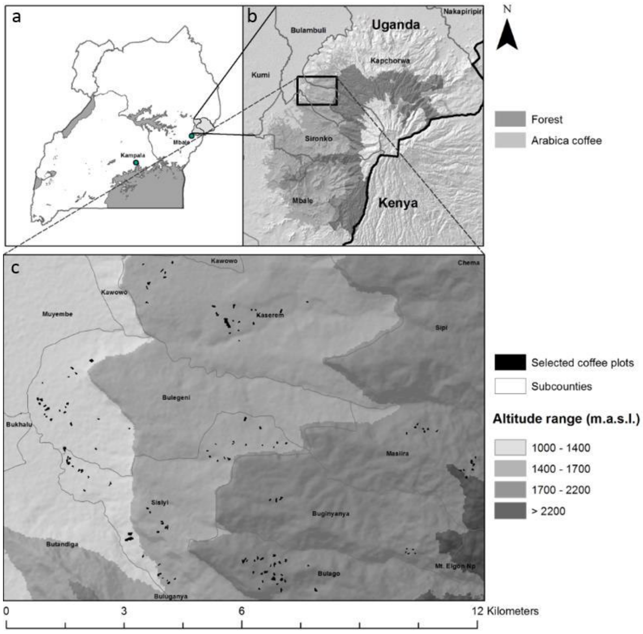

Fig. 1. a) Location of the study area within Uganda, Mount Elgon area, b) Districts of study area (Bulambuli, Kapchorwa), c) Study site with indication of three altitude ranges (determined by means of cluster analysis), sub counties and sample plots.

Using the FAO soil classification, the soils of the study area are mainly Nitisols with presence of Phaeozems at low altitude (De Bauw 2015). The climate is influenced by dry northeasterly and moist south-westerly winds, resulting in less rainfall on the north western transect as compared to elsewhere on the mountain. A bimodal rainfall pattern prevails in the area, with the wettest period during March/April to October/November, and a pronounced dry period from December to February and a period of less intense rains around July to August (Fig. 2). The wet season is prolonged on higher altitudes compared to lowlands. Mean annual rainfall ranges from 1200 mm at low altitudes to 1400 mm at mid altitudes and 1800 mm at high altitudes. The mean annual temperatures are 23°C, 21°C and 18°C, respectively (Hijmans et al. 2005). According to Mbogga (2012), the Mount Elgon region has experienced an increase in monthly temperatures in the range of 0.4 °C to 1.2 °C during the 2001-2011 period compared to the 1961-1990 period. Intensive rainfall has resulted in numerous landslides on the mountain slopes and floods on the foothill with hundreds of deaths. Increased drought periods are particularly a problem in the northern drier region and areas of low altitude causing stress to crops and scarcity of domestic water availability (Mbogga, 2012).

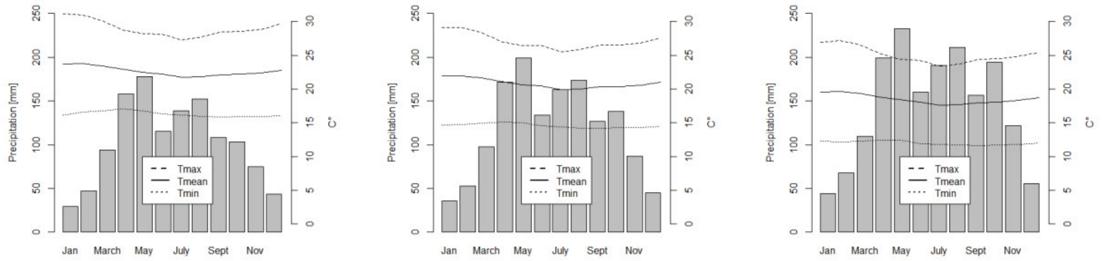

Figure 2: Climate diagrams of a) low (1100 - 1400 m.a.s.l.), b) mid (1400-1700 m.a.s.l.), and c) high altitude (1700-2100 m.a.s.l.) based on WorldClim database (Hijmans et al. 2005)

2.2 Plot selection

Participating coffee farmers were selected in a stratified random manner to obtain a representative sample of the existing production systems of the region. Administrative boundaries were used to make fieldwork more practical in terms of connecting to farmers and accessibility. In a first step two sub-counties per altitude class were selected, followed by two parishes within each sub-county, three villages within each parish, and 10 coffee farmers within each village. Finally one plot per farmer was selected. Participatory rural appraisal was conducted in each sub-county to familiarize farmers to the research objectives and activities, and to acquire local knowledge and perceptions concerning existing coffee production systems and activities, advantages and disadvantages of used shade trees and production constraints. A rapid self-assessment with respect to the coffee production systems (shaded mainly by trees, shaded mainly by banana, not shaded) served as an orientation for the final selection of 150 farmers (50 per altitude range) for the subsequent survey. Data from four farmers had to be rejected because of unreliable data, resulting in 146 farmers (48-49 per altitude range).

2.3. Data collection

During the months of April and May 2014 vegetation structure was measured on the 146 selected plots. The altitude and plot boundary coordinates were recorded using Garmin eTrex GPS. Plot size was calculated based on plot boundary coordinates in R Statistics (R Core Team, 2014). The number of coffee bushes, banana mats and stems, and shade trees were counted on the entire plot and densities (in number per hectare) were calculated. Shade tree species were identified and the number of species per plot recorded. The canopy closure as an indicator for average plot shade was estimated using a Forestry Suppliers spherical crown densiometer (convex model A) according to Lemmon (1957) at four positions within the plot. A composite soil sample of the topsoil (0-30cm) was taken from each plot and analysed for organic matter, soil pH, total nitrogen, available phosphorus, and exchangeable potassium using standard methods (Okalebo et al. 1993). The slope was measured using Suunto Tandem Global Compass/Clinometer. Soil erosion was evaluated visually. Data on age of the coffee bushes, yield, coffee management, perceived occurrence and impact of coffee pests and diseases, and livelihood characteristics were obtained through structured farmer interviews during farm visits. Outliers were identified by statistical process (box-plots and dotcharts in R) and empirical knowledge.

2.4 Typology of coffee systems

Data analysis was done using R statistics (R Core Team, 2014). The typology of coffee production systems was based on variables related to vegetation structure. Variables included were shade tree and banana densities per unit area, shade tree species diversity and canopy closure. K-means clustering was performed with standardized data in order to minimize the effect of scale differences. The variables were compared between the resulting coffee systems using the one-way ANOVA (with Tukey’s post hoc test).

2.5 Coffee yield

Multiple linear regression models were used to determine the effect of vegetation structure, altitude, management variables, pest and disease scores, and soil properties on coffee yield. Yield was log-transformed to meet the conditions of normality and homogeneity of variance. Collinearity among independent variables was identified by means of the variance inflation factor (car R package). Stepwise elimination was done in a two way procedure; first by eliminating independent variables with variance inflation factors higher than three, followed by identifying model with lowest AIC. The independent variables used in all models included coffee planting density (coffee plants ha^{-1}), shade (%), banana density (bananas ha^{-1}), shade tree density (trees ha^{-1}), shade tree species richness, altitude, mineral fertilizer application (kg ha^{-1}), fungicides application (kg ha^{-1}), insecticides application (liters ha^{-1}), farmers scores (0-5) on pests and diseases; White coffee stem borer (*Monochamus leuconotus*), coffee leaf rust (*Hemileia vastatrix*), coffee berry disease (*Colletotrichum kahawae*), and coffee berry moth (*Prophantis smaragdina*), and soil properties; pH, organic matter (%), nitrogen (%), phosphorous (ppm), potassium (cmol kg^{-1} soil).

2.6 Biodiversity

Comparison of tree species diversity between coffee systems was done by using species accumulation curves, and Shannon and inverse-Simpson diversity indices. Rènyi diversity profiles were plotted to examine if farm categories and altitude ranges could be ranked from low to high diversity. Species accumulation curves were calculated with the BiodiversityR package (Kindt & Coe, 2005). Native tree species were defined based on the potential natural vegetation types of the study area (van Breugel et al. 2014). The potential natural vegetation of the study area is Afromontane rain forest in the high altitude area and dry and moist *Combretum* wooded grassland subtype on low and mid altitude areas.

2.7 Determinants of adoption of different coffee production systems

The determinants of adoption of the different coffee production systems were investigated by means of a multinomial logistic regression approach (Hosmer and Lemeshow, 2000). Possible factors determining adoption were investigated first with coffee open sun systems as the baseline category and secondly with coffee-banana systems as baseline category. This allowed for estimating both the probability of a farmer adopting either the coffee-banana or coffee tree systems, instead of coffee open sun and the probability of a farmer adopting coffee tree systems instead of coffee-banana systems. As explanatory variables we used a number of possible variables that are believed to impact decision making (table 1), they are classified as socio-economic, social network, consequences and expectations, and contextual factors. Analysis was done with the “mlogit” R package (Croissant 2013).

3. Results

3.1 Coffee agro-ecosystem classification of Mt. Elgon, Uganda

Three distinct coffee production systems were identified, namely a sparsely shaded open canopy coffee system (CO), a coffee system with high banana densities (CB) and a highly tree shaded coffee system (CT) (Table 2). Vegetation structure of the coffee systems also showed clear relationship with altitude. Banana density was higher on mid and high altitude compared to low altitude (one-way ANOVA with Tukey post-hoc test, $p<0.05$), while shade tree density, shade tree species richness and canopy cover were higher on low altitude compared to mid and high altitude (one-way ANOVA with Tukey post-hoc test, $p<0.05$). Due to these spatial differences in banana and shade tree densities a significant association between the coffee production typologies and altitude range was found (X^2, $p < 0.001$). The majority of plots assigned to the CT system were found to be situated at lower altitudes between 1000 – 1400 m.a.s.l., while more CB and CO systems were present at mid to high altitudes between 1400 – 2200 m.a.s.l. Only few CB systems were found on low altitude.

