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Opportunities for sustainable intensification of coffee agro-ecosystems along an altitudinal gradient on Mt. Elgon, Uganda.

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Abstract

The viability of coffee farming in East Africa is endangered by multiple factors including climate change, population pressure, low yields, and coffee price volatility. Sustainable intensification (SI) through intercropping and/or agroforestry has been suggested to improve farmers' livelihoods, facilitate adaptation of coffee production to climate change and contribute to biodiversity conservation.

In order to understand how sustainable intensification through an ecosystem-based approach might offer opportunities to respond to changes in temperature and rainfall, we analyzed a variety of existing coffee agro-ecosystems that differ in vegetation structure, shade tree diversity, and socio-economic characteristics on Mt. Elgon, Uganda along an altitudinal gradient (1100 – 2100 m.a.s.l.). We (i) compared the performance of the agro-ecosystems regarding coffee yield and shade tree diversity, and (ii) analyzed determinants of adoption of each system. Three different coffee agro-ecosystems were identified: open canopy coffee system, coffee-banana intercropping, and coffee-tree systems, based on the vegetation structure of 144 coffee plots.

The vegetation structure of the analyzed coffee systems varied along the altitudinal gradient. Banana density increased with increasing altitude, while shade tree density and diversity increased with decreasing altitude. Coffee yield also increased with increasing altitude, but this relationship varied with shade level. Coffee yields benefited from shade trees at low altitudes, while no yield differences among systems were observed at mid and high altitudes. Increasing water availability and reliance on on-farm food crops with increasing altitude were identified as the main determinants of the increasing intercropped banana densities. High temperatures and longer dry season in combination with reduced access to forest products at lower altitudes, appeared to be the main driver for increased adoption of coffee-tree systems. Furthermore, socio-economic status of farmers influenced the type of coffee system adopted; poor farmers preferred high intercropping (either with bananas and/or shade trees) to diversify income and reduce risks related to open systems, while wealthier farmers mainly owned open canopy coffee systems.

Climate, farm and household size, and access to forests and markets, play a crucial role in determining what constellation of plot-level provisioning ecosystem services benefit farmers' livelihoods on Mt. Elgon. Our findings reveal inherent trade-offs in socio-ecological conditions. Minimizing these is required for achieving the multiple objectives of livelihood improvement, sustainable intensification of coffee production, and biodiversity conservation.

Keywords:

Sustainable intensification, ecosystem-based adaptation, *Coffea arabica* L., shade trees, adoption, Uganda

1. Introduction

Trees in tropical agricultural systems have gained increased interest due to their potential to mitigate climate change (IPCC 2000) and for their potential as climate change adaptation strategy (Beer et al. 1998; Lin 2010; Lasco et al. 2014). Additionally, there is an increased recognition that biodiversity in tropical rural landscapes can have high conservation value while sustaining rural livelihoods (Perfecto et al. 1996; Chazdon et al. 2009; Baudron & Giller 2014). The interest in trees within agricultural areas has been accompanied by a shift in scale of analysis from the plot to farm to landscape levels (Tittonell et al. 2005; Perfecto & Vandermeer 2010; Sayer et al. 2013). Yet recognition of the ecological values of trees has not necessarily been paralleled by landscape trajectories. Indeed, many formerly diverse coffee and cocoa agroforestry systems have been 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). In many tropical countries, this is further stimulated by increasing global demand for tropical crops such as coffee and cocoa (FAO, 2015).

In Sub-Saharan Africa, the coffee yield gap is particularly large (Wang et al. 2015), and coffee production in this region has attracted the attention of various national and international agencies seeking to realize the potential for higher yields (e.g. MAAIF 2010, USAID 2011). Efforts invested in reducing the yield gap in a sustainable way are, however, challenged by climate change, which is altering the environmental conditions on which coffee depends (Jaramillo et al. 2011; Craparo et al. 2015; Ovalle et al. 2015). This is putting at risk the livelihoods of coffee farmers and is affecting ecosystem services due to land-use change (Bunn et al. 2015; Magrach & Ghazoul 2015).

In East Africa, where most of the continent's Arabica coffee (*Coffea arabica* L.) is grown, the suitable climatic range for Arabica production is limited to highland areas, often on steep mountain slopes bordering remnant Afromontane rainforest with high biodiversity conservation and ecosystem service values. Climate change is expected to further shift coffee production to higher altitudes (Bunn et al. 2015; Magrach & Ghazoul 2015). Adaptation to climate change will be required to sustain coffee production, particularly at lower altitudes, given expected rising temperatures, changes in precipitation regimes, as well as more frequent extreme events (Vaast et al 2005). Adaptation strategies include new crop varieties, shifting the location of production, irrigation, and ecosystem-based approaches to improve system resilience (Schroth & Ruf 2014; Vignola et al. 2015; Perfecto & Vandermeer 2015). Adaptation strategies need to be context specific to take account of the environmental and socio-economic constraints of different coffee growing regions (Giller et al. 2011).

Sustainable intensification (SI) entails increasing food production from existing farmland in ways that minimize environmental impacts and which do not undermine our capacity to continue producing food in the future (Garnett et al. 2013). SI also entails other aspects of the food system, such as reducing food waste. Campbell et al. (2014) argue that SI is a key component of climate change adaptation, which requires going beyond crop yield increase to include diversified farming systems, local adaptation planning, building responsive governance systems, enhancing leadership skill, and building asset diversity.

While there are a multitude of SI pathways in the context of climate change adaptation, African smallholders are often unable to benefit from the potential yield gains offered by improved technology due to limited investment capacity. African smallholders are constrained by small farm sizes, lack of capital, insufficient inputs of nutrients and organic matter, and limited access to markets (Tittonel & Giller, 2013; Harris & Orr, 2014). In this context, an ecosystem-based adaptation approach is a promising strategy towards SI and climate change adaptation.

To understand how an ecosystem-based approach might offer opportunities for coffee farmers to respond to the expected climate change challenges, we analyzed a variety of existing coffee agro-ecosystems that differ in vegetation structure and socio-economic characteristics along an altitudinal gradient. We compared the agro-ecosystems in terms of (i) coffee yield, (ii) shade tree diversity, and (iii) determinants of adoption of each system. We discuss trade-offs between coffee productivity and the different farm system components in the context of climate change adaptation and farmers livelihoods.

2. Methods

2.1 Study area

The study was conducted in three neighboring districts (Bulambuli, Sironko and Kapchorwa) of Mt. Elgon, Uganda, an extinct volcano on the border between Uganda and Kenya of 4321 meters altitude (Fig. 1). The topography of the slope is characterized by two escarpments that naturally separate three altitude classes of < 1400 m.a.s.l., 1400 – 1700 m.a.s.l., and > 1700 m.a.s.l. within the inhabited area of the mountain. Local farming communities live on the foothills (1000 m.a.s.l.) up to the protected Mt. Elgon National Park (2200 m.a.s.l.), and depend heavily on this forest for construction material, stems used as crop-support, and biomass for charcoal and firewood. (Sassen et al. 2013, 2015; Sassen & Sheil 2013).

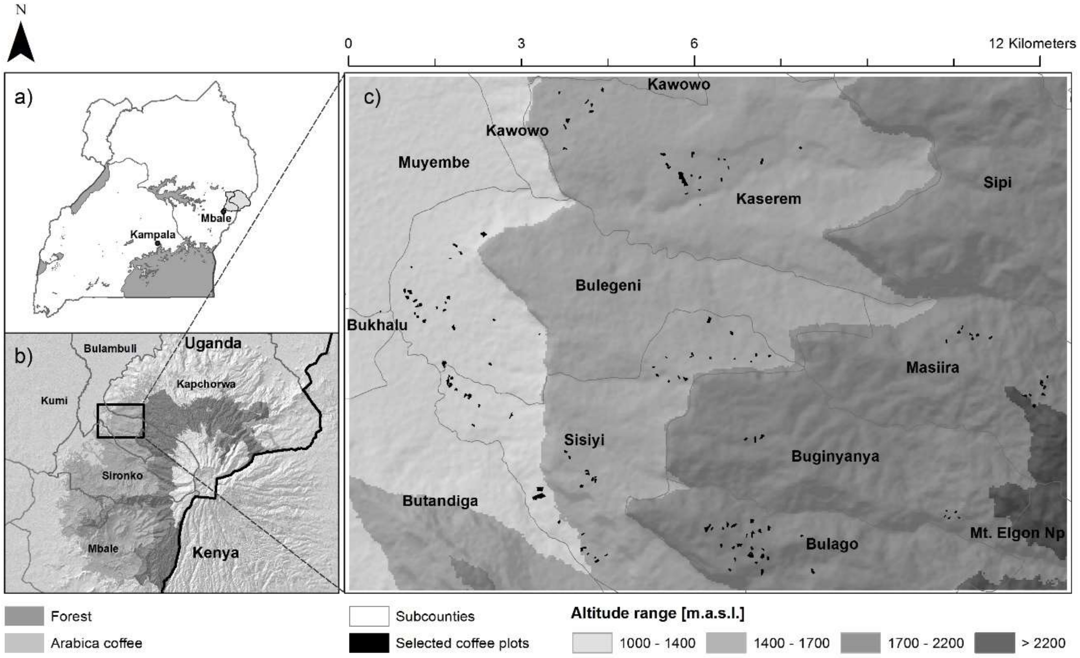

Fig. 1. a) Location of the study area within Uganda, Mt. Elgon area, b) Districts of study area (Bulambuli, Sironko, Kapchorwa), c) Study site with indication of three altitude ranges (determined by means of cluster analysis), sub-counties and sample plots.