Table 1: Factors analyzed as possible determinants for adoption

Adoption factors	**Variable**	**Description**
Socio-economic	Gender	Value 1 if gender of household head is male
	Age	Age of household head (years)
	Education	Highest education level of household head
	Wealth	Number of Tropical Livestock Units (TLU)
	Coffee importance	• Total number of plots • Number of coffee plots • Number of coffee plots of total number of plots
	family size and age	Number of family member above 16 years divided by total number of family members
Social network	Member of cooperative	Yes or no
	Extension service	How often the farmer has been visited by extension service
	Certification	Yes or no
	Access to borrow money	Yes or no
Consequences and expectations	Positive effects of intercropping	Coffee quality, soil fertility, weeds, wind break, P&D control, timber, humidity, food, fodder, erosion control → e.g.: Soil fertility is higher in intercropping systems = 1
	Negative effects of intercropping	Reduced productivity, host for P&D, increased workload, physical damage, more external inputs required, takes too long to grow, competition for nutrients → e.g.: Nutrient competition is a problem in intercropping = 1
Contextual factors	Altitude	Low, mid, high
	Slope	Flat (<10%), steep (>=10%)
	Aspect	N,E,S,W
	Plot-history	• Land-use before converted to coffee plot • Year converted to coffee plot
	Dist. Between homestead and plot	Distance in meters

Table 2: Vegetation structure of coffee production systems with means and standard errors

	Coffee open canopy n = 54			Coffee-banana n = 44			Coffee-tree n = 46		
Coffee density (coffee ha-1)	2255^a	±	125 (SE)	2094^a	±	127 (SE)	2095^a	±	112 (SE)
Banana density (bananas ha-1)	29^a	±	17 (SE)	1496^b	±	105 (SE)	278^c	±	82 (SE)
Shade tree density (trees ha-1)	63^a	±	6 (SE)	49^a	±	6 (SE)	146^b	±	16 (SE)
Shade tree species richness	2.8^a	±	0.2 (SE)	2.7^a	±	0.2 (SE)	6^b	±	0.4 (SE)
Shade (%)	21^a	±	1.4 (SE)	28^b	±	1.4 (SE)	48^c	±	2 (SE)

Means with different letters indicate significant differences (one-way ANOVA, with Tukey post-hoc test, p<0.05)

3.2 Coffee yield

No significant yield differences were found between the coffee systems irrespective of altitude (ANOVA, $p<0.05$). This does not mean that vegetation structure has no effect on yield (table 3). Overall, coffee yield is increased by coffee planting density and shade tree density but negatively affected by shade tree species richness. Altitude, mineral fertilizer application and soil potassium content also favoured higher yields, while the coffee berry moth negatively affected yields. The low shade tree densities of the CO systems positively affected coffee yields, next to mineral fertilizer and insecticide application, while fungicides were inappropriately used. Banana densities had a positive effect on coffee yields of CB systems, next to altitude, mineral fertilizer application and soil phosphorous content. On the contrary, the coffee berry moth appeared to be a problem for coffee production in CB systems. Too much shade and high shade tree species richness negatively affected yield of CT systems, while the application of insecticides and high soil potassium content favoured yield.

Table 3: Estimated model coefficients of linear model, with significance levels, and adjusted r^2 for coffee yield per hectare and coffee yield per coffee tree

	Response = Log(Yield[green bean kg ha^{-1}])			
	Models per Coffee System			
	All systems	**CO**	**CB**	**CT**
Intercept	5.8 ***	7 ***	4.8 ***	8.4 ***
Coffee density (bushes ha^{-1})	0.0002 .			
Shade (%)				-0.03 ***
Banana density (bananas ha^{-1})			0.0005 *	
Tree density (trees ha^{-1})	0.004 **	0.005 .		
Tree species richness	-0.15 **			-0.17 **
Altitude (m.a.s.l.)	0.0006 *		0.001 *	
Mineral fertilizer (kg ha^{-1})	0.0006 **	0.0006 *	0.008 .	
Fungicides (kg ha^{-1})		-0.04 **		
Insecticides (lit ha^{-1})		0.07 **		0.03 *
Coffee Berry Moth (score)	-0.15 *		-0.3 ***	
Soil P (ppm)			0.01 **	
Soil K (cmol kg^{-1} soil)	0.25 *			0.5 *
Adjusted r^2	0.26	0.3	0.43	0.51

Significance: *10%, **5% ***1%

3.3.6 Tree species richness

The total tree species richness found on the plots was 37 with 69% of the tree species being indigenous to the area. Two indigenous tree species (*Cordia africana* and *Ficus* spp.) made up 50% of tree species abundance. Overall tree species richness was significantly higher in coffee-tree systems compared to the other systems (figure 4) but not when compared on high altitudes (table 4). No significant difference was found between CO and CB. In the sparsely shaded coffee systems, 66% of the 23 tree species are indigenous. In coffee-banana systems, 69.5% of the 22 tree species are indigenous, while in the coffee-tree systems, 70% of the 29 tree species are indigenous. *Cordia africana* is the dominant tree species in CO and CB systems with 35% and 24% average occurrence, respectively, while *Ficus* spp. is the dominant shade tree species in CT systems. The Rény diversity profiles (figure 5) indicate highest diversity in CT systems followed by CB and CO systems. Plots on low altitudes have highest tree species diversity but no difference is found between plots on mid and high altitudes, since their diversity profiles intersect. Species are not evenly distributed in any of the coffee systems nor on any of the altitude ranges. The Shannon and the inverse Simpson index report on the tree species diversity of the three coffee systems and altitude ranges with highest diversity at low altitude and lowest at high altitude and highest diversity in CT systems at low and mid but not at high altitudes. At high altitude diversity was highest in CB systems. The richness estimators Jacknife 1 and Bootstrap indicate that 21 to 37 more species were needed to have complete species inventories of the study area (table 4).

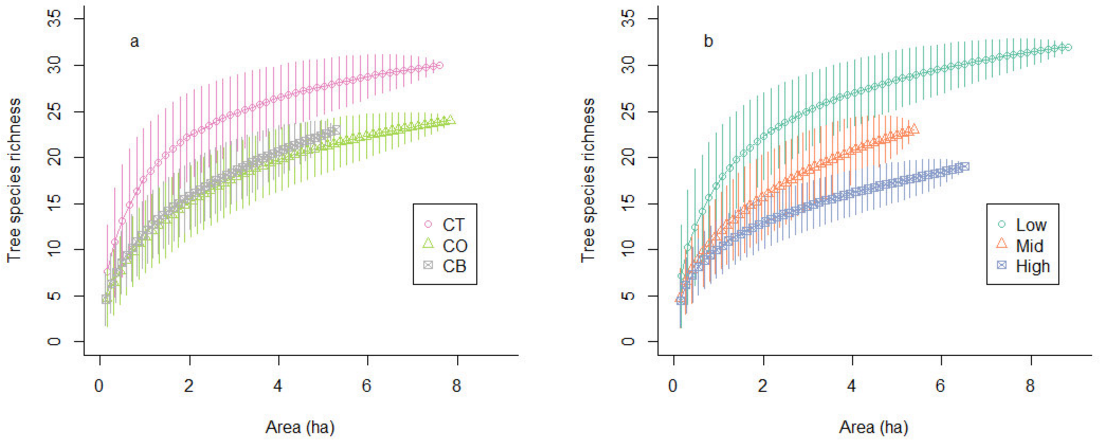

Fig. 3: Tree species accumulation curves with confidence intervals for a) coffee-tree (CT), coffee-banana (CB), and coffee open sun systems (CO) and b) low, mid, and high altitude.

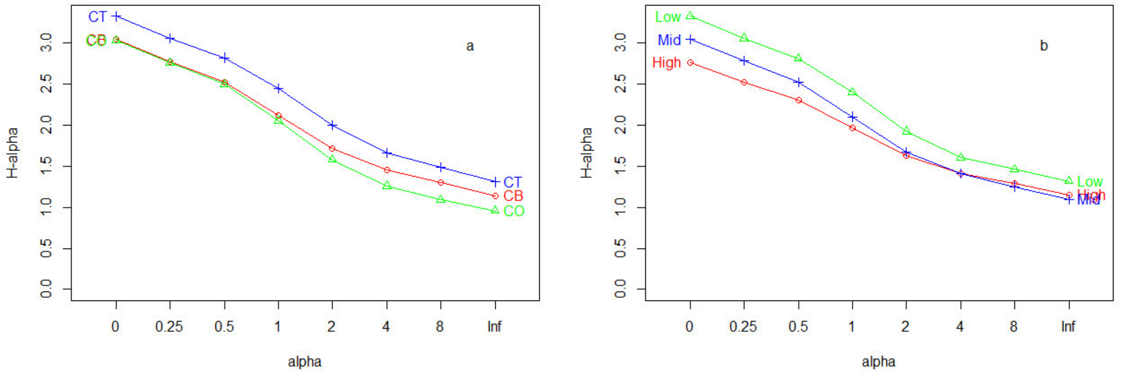

Figure 4: Rény diversity profiles for a) the coffee systems and b) the altitude ranges.

Table 4: Total plot area, tree richness, abundance and diversity indices compared between the different coffee systems and altitude ranges.

Coffee system	Total plot area [ha]	Richness (mean)	Richness estimators		Abundance [per ha] (mean)	Shannon index	Inverse-Simpson index
			Jack1	Boot			
CO	7.8	23	29	26	365 (47)	2.13	5.05
CB	5.3	22	31	26	221 (42)	2.18	5.82
CT	7.6	29	34	32	751 (99)	2.48	7.53
Low	8.8	31	37	34	814 (93)	2.46	7.11
Mid	5.4	22	30	26	239 (44)	2.16	5.57
High	6.5	18	25	21	284 (44)	2.05	5.38
All	20.7	37	43	40	1337 (65)	2.45	6.98

	Low altitude				Mid altitude				High altitude			
	CO	CB	CT	*p*	CO	CB	CT	*p*	CO	CB	CT	*p*
Tree density (trees ha-1)	86	72	146	*	65	55	264	***	48	46	122	***
Tree species richness	20	11	27	***	11	12	15	*	11	13	9	
Inverse Simpson	4.9	4.7	6.9	***	4.3	4.7	6.6	***	4.6	5.8	4.7	*

Significance: *10%, **5% ***1%

3.5 Determinants of coffee system vegetation structure

Maximum likelihood estimates of parameters in the multinomial logistic regression of the reduced model are presented in table 3 together with the significance level and the odds ratio (Exp(β)). The full model is not presented due to lack of significance of many of its variables and high AIC. The odds ratio is the factor explaining how much more likely (or unlikely) it is to adopt (a) coffee-banana or coffee tree systems instead of coffee open sun and (b) coffee tree systems instead of coffee banana, after a one unit change in the explanatory variable. Altitude has a significant influence on adopting coffee-tree systems. A one-unit change in altitude range (from mid/high to low) increases the likelihood of a farmer to adopt coffee tree systems followed by coffee open canopy systems. Hence, on low altitude it is least likely that a farmer adopts a coffee-banana system. The fewer coffee plots a farmer has the higher the likelihood he intercrops with shade trees followed by intercropping with banana. The higher the proportion of household members above 16 years (i.e. the fewer children below 16 years per household) the more likely farmers adopt CO systems. More CO farmers perceive intercropping as resulting in nutrient competition, whereby no perceived differences between CB and CT farmers were found. The model allowed a good distinction when the systems are compared to CO but not when CB and CT are compared.

Table 5: Estimates for adoption of coffee system type (reduced model with lowest AIC)

	Variables	β		Wald	Exp(β)
Coffee-banana[a]	Intercept	2.176	**	8.373	
	Low altitude[c]	-1.125	**	4.141	0.325
	No. of coffee plots	-4.084	*	3.380	0.017
	People>16y Quotient	-2.341	**	4.484	0.096
	Nutrient competition[c]	-1.095	**	3.843	0.335
Coffee-tree[a]	Intercept	1.256		2.503	
	Low altitude[c]	1.614	***	11.441	5.022
	No. of coffee plots	-7.745	***	8.093	0.000
	People>16y Quotient	-1.771	*	2.458	0.117
	Nutrient competition[c]	-1.522	***	6.570	0.218
Coffee-tree[b]	Intercept	-0.920		1.306	
	Low altitude[c]	2.739	***	24.750	15.466
	No of coffee plots	-3.661		1.547	0.026
	People16 quotient	0.570		0.206	1.768
	Nutrient competition[c]	-0.427		0.393	0.652

AIC: 257.896
Chi^2 test of the model: 59.258***
Pearson test: 256.679
Nagelkerke R^2: 0.378

Significance: *10%, **5% ***1%

[a] The reference category is coffee open sun

[b] The reference category is coffee-banana

[c] The reference category is 0, i.e. mid and high altitude / no nutrient competition

4. Discussion

4.1 Climate induced constraints driving vegetation structure

The climate gradient with higher temperatures and increased drought stress at low altitude affected farmers' choice regarding vegetation structure significantly. Farmers adapted their farming practices to these adverse conditions mainly by increasing shade using a diversity of tree species. Bananas, on the other hand, appear less favorable in the drier and hotter low altitude areas (see also van Asten et al. 2011a) as both coffee and banana require large amounts of water (Carr 2012). Farmers at low altitude, therefore, intercropped banana at lower densities, and CB systems were less prevalent. By contrast, the higher rainfall at higher altitudes allows for increased intercropped banana densities. This is clear evidence of ecosystem-based adaptation to differences in mean temperature and precipitation. The non-significant differences between coffee yields among systems across all altitudes is surprising, as we had expected that low shaded systems would outperform highly shaded systems under optimal climatic conditions, as documented in the literature (e.g. Beer et al. 1998; Vaast et al. 2008; Pinard et al. 2014). For example, Vaast et al. (2008) found shade to benefit coffee production under intensive management levels but suboptimal climatic conditions. Pinard et al. (2014) found that shaded coffee was more productive compared to coffee monocropping under optimal climatic conditions but low management intensity. Other previous studies in the area have already shown insignificant yield differences between coffee systems (van Asten et al. 2011b; van Rikxoort et al. 2013; Wang et al. 2015), although they did not compare systems within similar climatic conditions. Regression analysis further indicated, that while many of the CO systems would benefit from increased shade cover, the highly shaded tree cover of some of the CT systems negatively affected coffee yield, but no clear relationship between shade, altitude and coffee yield was found. On the other hand, increased banana densities appeared to have a positive effect on coffee yield on higher altitudes, but required sufficient nutrients to account for competition. As there are no evident yield differences between the analyzed coffee systems, the different patterns of system adoption along the altitude gradient can be explained by additional socio-economic factors.

4.3 Socio-economic constraints driving vegetation structure

Next to biophysical factors related to altitude (e.g. climate, soil) and coffee system components (microclimate modification from intercropping banana and trees, competition for water and nutrients) that clearly affect many of the ecosystem service benefits of the analyzed systems, social aspects additionally determine what benefits are preferred by the farmers. Farmers' constraints, such as issues around food security (farm size, household size, access to markets and forests, etc.), production constraints (coffee management knowledge, labor, access to inputs, credits, etc.) and objectives (e.g. importance of coffee as livelihood strategy) influence farmers choices related to coffee plot vegetation management.

In this study, altitude, number of coffee plots, the ratio of kids per household, and the belief that nutrient competition is an important constraint to intercropping, was most decisive in farmers' adoption of coffee system. Altitude, one of the main drivers affecting adoption of CB and CT systems, is not only a proxy for climate but also for the proximity to forest resources at high altitudes, particularly firewood (Sassen et al. 2015), and distance to important markets such as the city of Mbale. Farmers at low altitudes depend much more on trees to mitigate climatic effects due to increased temperature and prolonged dry season. They also rely on tree resources from farm trees, owing to the lack of trees outside the coffee plots where land-use is primarily dedicated to annual crops.

Labor intensity was not significantly different between systems and altitude ranges. Farm and household size, as well as the importance of coffee as a livelihood strategy, did, however, seem to play an important role regarding coffee system adoption. Intercropping, particularly with shade trees, is associated with smaller farms, larger household sizes, and fewer cultivated coffee plots. Sassen et al. (2015) found that the most populated areas on Mt. Elgon were also the ones with highest tree densities, which corroborates our results. It can be concluded, therefore, that CO systems are only possible if land requirements for meeting household food needs result in a 'land surplus' rather than a 'land gap' (Hengsdijk et al. 2014). This implies that self-sufficiency is the primary driver in decision making regarding coffee plot structure.

Belief systems related to the benefits and constraints of intercropping also play an important role. Farmers with low intercropped banana and shade tree densities (i.e. CO systems) tend to perceive nutrient competition as a major constraint to intercropping. This perception is shared by all coffee stakeholders and is disseminated through extension service (Jassogne et al. 2013). Although intercropping might be constrained by nutrient limitations in many situations, not intercropping under current situation does not necessarily lead to higher yields, as illustrated by our data.

4.4 Implications for biodiversity conservation

On Mt. Elgon, trees improve coffee production to some degree. Beyond coffee production, trees and intercropped bananas improve farmer livelihoods, particularly where land is scarce and access to trees outside their farms is lacking. This has important consequences for biodiversity conservation and related ecosystem services. Controversially, tree biodiversity on coffee plots decreases with altitude and socio-economic status of farmer, while the area cultivated with coffee increases with altitude, impacting biodiversity negatively on a landscape scale. Higher yields were generally found on plots with lower species richness, indicating that increased biodiversity conservation within a SI model is a challenge (see also Garcia et al. 2010; Boreux et al. 2013; Carsan et al. 2013). This suggests that appropriate incentives will be required to retain high biodiversity within the agricultural area of Mt. Elgon. These incentives should be based on principles of ecological intensification and taking into account the socio-economic heterogeneity of famers' livelihoods (Giller et al. 2011; Vignola et al. 2015). Based on the historically contested relationship between the Mt. Elgon National Park and the farmer communities bordering it (Cavanagh & Benjaminsen 2014), we see strong necessity and potential for collaboration. Instead of only focusing on protecting the remnant forest, certain measures could conserve biodiversity within the agricultural area where synergies with coffee production and farmers' livelihoods are met (see also Baudron & Giller 2014). Ideally, this initiative should be integrated with work conducted by local coffee certification bodies which focus on biodiversity. This could also expand to other ecosystem services, such as landslide prevention measures, where diversified coffee agroforestry could be strategically promoted on landslide prone areas (Knapen et al. 2006; Claessens et al. 2007; Mugagga et al. 2012).

4.5 Sustainable intensification of coffee production in the face of climate change

Under current management, intercrops and shade do not affect coffee production negatively under optimal climatic conditions, nor do they improve coffee production under suboptimal climatic conditions. Other management aspects such as nutrient management and pest and disease control play a more important role. Under current management, most CO systems could benefit by intercropping more bananas and/or shade trees due to the non-significant differences in coffee yield while taking into account the additional benefits of fruits, firewood, timber, and mulch provided by bananas and shade trees. Significantly higher coffee yields in CO systems could only be achieved if planting densities were increased, substantially higher nutrient inputs were applied and if pest and disease control were improved. Although CO systems in this study area tended to be owned by wealthier families (more farmland, smaller household size) that pursued coffee as a more serious business (more land devoted to coffee), their management is still not sufficient to significantly increase yield by reducing potential competition for light, water, and nutrients. In East Africa high input systems in smallholder contexts are rarely the case (Tittonell & Giller 2013), leading to the conclusion that unshaded systems are less appropriate for the majority of East African smallholder farmers if not accompanied by changes towards a stimulating socio-economic context allowing for adequate management.