Soils of the study area are mainly Nitisols (FAO soil classification) with presence of phaeozems at low altitude (De Bauw et al. 2015). The climate is influenced by dry northeasterly and moist south-westerly winds, resulting in less rainfall on the north western slopes as compared to elsewhere on the mountain. A bimodal rainfall pattern prevails, with the wettest periods during March/April to October/November, a pronounced dry period from December to February, and a period of less intense rainfall 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 (1000 m.a.s.l.) to 1400 mm at mid altitudes (1500 m.a.s.l.) and 1800 mm at high altitudes (2000 m.a.s.l.). The mean annual temperatures are 23°C, 21°C and 18°C, respectively (Hijmans et al. 2005).

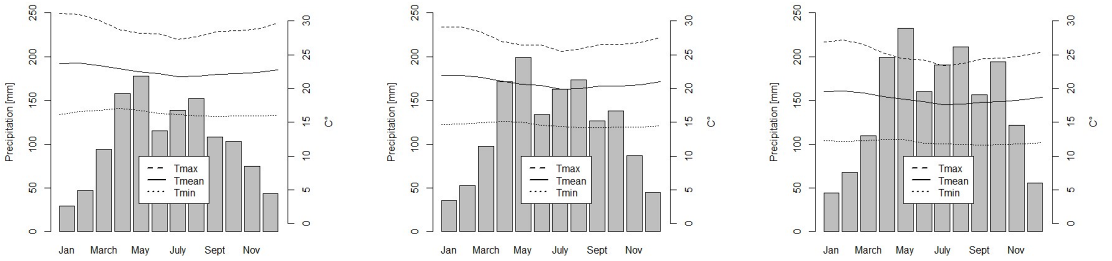

Figure 2: Climate diagrams of a) low (1100 - 1400 m.a.s.l.), b) mid (1400-1700 m.a.s.l.), and c) high altitude (1700-2100 m.a.s.l.) based on WorldClim database (Hijmans et al. 2005)

2.2 Plot selection

The selection of farmers followed a stratified random sampling approach. For each of the three altitude ranges and within the three selected districts, the existing sub-counties were listed in spread sheets with random numbers assigned to each sub-county. The first two sub-counties were selected within each altitude range, resulting in 6 sub-counties. The same procedure was repeated within each of the sub-counties to select parishes and finally farmers. A total of 300 coffee farmers (50 per sub-county) were invited for Participatory Rural Appraisals (PRA). These were organized in the six selected sub-counties and were conducted in April 2014 in order to introduce the project's objectives and activities to the participating communities and to acquire insights on existing agro-ecosystems and farmer perceptions of limiting factors for coffee yield. Applied tools included rankings, seasonal calendars and focus group discussions (FAO 1999). For the classification of existing coffee agro-ecosystems, a subset of 150 farmers of the previous PRA list was selected following the sampling procedure described above (random selection stratified by altitude and sub-counties), but additionally taking into account farmer information on agro-ecosystems. This enabled us to come up with a more balanced representation of coffee systems along the altitudinal transect. One plot for each of the selected farmers was chosen to collect plot scale descriptors of vegetation structure relevant for deriving coffee agro-ecosystem 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 trees must be above 4 years.

2.3. Data collection

During the months of April and May 2014, vegetation structure was measured on the 150 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) using the sp package (Pebesma & Bivand 2005). The number of coffee trees, banana mats and stems, and shade trees were counted on the entire plot and densities (in number per ha) were calculated. Shade tree species were identified and the number of species per plot recorded. The canopy closure as an indicator for average plot-level shade was estimated using a Forestry Suppliers spherical crown densiometer (convex model A) according to Lemmon (1957) at four positions within the plot.

Coffee yields were obtained through farmer recall per plot of the various harvests of the year and provided as coffee cherries or parchment, which was then converted into green been. The cumulative annual production was divided by the plot size and number of coffee trees to obtain green bean yield per hectare and green bean yield per coffee tree, respectively. The recall data was obtained using triangulation questions by an experienced local team, which proved to be successful in previous studies (van Asten et al. 2011a; Wang et al. 2015). This allows a wide coverage of yield data. Data on age of the coffee trees, coffee management, and livelihood characteristics were obtained through structured farmer interviews during farm visits. Outliers were identified using box-plots and dotcharts. Coffee management indices (fertilizer index, pest and disease control index, weeding index, overall management index) were made by summing the standardized values of the amount of applied fertilizers, insecticides, fungicides, herbicides, and the frequency of mechanical weeding. Data from six farmers had to be rejected because of unreliable or missing data on either plot size or vegetation structure, resulting in 144 farmers (44-45 per altitude range).