Appropriate management of vegetation structure, with site-specific adapted intercropped species and planting densities, provides a valuable approach towards SI (increased overall production per unit area) and climate change adaptation (increased resiliency to climate extremes). While this approach to SI contributes to the improvement of farmers' livelihoods, it does not necessarily increase overall coffee production, and might potentially conflict with SI goals of the coffee sector. Other important factors that might affect coffee yields include improved nutrient management, and pest and disease control. These need to consider the resources available to farmers (principally mulch and manure), and the relationship between pests and diseases, climate, and vegetation structure, which to a large extent remains unknown.

This study shows the inherent difficulty in applying SI, as what is interpreted as SI for one stakeholder (e.g. farmer) might not hold true for another (e.g. coffee sector). Understanding the relationships and trade-offs between coffee yield increase, farmers' livelihoods, and biodiversity conservation is therefore crucial for effective implementation of SI. Furthermore, different pathways that lead to yield increases have different impacts on biodiversity and related ecosystem services (Tscharntke et al. 2012). Learning from past successes and failures of intensification pathways that occurred in other regions (e.g. Garcia et al. 2010; Boreux et al. 2013; Vignola et al. 2015) with consideration of their costs related to farmers' livelihoods and ecosystem services can contribute in finding adequate models of SI.

To achieve this, best-fit management practices have to be tailored according to the socio-economic aspects of the farming system and their environmental context (table 6; Ojiem et al. 2006; Giller et al. 2011; Tittonell et al. 2011; Coe et al. 2014; Lescourret et al. 2015). This requires an enabling environment that responds to the socio-ecological heterogeneity of farming systems. Furthermore, eliciting the perceptions and interests of different stakeholders, including their definitions of SI, allows to minimize conflicting objectives and actions. Using typologies of coffee systems on plot scale, combined with typologies of farming systems (livelihood strategies) in contrasting environmental settings enables adequate characterization of the socio-ecological heterogeneity. These typologies provide a basis for multi-stakeholder engagement to explore appropriate interventions and evaluate possible trade-offs and synergies.

Table 6 : Management recommandations based on socio-ecological context

Agro-ecological context:	Climate *x* soil *x* landscape $aec_1, aec_2, aec_3, aec_i, \ldots$
Socio-economic context:	Farm size, age of farmer, gender, household size, wealth, objectives, etc. $sec_1, sec_2, sec_3, sec_i, \ldots$
Socio-ecological context:	$aec_i \times sec_i$ → Management recommandations

Conclusions

This study investigated the potential for ecosystem-based adaptation to climate change along the slopes of Mt. Elgon, Uganda as a means towards sustainable intensification. Our results suggest that smallholder coffee systems benefit from intercropping, but that the choice of intercrop type is highly dependent on the socio-ecological conditions. Climate had a great influence on farmers' adoption of a certain coffee system. While high rainfall amounts at high altitude allow for intercropping high banana densities, farmers responded to the high temperature and drought stress on low altitude with increased shade tree densities. The landscape setting, such as access to forest and markets, as well as climatic factors, drive the relative benefits of different intercrops. High rainfall at high altitudes allowed for high intercropped banana densities, which given the remote distance to markets, has importance for food security. Consequently, biodiversity conservation within coffee plots was highest furthest from the protected forest, where land-use is dominated by annual crops and tree cover outside the coffee plots is generally lowest.

The study clearly shows that managing vegetation structure to balance the trade-offs among pests and diseases, nutrient and water competition, micro-climate, and resilience to climatic and market shocks, is highly complex. These relationships also need to be understood in the context of local farmers' realities. Different concepts of sustainable intensification and climate-smart agriculture need to be explored among all stakeholders to achieve common understanding and identify appropriate development pathways.

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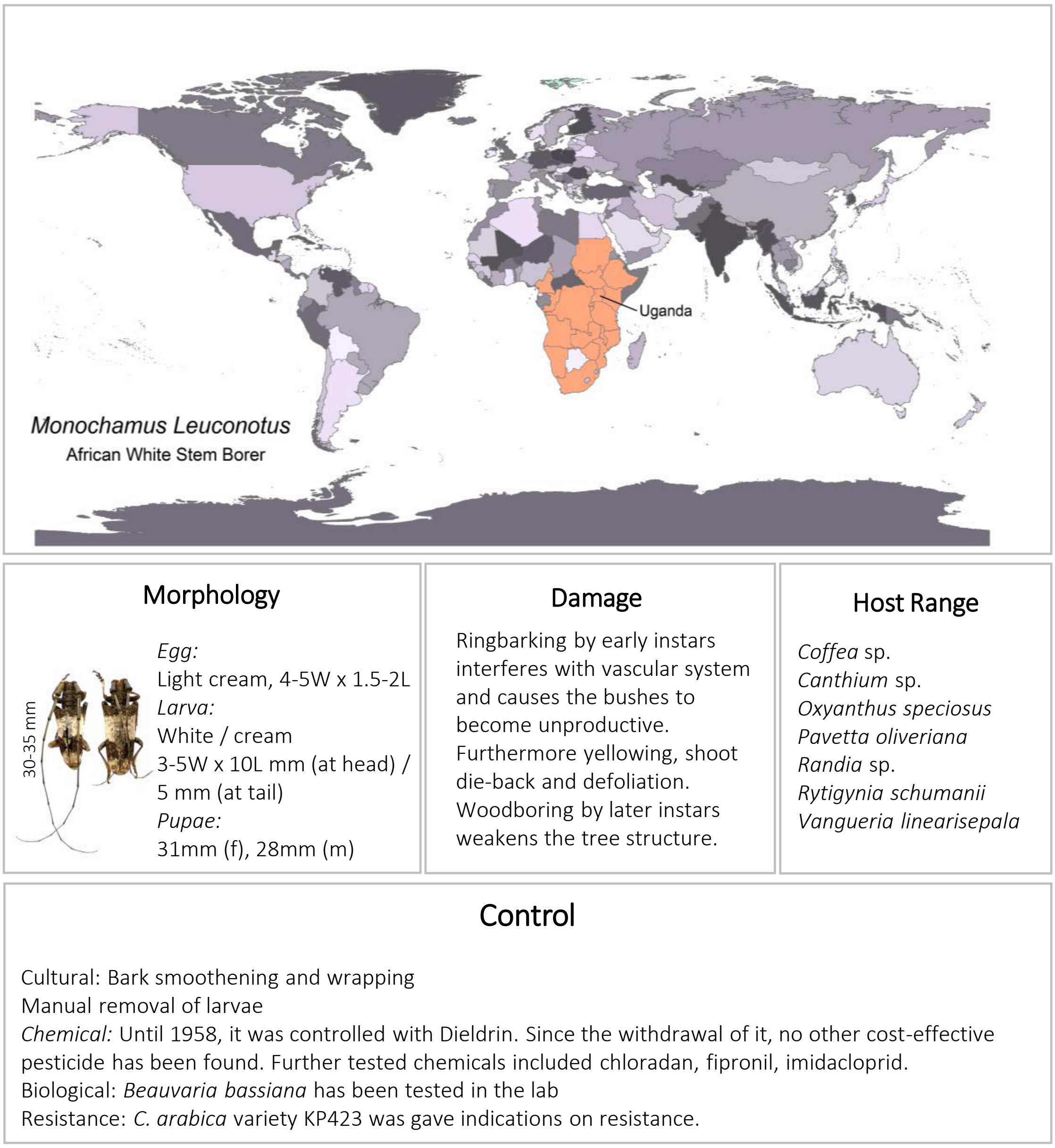
A.2 Figures



Morphology

Egg:
Light cream, 4-5W x 1.5-2L
Larva:
White / cream
3-5W x 10L mm (at head) / 5 mm (at tail)
Pupae:
31mm (f), 28mm (m)

Damage

Ringbarking by early instars interferes with vascular system and causes the bushes to become unproductive. Furthermore yellowing, shoot die-back and defoliation. Woodboring by later instars weakens the tree structure.

Host Range

Coffea sp.
Canthium sp.
Oxyanthus speciosus
Pavetta oliveriana
Randia sp.
Rytigynia schumanii
Vangueria linearisepala

Control

Cultural: Bark smoothening and wrapping
Manual removal of larvae
Chemical: Until 1958, it was controlled with Dieldrin. Since the withdrawal of it, no other cost-effective pesticide has been found. Further tested chemicals included chloradan, fipronil, imidacloprid.
Biological: *Beauvaria bassiana* has been tested in the lab
Resistance: *C. arabica* variety KP423 was gave indications on resistance.

Figure 20: Factsheet *Monochamus leuconotus* (WCSB), 1.

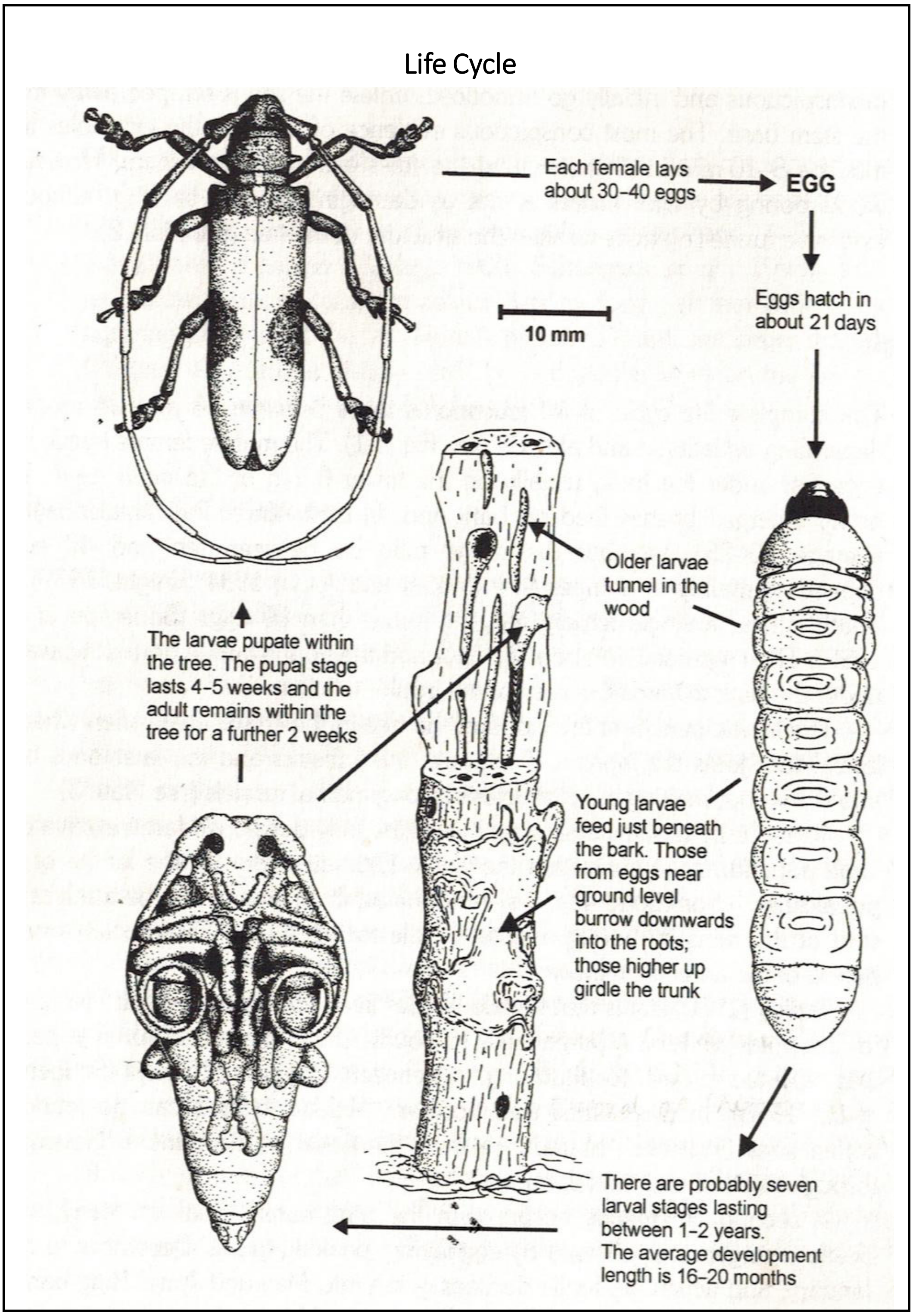
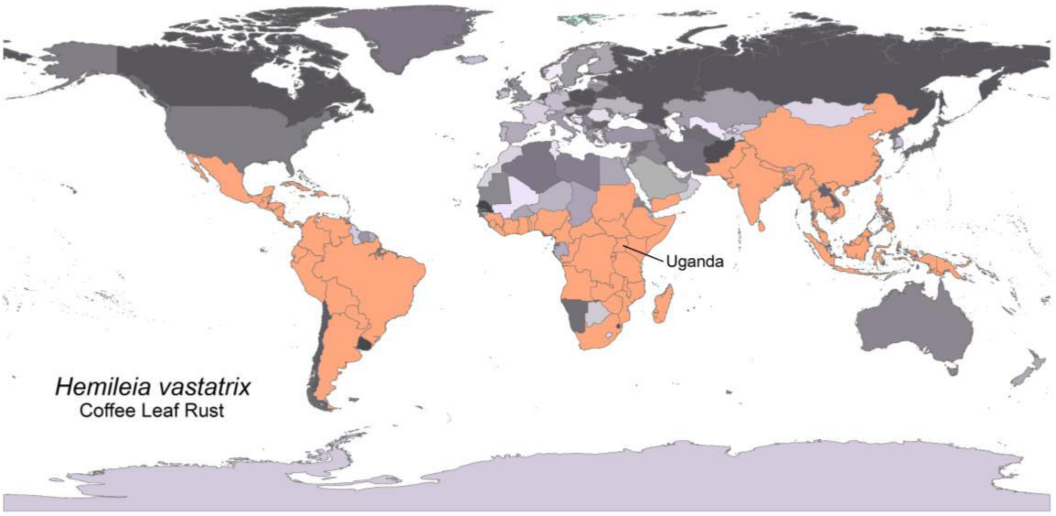
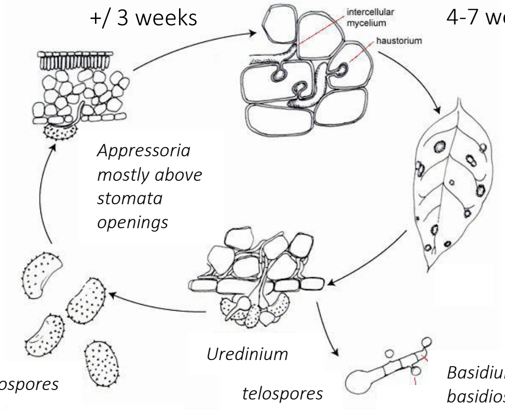


Figure 21: Factsheet *Monochamus leuconotus* (WCSB), 2. References: Dufpy et al. (1957); Tapley (1960); Le Pelley (1973); Schoeman and Pasques (1993); Schoeman et al. (1998); Waller et al. (2007); Karanja et al. (2010); Egonyu et al. (2015); Cerambycoidea (n.a.); Plantwise (n.a.)



Symptoms, Morphology & Epidemiology



Latent period:
+/ 3 weeks

Incubation period:
4-7 weeks

Symptoms:
Orange powdery spots on underside of leaves & chlorotic patches on upper side, defoliation

Infection:
Uredospores need liquid water for germination.
Opt. temp.: 21-25 °C

Dispersal : By wind and rain

Host Range

Mainly
Coffea arabica and
Coffea canephora.

Control

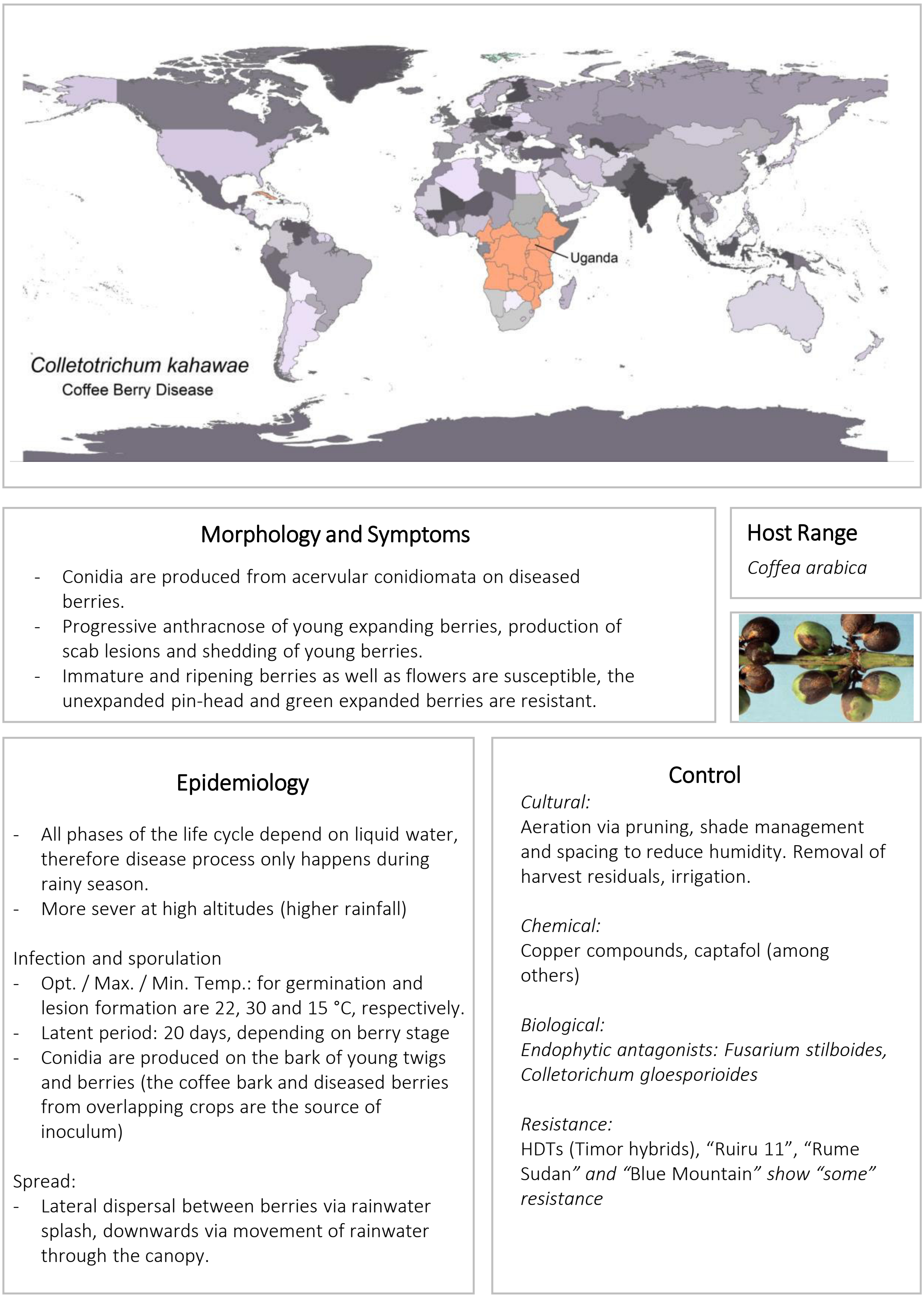
Cultural: Use of resistant varieties, shade management, maintaining plant vigor by proper pruning and weeding

Chemical: Copper and Triazole compounds Strobilurins

Biological: Hyperparasites (Lecanicillium lecanii), Endophytic bacteria (*Bacillus* sp.)