2.4 Data analysis

2.4.1 Typology of coffee agro-ecosystems

Data analysis was done using R statistics (R Core Team, 2014). The typology of coffee agro-ecosystems was based on variables related to vegetation structure using the remaining sample of 144 coffee plots. Variables were shade tree and banana densities per unit area, shade tree species diversity, and canopy closure. K-means clustering was performed with standardized data 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.

2.4.2 Coffee yield

Generalized linear regression models were used to determine the effect of vegetation structure, altitude, management variables (fertilizer use, pest and disease control, and weeding) and Arabica variety on coffee yield. Coffee varieties could only be determined for 96 of the selected plots. Therefore the regression analysis on yield, was performed using only these 96 plots. We used a generalized linear model (GLM) based on a Gamma distribution and log link. The Gamma distribution accounts for the strictly positive data of coffee yield and allowed to meet all assumptions of normality of residuals and homogeneity. Most farmers (i.e. 61) used the traditional Bugisu variety, which is also known as Nyasa or Typica (Willson 1985). Several other varieties (i.e. SL14, Catimor, Ruiru11, SL28) were less prevalent (35) and had to be aggregated into a class termed "non-Bugisu" varieties. These two classes (i.e. Bugisu and non-Bugisu) of Arabica coffee varieties were equally distributed along the altitude transect and shade levels. 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 Akaike Information Criterion.

2.4.3 Shade tree species diversity

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 at low and mid altitude areas.

2.4.4 Determinants of adoption of different coffee agro-ecosystems

The determinants of intercropping bananas and shade trees were estimated using zero-altered negative binomial models (ZANB) to cope with an overabundance of zeros (Zuur et al. 2009). This approach allows to first differentiate factors influencing whether banana or shade trees are part of the system (presence/absence) by using binomial GLM and then identify factors that influence the density of banana and shade trees by using zero-truncated negative binomial GLM. Analysis was done with the "pscl" R package (Zeileis et al. 2008). Additionally, we used multinomial logistic regression with nnet R package (Venables & Ripley 2002) to identify determinants of adoption of the coffee systems as identified by the cluster analysis described in section 2.4.1. We tested possible explanatory variables that might influence decision making (Ojiem et al. 2006), classified as socio-economic, social network, consequences and expectations, and contextual factors (table 1).

Table 1: Candidate predictors as likely 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, i.e. farmers' perceptions	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

3. Results

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

Three distinct coffee agro-ecosystems were identified by K-means clustering, 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 a clear relationship with altitude. Banana density was significantly higher at mid and high altitudes compared to low altitudes (one-way ANOVA with Tukey post-hoc test, *p*<0.05), while shade tree density, shade tree species richness and canopy cover were significantly higher at low altitude compared to mid and high altitudes (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 agro-ecosystem typologies and the altitude ranges was found (X^2, $p < 0.001$). Most 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 at low altitude.

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 (plants ha^{-1})	2255^{a} ± 125	2094^{a} ± 127	2095^{a} ± 112
Banana density (mats ha^{-1})	29^{a} ± 17	1496^{b} ± 105	278^{c} ± 82
Shade tree density (trees ha^{-1})	63^{a} ± 6	49^{a} ± 6	146^{b} ± 16
Shade tree species richness	2.8^{a} ± 0.2	2.7^{a} ± 0.2	6^{b} ± 0.4
Shade (%)	21^{a} ± 1.4	28^{b} ± 1.4	48^{c} ± 2
	Low altitude n = 57	**Mid altitude** n = 40	**High altitude** n = 47
Coffee density (plants ha^{-1})	2115^{a} ± 113	2285^{a} ± 128	2093^{a} ± 127
Banana density (mats ha^{-1})	283^{a} ± 71	687^{b} ± 145	778^{b} ± 131
Shade tree density (trees ha^{-1})	115^{a} ± 13	78^{b} ± 11	53^{b} ± 6.6
Shade tree species richness	5.2^{a} ± 0.4	3.0^{b} ± 0.3	2.8^{b} ± 0.2
Shade (%)	41^{a} ± 2.3	28^{b} ± 1.7	24^{b} ± 1.8

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

3.2 Coffee yield

A three way interaction between altitude, shade level and genotype best explained the variability of the coffee yield data (Table 3). Yield was significantly affected by genotype and planting density ($p<0.01$), as well as altitude, and fertilizer use intensity ($p<0.05$). A significant ($p<0.01$) interaction between the coffee variety categories and shade was found. On the contrary, the interaction between altitude and shade level was only significant ($p<0.05$) when accounting for the variable responses among genotypes. Banana and/or shade tree density did not affect coffee yield and were excluded from the model. Pest and disease control and weeding did not affect coffee yield either and were also excluded from the model.

Table 3: Effects of altitude, fertilizer index, planting density, shade level and genotype on coffee yield based on gamma distributed GLM with log link.

	Estimate	**Std. error**	**t value**
Intercept	2.1	1.3	1.6
Altitude [m.a.s.l.]	0.0023 *	0.0009	2.5
Fertilizer index [-]	0.6 *	0.025	2.6
Coffee density [bushes ha^{-1}]	0.00027 **	0.00009	3.1
Shade [%]	0.06 .	0.003	1.8
Other genotypes	5.0 **	1.8	2.8
Altitude : Other genotypes	-0.003*	0.0012	-2.3
Altitude : Shade	-0.00003	0.00002	-1.5
Others genotypes : Shade	-0.1 **	0.04	-2.7
Altitude : Other genotypes : Shade	0.0007*	0.00003	2.2

Null deviance is 51.6 on 90 degrees of freedom
The residual deviance is 33.7 on 77 degrees of freedom

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

Figure 3 shows the predicted relationships between yield and each of the independent variables based on the fitted Gamma GLM. Yield values of both analyzed coffee variety categories increase with altitude, whereby the traditional Bugisu variety has on average lower yields than the non-Bugisu varieties (Figure 3a). Yield increases with altitude, irrespective of fertilizer use intensity, but the yield response to fertilizer use intensity slightly increases with altitude (Figure 3b). The response seems to be very similar for both coffee variety categories (Figure 3e). The increase in yield with increasing altitude differs among the shade levels of the three coffee agro-ecosystems. Shade cover as found in the CT systems, appears to be more beneficial at low altitudes, while low shade cover as found in CO and CB systems appears to be more beneficial at high altitudes (Figure 3 c).

The shade response is genotype specific, with the traditional Bugisu variety responding positively to shade, yet the non-Bugisu category shows highest mean yield values with low shade cover (Figure 3d). All coffee varieties have a similar positive response to increased planting density (Figure 3f).

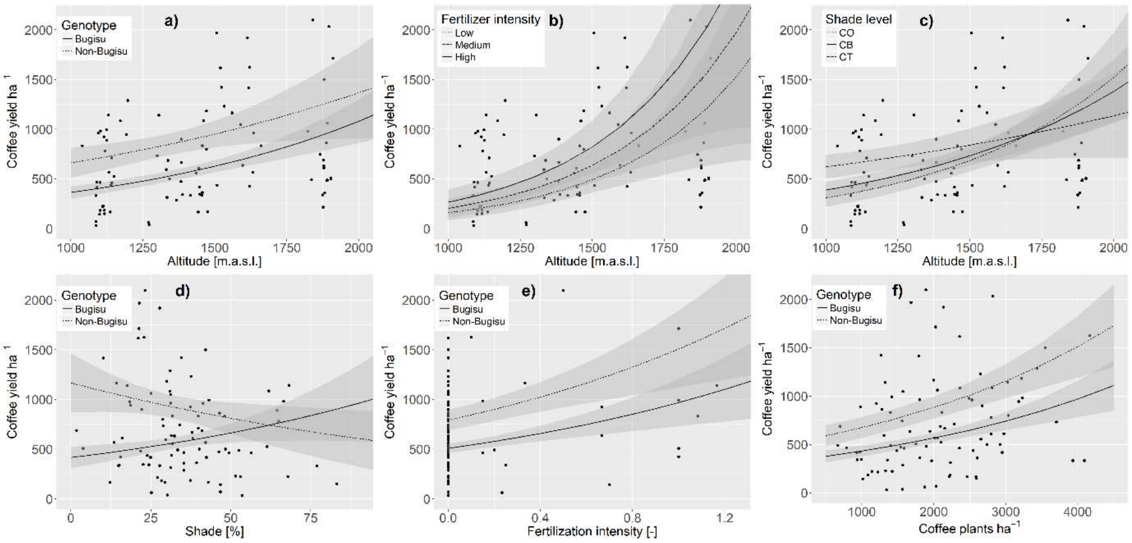

Figure 3: Predicted relationship between yield and each of the independent variables based on the fitted Gamma GLM. Average values were used for variables not displayed in the plots. Line types refer to mean predicted yield and grey areas refer to the standard error. A) Relationship between yield and altitude of different coffee cultivars. B) Relationship between yield and altitude for different intensities of fertilizer application for Bugisu variety. C) Differences between yield response to altitude of the coffee systems' shade levels (CO = coffee open canopy, CB = coffee banana, CT = coffee tree) for Bugisu variety. D) Yield responses of genotypes to shade. E) Yield responses of genotypes to fertilizer use intensity. F) Yield responses of genotypes to planting density.