Resistance: HDT hybrids (Arabica x Canephora, e.g Catimores, Sarchimores, Colombia))

Figure 22: Factsheet *Hemileia vastatrix* (CLR). References:Rayner (1952); De Jong et al. (1987); Kushalappa and Eskes (1989); Waller et al. (2007); Haddad et al. (2009); Vandermeer et al. (2009); Matovu et al. (2013); CAB Direct (n.a.); Apsnet (n.a.)



Morphology and Symptoms

- Conidia are produced from acervular conidiomata on diseased berries.
- Progressive anthracnose of young expanding berries, production of scab lesions and shedding of young berries.
- Immature and ripening berries as well as flowers are susceptible, the unexpanded pin-head and green expanded berries are resistant.

Host Range

Coffea arabica

Epidemiology

- All phases of the life cycle depend on liquid water, therefore disease process only happens during rainy season.
- More sever at high altitudes (higher rainfall)

Infection and sporulation
- Opt. / Max. / Min. Temp.: for germination and lesion formation are 22, 30 and 15 °C, respectively.
- Latent period: 20 days, depending on berry stage
- Conidia are produced on the bark of young twigs and berries (the coffee bark and diseased berries from overlapping crops are the source of inoculum)

Spread:
- Lateral dispersal between berries via rainwater splash, downwards via movement of rainwater through the canopy.

Control

Cultural:
Aeration via pruning, shade management and spacing to reduce humidity. Removal of harvest residuals, irrigation.

Chemical:
Copper compounds, captafol (among others)

Biological:
Endophytic antagonists: Fusarium stilboides, Colletorichum gloesporioides

Resistance:
HDTs (Timor hybrids), “Ruiru 11”, “Rume Sudan*” and “*Blue Mountain*” show “some” resistance*

Figure 23: Factsheet *Colletotrichum kahawae* (CBD). References:Rayner (1952); Nutman and Roberts (1961); van der Vossen et al. (1976); Mulinge (1970); Griffiths and Waller (1971); Waller (1972); Firman et al. (1977); Waller and Masaba (2006); Waller et al. (2007); Plantwise (n.a.); Citelighter (n.a.)

1)	**Agricultural activities during the year**	
	Key questions:	*Tool:*
a)	When are rainy (and dry) seasons?	
b)	Cropping periods for different crops (planting to harvesting for annual crops, harvesting for perennial crops)	Seasonal calendar
c)	Activities for coffee: When are fertilizer, herbicides, insecticides, fungicides applied, when is pruned?	
d)	Overlaps with activities for other crops?	
2)	**Importance of food and cash crops and Food security**	
	Key questions:	*Tool:*
a)	List 5 most important cash crops of the region and rank them.	
b)	List 5 most important food crops of the region and rank them.	Ranking
c)	What foods do you eat normally?	
d)	How often do you eat each of these foods?	
e)	Which foods become scarce first during the year and in which months?	
f)	During such months, how many times do you eat a day?	Group discussion
g)	If you had a problem to get a good diet last year, what were the reasons for these problems? What did the community and households do to resolve these problems?	
3)	**The use of shade / banana trees and constraints for coffee production (including P&D)**	
	Key questions:	*Tool:*
a)	Which shade trees (including banana) are prevalent in the community?	Open conversation
b)	Are there more shade trees now than in former times and why?	
c)	If you want to plant a shade tree, in which crop would you plant it and why?	
d)	What are the challenges in increasing area under shade trees in your field?	Ranking
e)	What are the yield limiting factors?	
f)	Rank these factors according to their severity.	
g)	Major P&D problems (in the last 5 years) in rainy and dry season.	
4)	**Perception of climate change**	
	Key questions:	*Tool:*
a)	Is climate changing and if yes, what has changed in the last 10 years?	Group discussion
b)	How has climate change affected agriculture? Please rank effects.	
c)	What crops are most affected by climate change in agriculture? How is coffee affected?	
d)	How do the farmers strategically cope with the changes in climate in coffee production?	Rank effects
e)	In this community, have you received any training on climate change or natural resource management? What was the training about?	Rank crops
f)	Are there any bi- laws or rules and regulations governing the use of natural resources in this community and if yes mention some of them and who enforces them?	Rank strategies
g)	How is the community affected (positively and negatively) from the above mentioned bi-laws?	
h)	Is the local community involved in the policy formulation? If yes how and when is the community involved?	

Figure 24: Participatory Rural Appraisals (PRAs). Used tools for baseline survey (March/April 2014)

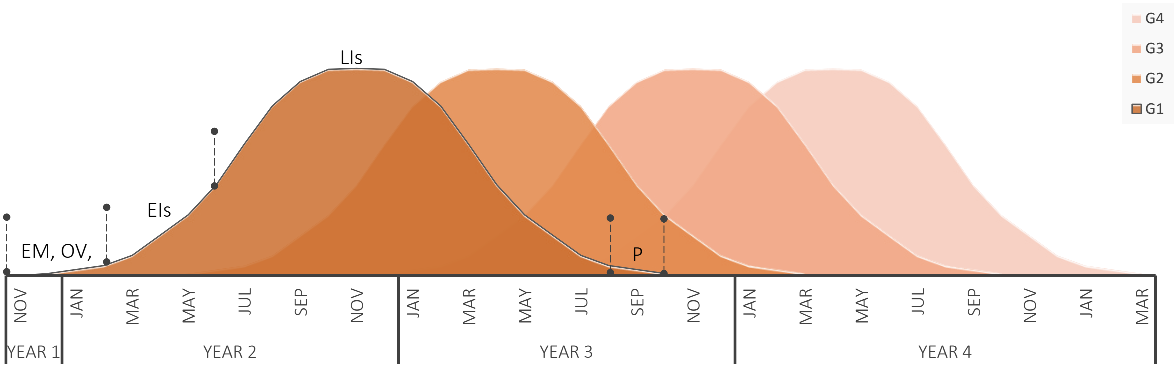


Figure 25: Theoretical WCSB phenology showing overlapping generations of 4 subsequent years. EM = Emergence of adults (with following feeding and mating), OV = Oviposition, HT = Hatching of eggs, EIs = Early-Instar ringbarking stages feeding on phloem and cambium tissue, LIs = Late-instar woodboring stages feeding mainly on xylem tissue, P = Pupal stage. Life cycle information is based on Knight (1939), Tapley (1960), Schoemann et al., (1998) and Gichuhi et al., (2016). The duration of individual life cycle stages varies depending on study, altitude and latitude, respectively

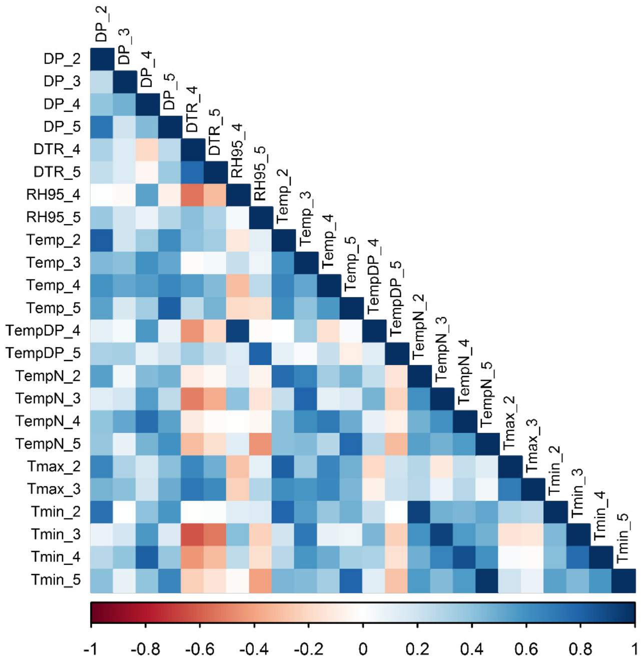


Figure 26: Selection procedure for micro-climatic variables and respective time periods to use in piecewise SEM. (A) Visualization of the correlation coefficients matrix between micro-climatic variables and respective periods, related with CLRmax (verified by plotting CLRmax against each potential micro-climatic variable. Out of the initial number of 63 variables, 24 showed a relationship with CLRmax). Numbers refer to monitoring dates: (2) May/June, (3) July/August, (4) September, (5) October / November

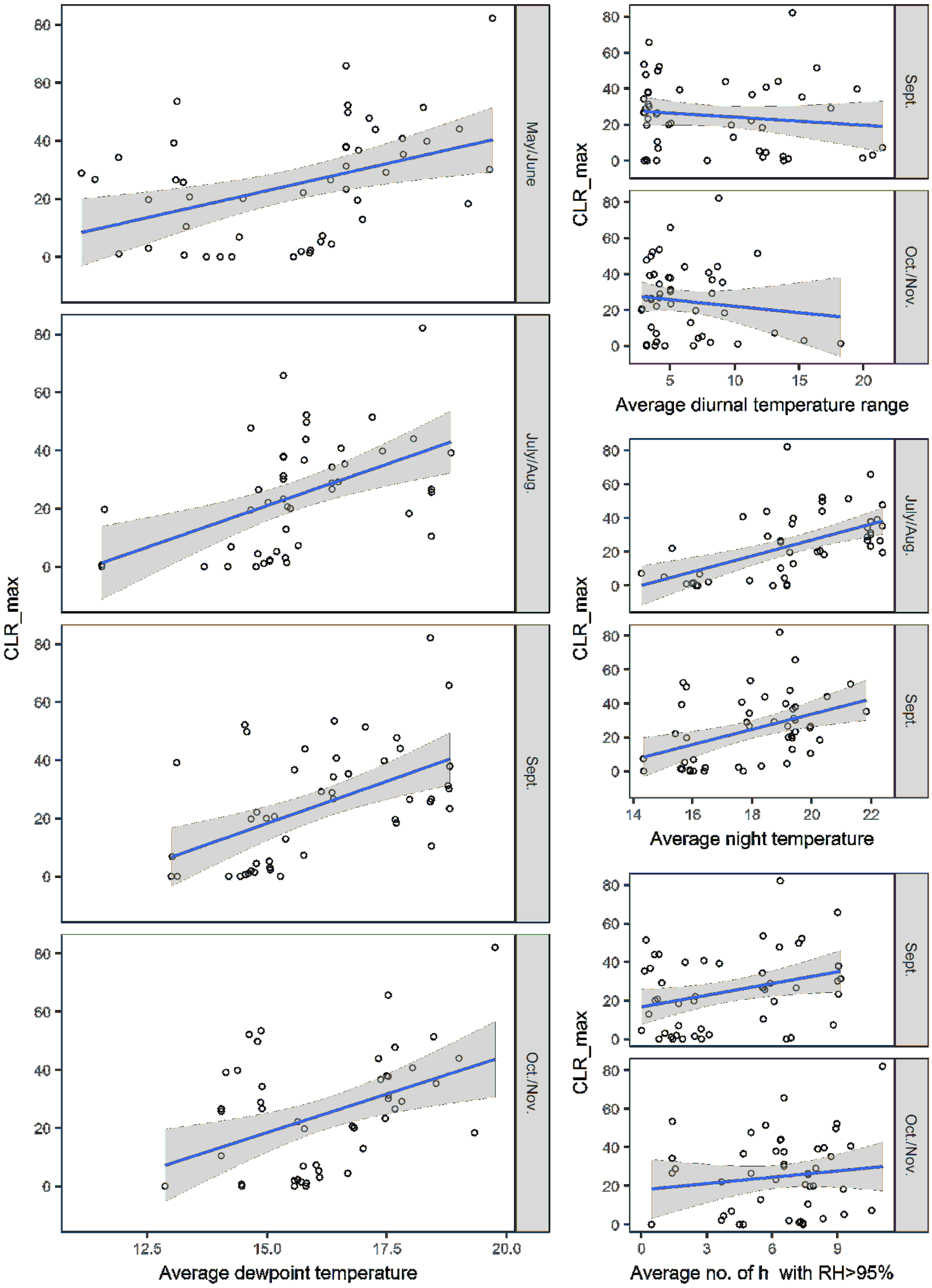


Figure 27: (B) Remaining 10 variables after exclusion of highly correlated variables (identified via significant tests of the correlation coefficients) showing its relationship with CLRmax. Since time periods within a variable of micro-climate were autocorrelated among themselves, they were joined to one variable (e.g. dew point temperature of the four time periods were joined to dew point temperature for the period between May–November), resulting in a final number of four micro-climatic variables used in the piecewiseSEM

A.3 Tables

Table 13: Dataset for spatial analysis. Number of plots per altitude range and system

	Altitude range			
Coffee system	**Low**	**Mid**	**High**	*Total*
CB	26	13	20	59
CO	12	13	24	49
CT	40	22	10	72
Total	78	48	54	180

Table 14: Categorization of input data for MCA, WCSB analysis

	WCSB	*n*	**CanClos**	*n*	**NoST_ha**	*n*	**NoSTS**	*n*	**NoBM_ha**	*n*	**NoS**	*n*
1	0	20	10.07	24	3.03	14	1	26	38.78	39	15.8	27
2	0.15	29	25.5	25	28.23	20	3.48	31	1266.56	44	23.9	28
3	0.39	17	47.89	34	56.77	23	6.45	26			34.3	28
4	0.63	17			100.9	18						
5					237.29	8						

Table 15: Analysis of variance for generalized model (GLM) for WCSB incidence

	Chisq	**Df**	**Pr>Chisq**
Alt_cat	9.525	2	<.001**
CS	39.178	2	<.0001***
Alt_cat x CS	35.976	4	<.0001***

n = 84, AIC =293.054, likelihood ratio test: χ^2 (1) = 118.79, p < .0001***

Table 16: Analysis of variance for linear mixed-effects model for minimum and maximum temperature

	Minimum Temperature			**Maximum Temperature**		
	Chisq	**Df**	**Pr>Chisq**	**Chisq**	**Df**	**Pr>Chisq**
Alt_cat	na			40.72651322	2	<.0001***
CS	na			57.56678302	2	<.0001***
Month	na			295.9666421	8	<.0001***
Alt_cat x CS	61.14309181	4	<.0001***			
Alt_cat x Month	155.2628247	16	<.0001***			
Alt_cat x CS x Month	125.9868322	32	<.0001***			

n = 142. AIC = 73.687 and R^2(combined) = 0.98 (Min. Temp.) and AIC = 553.94 and R^2(combined) = 0.78 (Max. Temp.). Given the strong interactions in the model for minimum temperatures, the global effects (grey font colour) are not considered.

Table 17: Differences in predicted minimum temperatures between months by altitude and coffee system

	Minimum temperature								
	Mar	*Apr*	*May*	*July*	*Aug*	*Sept*	*Oct*	*Nov*	*Dec*
				Low					
CB	b	a	a	a	a	a	a	a	a
CO	c	a	a	ab	ab	ab	ab	ab	b
CT	c	abc	bc	abd	ad	d	abcd	abc	ad
				Mid					
CB	b	a	a	a	a	a	a	a	a
CO	b	a	a	a	a	a	a	a	a
CT	b	a	a	a	a	a	a	a	a
				High					
CB	b	a	a	a	a	a	a	a	a
CO	e	abc	ce	a d	d	ad	bc	abcd	abd
CT	c	ab	ab	a	ab	ab	b	ab	ab

Tukey-type comparisons of LMM-parameters, p<.05, tested separately for each altitude category and coffee systems. Means within rows with different letters indicate significant differences (tested for each altitude category separately)

Table 18: Stumping activities of farmers based the baseline survey (Chap. 2)

Time of stumping 1)	*Jan*	12.84%
	Feb	10.81%
	Mar	8.11%
	Apr	2.70%
	May	0.68%
	Jun	0.68%
	Jul	2.03%
	Dec	2.70%
	na	59.46%
Use of pruned stuff 2)	Yes	92.57%
	Mulching	4.40%
	Firewood	46.52%
	Kraal construction	15.38%
	Animal feed	6.23%
	Thatching	24.54%
	Sticking	2.93%
	No	6.76%
	na	0.68%

Table 19: References for conceptual model illustrating potential relationships between components of the environment, coffee production system, micro-climatic indicators, coffee productivity and coffee pests and diseases

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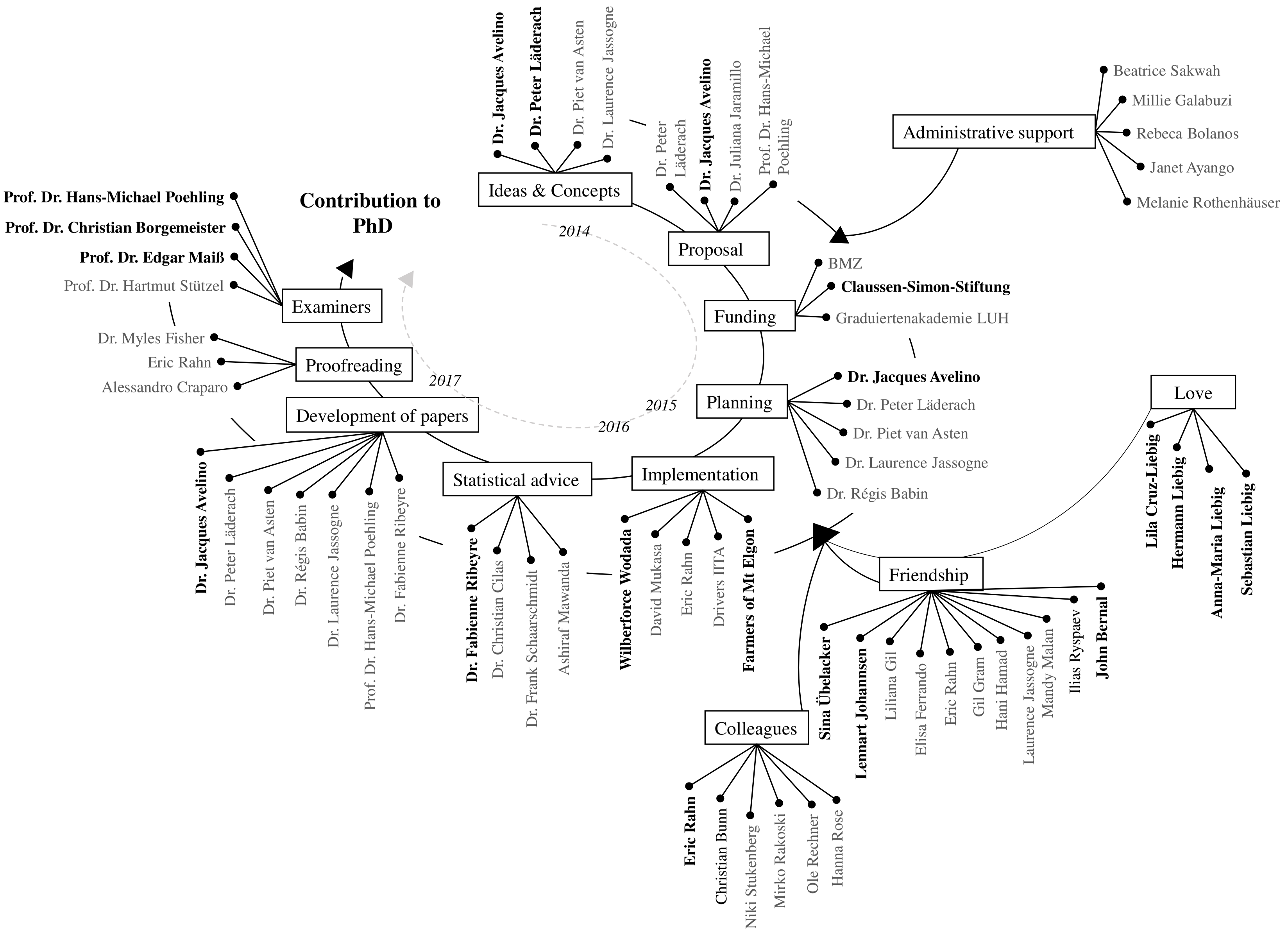
Contribution to PhD
Examiners
Prof. Dr. Hans-Michael Poehling
Prof. Dr. Christian Borgemeister
Prof. Dr. Edgar Maiß
Prof. Dr. Hartmut Stützel
Proofreading
Dr. Myles Fisher
Eric Rahn
Alessandro Craparo
Development of papers
Dr. Jacques Avelino
Dr. Peter Läderach
Dr. Piet van Asten
Dr. Régis Babin
Dr. Laurence Jassogne
Prof. Dr. Hans-Michael Poehling
Dr. Fabienne Ribeyre
Statistical advice
Dr. Fabienne Ribeyre
Dr. Christian Cilas
Dr. Frank Schaarschmidt
Ashiraf Mawanda
Implementation
Wilberforce Wodada
David Mukasa
Eric Rahn
Drivers IITA
Farmers of Mt Elgon
Ideas & Concepts
Dr. Jacques Avelino
Dr. Peter Läderach
Dr. Piet van Asten
Dr. Laurence Jassogne
Proposal
Dr. Peter Läderach
Dr. Jacques Avelino
Dr. Juliana Jaramillo
Prof. Dr. Hans-Michael Poehling
Funding
BMZ
Claussen-Simon-Stiftung
Graduiertenakademie LUH
Planning
Dr. Jacques Avelino
Dr. Peter Läderach
Dr. Piet van Asten
Dr. Laurence Jassogne
Dr. Régis Babin
2014
2015
2016
2017
Administrative support
Beatrice Sakwah
Millie Galabuzi
Rebeca Bolanos
Janet Ayango
Melanie Rothenhäuser
Love
Lila Cruz-Liebig
Hermann Liebig
Anna-Maria Liebig
Sebastian Liebig
Friendship
Sina Übelacker
Lennart Johannsen
Liliana Gil
Elisa Ferrando
Eric Rahn
Gil Gram
Hani Hamad
Laurence Jassogne
Mandy Malan
Ilias Ryspaev
John Bernal
Colleagues
Eric Rahn
Christian Bunn
Niki Stukenberg
Mirko Rakoski
Ole Rechner
Hanna Rose