3.3 Tree species richness

The total tree species richness found on the coffee plots was 37 with 69% of the tree species being indigenous to the area. The indigenous *Cordia africana* and *Ficus* spp. (mainly *F. natalensis* and *F. sur*) accounted for 50% of tree abundance (Table S1). Taking into account the difference in sampled area by using tree species accumulation curves, tree species richness was significantly higher in CT systems compared to the other systems (Fig. S2). No significant difference was found between CO and CB. In the sparsely shaded CO coffee systems, 66% of the 23 tree species were indigenous. In CB systems, 69.5% of the 22 tree species were indigenous, while in the CT systems, 70% of the 29 tree species were indigenous. *Cordia africana* was the dominant tree species in CO and CB systems with 35% and 24% average occurrence, respectively, while the *Ficus* spp. were the dominant shade trees in CT systems. The Rény diversity profiles (Fig. S3) indicated highest diversity in CT systems followed by CB and CO systems. Plots at low altitudes had highest tree species diversity but no difference was found between plots at mid and high altitudes, since their diversity profiles intersect. Species were not evenly distributed in any of the coffee systems nor at any of the altitude ranges. The Shannon and the inverse Simpson indices (Table 4) of tree species diversity reveal that highest diversity was found at low altitude, corresponding to the prevalence of CT systems. At high altitude, diversity was highest in CB systems.

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%

3.4 Determinants of coffee agro-ecosystem adoption

Spearman's correlation matrix (Table S2) indicated that the size of the sampled coffee plots was positively correlated (p<0.01) with tropical livestock unit per farm (r=0.42), the number of plots owned by the farmer (r=0.43), the fraction of hired labor (r=0.22), and (p<0.05) the distance of the plot from the home (r=0.2). The number of plots owned by a farmer was positively (p<0.01) correlated with the number of household members (r=0.23), and (p<0.05) tropical livestock units (r=0.19). Altitude was positively (p<0.01) correlated with plot age (r=0.27) and the fraction of hired labor (r=0.22). The frequency a farmer met with extension service was positively (p<0.01) correlated with access to credit (r=0.25).

The ZANB models (Table S3) indicated that the presence of bananas in a coffee plot was positively related to altitude (1.8, $p<0.001$) and plot age (0.9, $p=0.05$), with a negative interaction among these two variables (-0.1, $p=0.047$) (Table S3). This means that the higher the altitude, the lower is the effect of 'plot age' on the odds of a farmer intercropping coffee with banana. Furthermore, the planting density of bananas was negatively related to the number of coffee plots the farmers owned (-0.05, $p=0.023$) and the plot size (-0.76, $p<0.001$). The presence of shade trees (Table S3) was negatively related with the frequency at which a farmer exchanged with an extension officer (-0.5, $p=0.037$). On the other hand, the shade tree density was negatively related to altitude (-0.26, $p<0.001$), plot size (-4.6, $p<0.001$) and whether the farmer had access to borrow money (-0.3, $p=0.01$). Finally, Table 5 shows the results of the multinomial logistic regression, which indicates that altitude and number of coffee plots had significant effects on coffee system adoption. The fewer the number of coffee plots a farmer had, the higher the odds the farmer intercropped coffee with bananas and/or shade trees. Again, the odds a farmer had a CB system increased with altitude, while the odds a farmer had a CT system decreased with altitude.

Table 5: Estimates for adoption of coffee system type by multinomial logistic regression

	Variables	β	Std. error	z-value	Prob > z
Coffee-banana[a]	Intercept	-1.103	0.002	-693.6	0.000
	Altitude [m.a.s.l.]	0.001	0.0002	4.4	1.25e-05
	No. of coffee plots	-0.164	0.08	-2.0	0.044
Coffee-tree[a]	Intercept	4.833	0.002	2418	0.000
	Altitude [m.a.s.l.]	-0.003	0.0002	-12.5	0.000
	No. of coffee plots	-0.159	0.08	-2.1	0.038
Coffee-tree[b]	Intercept	5.935	0.003	2010.5	0.000
	Altitude [m.a.s.l.]	-0.004	0.0003	-15.1	0.000
	No of coffee plots	0.005	0.097	0.1	0.958

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

[a] The reference category is coffee open sun

[b] The reference category is coffee-banana

4. Discussion

Many of the studied variables co-varied with altitude. It is important to note, that altitude is not only a proxy for climate, but also relates to the distance to urban markets and forests. Furthermore, population density might change along the altitudinal gradient, but we lack the data to quantify this. It is difficult, therefore, to clearly identify causality and many of these variables partially influence the observed spatial pattern of the farming systems. We structured the discussion as follows: We first discuss climate induced constraints driving vegetation structure and then focus on the socio-economic constraints. We proceed with the implications for tree species diversity conservation and recommendations on sustainable intensification of coffee production.

4.1 Climate induced constraints driving vegetation structure

The presented data provide convincing indications of ecosystem-based adaptation to altitude-induced differences in mean temperature and precipitation. At low altitudes, where higher temperatures and increased drought stress prevail, we found increased shade levels of a diversity of tree species. On the other hand, intercropping bananas at high densities (CB systems) under these conditions was much less prevalent, which might be influenced by water constraints induced by warmer temperature and higher evapotranspiration potential but lower annual rainfall regime. By contrast, the increased intercropped banana densities found at higher altitudes might be a response to the higher annual rainfall regime. This indicates that intercropped banana densities have to be adjusted to water availability to reduce possible water competition (van Asten et al. 2011a/b). We did not find any indications that the adoption of CO systems were related to environmental conditions, on the contrary, socio-economic factors appeared more important (see section 4.2).

When accounting for differences in management intensity and planting density with the Gamma GLM, we found that 50% shade as provided on average by CT systems, benefits coffee yield at low altitude, particularly in the case of the traditional Bugisu variety. This confirms previous findings that shade benefits coffee production under suboptimal conditions (e.g. Beer et al. 1998; Vaast et al. 2008). When not accounting for altitude, we found no significant differences in coffee yield among the coffee systems, which is in agreement with previous studies conducted in the area (van Asten et al. 2011a; van Rikxoort et al. 2013). Coffee yield tended to increase with altitude, while this relationship is likely stronger or weaker depending on a dry or wet year, respectively.

The GLM also indicated different responses among genotypes, with the traditional Bugisu coffee variety benefitting from increasing shade, while the pool of "non-Bugisu" varieties appeared to yield higher on average under low shade. Because the "non-Bugisu" varieties are a mixture of coffee cultivars, pooled together due to low individual sample sizes, the found relationships cannot be attributed to any particular cultivar. The Bugisu variety is the first Arabica variety that has been introduced into Mt. Elgon around 1912 (Willson 1985; Sassen et al. 2013), while all other varieties stem from intentional selection on research stations aiming at increased productivity and/or pest and disease resistance. It is well known that the traditional coffee varieties of Typica descent (i.e. Bugisu) respond well to shade, mainly due to a less dense canopy architecture which is more exposed to atmospheric temperature and humidity (Tausend et al. 2000). Some of the more modern non-Bugisu varieties (i.e. Catimor, Ruiru 11), however, are dwarf shaped and have more dense canopy with high self-shading, thereby they often grow well with less shade (Montagnon et al. 2012).

While pest and disease control and weeding did not affect coffee yield, fertilizer use intensity generally increased coffee yield. Liebig et al. (2016) illustrated the complex dynamics of pests and diseases and their relationship with environmental conditions and therefore altitude and vegetation structure in our study area. They showed that pest and disease control is often inadequately practiced, often by using the wrong agro-chemicals or not applying any control at all. It is likely, therefore, that this explains why our analysis did not find pest and disease control to affect yield. The relatively low relationship between fertilizer use intensity and yield, may likewise be due to generally low and/or inadequate application. Furthermore, it has been reported that fake agro-chemicals are often sold on the market (Liebig et al. 2016), acerbating this problem greatly. Clearly, adequate plant management is crucial for sustainable intensification and climate change adaptation, as healthier plants can better withstand abiotic and biotic stresses (Bertrand et al. 2016). The generally low management intensity could also be due to higher priority setting for other crops, mainly food crops, or activities that fulfill more immediate needs and provide more short-term benefits to farmers and their households.

4.2 Socio-economic constraints driving vegetation structure

Next to biophysical factors, socio-economic aspects additionally determine which coffee systems are preferred by farmers. Livelihood constraints, such as issues around food security and diversification needs (farm size, household size, access to markets and forests, etc.), production constraints (coffee management knowledge, labor, access to inputs, credit, etc.) and objectives (e.g. importance of coffee as livelihood strategy) influence farmers' choices related to coffee plot vegetation management (Oduol & Aluma 1990).

Our data indicated that altitude, plot age, and whether bananas were planted on other plots of the farm influenced farmer's decision to intercrop bananas within the coffee systems. There was a tendency of increased banana planting density when farmers had fewer numbers of coffee plots and smaller plot sizes. Most farmers had at least one shade tree within their plot, yet the few ones that had none, had met more frequently with extension agents. Shade tree density appeared to be related with smaller plot size and lack of access to credit. Therefore, it seems that mono-crop coffee systems with little to no intercropping of bananas or shade trees are only possible when farm size exceeds household food needs resulting in a 'land surplus' rather than a 'land gap' (Hengsdijk et al. 2014). This implies that self-sufficiency and altitude are the primary drivers in decision making regarding coffee plot vegetation structure. This is corroborated by the findings of Sassen et al. (2015), who found that the most populated areas on Mt. Elgon were also the ones with highest tree densities.