C Curriculum Vitae

Theresa I. Liebig

theresa.liebig@gmail.com | (+49) 176 789 28 003

PERSONAL

Date of birth
26 of September 1986
Place of birth
Fulda, Germany
Nationality
German/Colombian
Marital status
Single

EDUCATION

LEIBNIZ UNIVERSITY HANOVER (LUH)
PhD
Grad. July 2017 (s.c.l.) | Hanover Germany

UNIVERSTIY OF HOHENHEIM
Diploma/Masters
Agricultural Biology
Grad. July 2012 (1.6)|
Hohenheim, Germany

EDUARD-STIELER-SCHULE
Secondary school
Grad. June 2006|
Fulda, Germany

SKILLS

SOFTWARES

- R
- ArcGIS
- LaTex
- Microsoft Office

LANGUAGES

- German, mothertounge
- Spanish, good in written spoken
- English, good in written spoken

REFERENCES

Dr. Jacques Avelino
jacques.avelino@cirad.fr
Dr. Peter Laederach
p.laderach@cgiar.org
Dr. Laurence Jassogne
l.Jassogne@cgiar.org
Dr. Piet van Asten
p.vanasten@cgiar.org

EXPERIENCE

LUH / CIAT / IITA | PhD student
since February 2014 | Germany / Uganda / Colombia

- Project title: Abundance of pests & diseases in Arabica coffee production systems in Uganda - ecological mechanisms and spatial analysis for site specific crop health management in the face of climate change

CIAT / DAPA | Visiting researcher
July 2012 – January 2014 | Cali, Colombia

- Project title: Spatial decision support for coffee pests disease risk management in Central America
- Project title: The Thin month – socioeconomic study on livelihoods of coffee farmers in Central America
- Activities: Data analysis, GIS based modelling, farmer surveys, workshops, data analysis, report writing

CIAT / PHYTOPATHOLOGY LABORATORY | Diploma thesis
July – December 2011 | Cali, Colombia

- Project title: Evaluation of Phaseolus bean accessions for identification of sources of resistance to Macrophomina Phaseolina under drought stress

CIAT / TROPICAL FRUIT & FORAGES PROGRAM Internships
April - June 2011 & March - May 2010 | Cali, Colombia

- Project title: Sustainable options for soil management to reduce the effect of Ralstonia Solanacearum, Moko disease-causing agent in the cultivation of banana
- Activities: Inoculation trials in greenhouse, isolation and purification of bacterial cultures, DNA extraction and PCR.
- Project title: Isolation and identification of the causal agent of bacterial wilt in Brachiaria
- Activities: Laboratory tests of antibacterial effect of natural banana residues, chemical analysis of compounds

ASOCIACIÒN DE AGRICULTURA ECOLOGICA Internship
August - September 2009 | Puerto Maldonado, Peru

- Agriculture with agroforestry practices

UNIVERSITY OF HOHENHEIM Tutor
2009 - 2011 | Hohenheim, Germany

SCHOLARSHIPS

German development agency (GIZ), Grant for Diploma thesis (2011)
Agricultural and Environmental Compensation Foundation, travel grant (2014)
Claussen-Simon-Stiftung, 3-year grant for PhD (2014-16)
Graduate Academy of Leibniz Universität Hannover, travel grant (2016)

CONFERENCES

2016, Kunming, China, The 26th international conference on coffee science
2015, Berlin, Germany, Tropentag
2014, Armenia, Colombia, The 25th international conference on coffee science
2012, Costa Rica, National The 25th international conference on coffee science
2011, Brazil, Colloquium on Certification of planting Material of Grapevine

D List of publications

Peer reviewed

- **Liebig, T.**, Jassogne, L., Rahn, E., Läderach, P., Poehling, H. M., Kucel, P., van Asten, P. and Avelino, J. (2016). Towards a Collaborative Research: A Case Study on Linking Science to Farmers Perceptions and Knowledge on Arabica Coffee Pests and Diseases and Its Management. PloS one, 11(8), e0159392.

Submitted / In process

- **Liebig, T.**, Ribeyre, F., Läderach, P., Poehling, H. M., van Asten, P. Jassogne, L. Cilas, C. and Avelino, J. (2017). Direct, indirect and interactive effects in coffee agroecosystems: A case study on the role of micro-environments on Coffee Leaf Rust. *In process* (Agriculture, Ecosystems & Environment)
- **Liebig, T**., Babin, R., Ribeyre, F., Läderach, P., Poehling, H. M., van Asten, P. Jassogne, L., Cilas, C. and Avelino, J. (2017). Cross-scale bioecology of the White Coffee Stem Borer (*Monochamus leuconotus*) *Submitted* to Journal of pest science
- Rahn, E, **Liebig, T**., van Asten, P., Jassogne, L., E., Ghazoul J., Vaast, P. and Garcia C. and Läderach, P. (2017) Sustainable intensification of coffee agro-ecosystems in the face of climate change along the slopes of Mt. Elgon, Uganda. *Submitted* to Agriculture, Ecosystems & Environment

Non peer reviewed

- **Liebig, T**., Jassogne, L., Rahn, E., Läderach, P., Poehling, H. M., Kucel, P., van Asten, Piet and Avelino, J. (2015). Knowledge Gaps between Farmers and Scientists: A Case Study on Perceptions and Knowledge on Arabica Coffee Pests and Diseases of Mount Elgon, Uganda., Poster session presented at the Tropentag, Berlin, Germany.
- Rahn, E., **Liebig, T**., Jassogne, L., Läderach, P., van Asten, P., Vaast, P. and Ghazoul, J. (2015) Interactive Effects of Altitude and Management on Coffee Agro-Ecosystems Along a Transect on Mount Elgon, Uganda. Poster session presented at the Tropentag, Berlin, Germany.
- Gehling, M., **Liebig, T**., Graefe, S., Vaast, P., van Asten, P. and Jassogne, L. (2015) Characterisation and Spatial Distribution of Shade Trees and Bananas in Arabica Coffee Systems of Eastern Uganda. Poster session presented at the Tropentag, Berlin, Germany.

- Caswell, M., Mndez, V. E., Baca, M., Läderach, P., **Liebig, T**., Castro-Tanzi, S. and Fernndez, M. (2014). Revisiting the Thin MonthsA Follow-up Study on the Livelihoods of Mesoamerican Coffee Farmers. CIAT Policy Brief No 19.
- **Liebig, T**., Läderach, P., Quiroga, A., Anzueto, F., Matute, N. and Avelino, J. (2014). Spatial Decision Support for Coffee Disease Management: Site-Specific Shade-Environment Interaction affecting American Leaf Spot Disease. Poster session presented at the 25th International Conference on Coffee Science, Armenia, Colombia.
- **Liebig, T**., Ribeyre, F., Läderach, P., Jassogne, L., Poehling, H. M., van Asten, P. and Avelino, J. (2016). Characterisation of microclimatic indicators in coffee production systems under varying biophysical contexts and its relation to fungal coffee diseases. Paper presented at the 26th International Conference on Coffee Science, Kunming, China.