4.3 Implications for tree species diversity conservation

Tree diversity and abundance on coffee plots decreased with increasing altitude and socio-economic status of farmers, while the total area cultivated with coffee increased with altitude. At mid to high altitudes, higher yields were generally found on plots with lower shade cover and species richness. This suggests that increased tree species conservation through SI may be a challenge in these areas (Garcia et al. 2010; Boreux et al. 2013; Carsan et al. 2013). This could change as shade likely becomes more important at higher altitudes due to climate change (Bunn et al. 2015). Incentives for promoting tree diversity and abundance within the agricultural area of Mt. Elgon need to account for the socio-economic heterogeneity of farmers' livelihoods (Giller et al. 2011; Vignola et al. 2015). Based on the historically contested relationship between the Mt. Elgon National Park and the rural communities living at its border (Cavanagh & Benjaminsen 2014), we see strong necessity and potential for collaboration. Instead of only focusing on protecting the remnant forest, measures could conserve biodiversity within the agricultural area where synergies with coffee production and farmers' livelihoods are met (Baudron & Giller 2014). This could also include other ecosystem services provided by trees, such as their potential contribution to landslide prevention (Vaast et al, 2004; Kobayashi & Mori 2017). Intensive rainfall has already resulted in numerous landslides on the mountain slopes and floods on the foothills resulting in hundreds of deaths (Knapen et al. 2006; Claessens et al. 2007; Mugagga et al. 2012). Ideally, initiatives to strengthen ecosystems services should be integrated with work already conducted by local coffee certification bodies and actors focusing on biodiversity conservation and climate change adaptation.

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

This study indicates that under current management and yield levels, most farmers practicing CO systems could benefit from intercropping more bananas and/or shade trees due to the non-significant differences in coffee yield while gaining additional benefits of fruits, firewood, timber, and mulch provided by bananas and shade trees. This is in agreement with an earlier study where coffee-banana intercropping has been identified as more profitable compared to mono-cropping of either coffee or banana on Mt. Elgon (van Asten et al. 2011a). Yet we have no data on financial profitability to confirm whether this also holds true for coffee-tree systems. But, financial profitability and cost-efficiency has been found to often be higher in shaded systems (Jezeer et al. 2017). Additional knowledge is required on what tree species and densities would enable this to happen, by considering farmers' preferences (van der Wolf et al. 2016) and the benefits of these tree species for coffee and other ecosystem services (Vaast et al. 2015; Cerda et al. 2016). CO systems could potentially outperform CB and CT systems at least in terms of coffee yield, if planting densities were increased using modern dwarf varieties, substantially higher nutrient inputs were applied and if pest and disease control were improved. But this could also lead to negative environmental externalities, increased exposure to risks and would not necessarily lead to higher profitability (Beer et al. 1998). The CO systems in this study area tended to be owned by wealthier families (more farmland, smaller household size), yet their management was still suboptimal with yields far below the intensified systems in Latin America (> 3 t ha^{-1}). In the East African context, high input systems in smallholder contexts are rare (Tittonell & Giller 2013). This suggests that unshaded systems are less appropriate for the majority of East African smallholder farmers if not accompanied by adequate management supported by access to credit, knowledge and external inputs. It remains to be shown whether the environmental conditions of Mt. Elgon allow for non-shaded systems to outperform shaded systems' yield and achieve higher profitability.

This study shows the inherent difficulty in applying SI, as what is interpreted as beneficial for one stakeholder (e.g. farmer) might not always hold true for another (e.g. coffee sector, biodiversity conservation). 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 from 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 to improved SI models. To achieve SI, 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).

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 x 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 toward 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. While the attained yield increases with altitude, the benefit of shade decreases with altitude. Traditional coffee varieties respond more positively to shade compared to more modern varieties. Climate influenced farmers' choice of coffee management system. While high rainfall amounts at high altitude allow for intercropping high banana densities, the higher shade tree densities and diversity at low altitudes are a likely response to the warmer temperature and higher drought stress. Climatic factors, socio-economic conditions and landscape setting, such as access to forest and markets, drive the relative benefits of different intercrops.

Tree species conservation within coffee plots was highest further away from the protected forest, where land-use is dominated by annual crops and tree cover outside the coffee plots is generally lowest. Management of vegetation structure tailored to the heterogeneous socio-ecological contexts demands appropriate tools which will be crucial for meeting the multiple objectives placed on coffee landscapes. This study contributes to conceptualizing the requirements of such tools. There is significant scope for sustainable intensification of coffee on Mt. Elgon, requiring improved stakeholder engagement, access to knowledge and inputs, and improved insights into the synergies and trade-offs between stakeholder objectives and ecosystem services will be key. Translating the findings of studies such as these into practical guidelines for private and public actors will be required to achieve the multiple objectives of improving livelihoods, enhancing coffee export, and increasing ecosystems resilience.

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