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Pathways to sustainable intensification of the coffee-banana agroecosystems in the Mt. Elgon region

Christopher Sebatta[1]*, Johnny Mugisha[1], Fredrick Bagamba[1], Ernst A. Nuppenau[2], Stephanie E. Domptail[2], Benjamin Kowalski[2], Matthias Hoeher[2], Anthony R. Ijala[3] and Jeninah Karungi[3]

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Abstract: Despite the importance of coffee and banana as key income and food sources for millions of farmers inhabiting the densely populated East African highlands as well as and urban dwellers, there are declining yields. One of the causes for this decline is increased soil degradation that has led to recent conversions of more forest land into crop land in marginal and sensitive mountain ecosystems. However, evidence shows that only a few households manage the desired shift to sustainable production systems, mainly due to social, economic and environmental constraints. In this study we therefore, set out to find out typologies of coffee-banana farms based on intensification levels and pathways taken using a number of agricultural intensification surrogate indicators. We also sought to find the driving factors and barriers for intensification. Using Principal Component, cluster and Pearson correlation analyses, and later both a Generalised Linear and Multinomial Logit models, results revealed four distinct intensification pathways, one of which is a high-input-high-output conventional pathway and the other three were low-to-medium input

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ABOUT THE AUTHOR

Christopher Sebatta The authors of this study come from Makerere University in Uganda and Justus-Liebig University Giessen in Germany, collaborating on a research project entitled **“Productivity and biological diversity in the coffee-banana system in the Mt. Elgon Region of Uganda: Establishing Trends, Linkages and Opportunities”** that is funded by the Volkswagen Foundation.

The project’s main objective is to promote sustainable agricultural systems in the Mt. Elgon region (MER) through working with farmers and other stakeholders in valuation of Ecosystems Services, and pro-active maintenance of a nature matrix in the area. The project aims to identify the socio-economic and biophysical drivers of agricultural land use, management and outputs in the coffee-banana systems of MER, assess the impact of land use, management options and landscape on biological diversity and productivity in coffee-banana systems, and establish optimal level of interaction between the ecological and economic goods (agriculture production and ecosystem services).

PUBLIC INTEREST STATEMENT

The world will have 9 billion mouths to feed by 2050, majority of whom in developing countries like Uganda. Food systems in such countries are still poorly managed and yields are dwindling by day, putting the food, nutrition and livelihood security of millions at risk. Farming systems in the developing world in the next 50 years will not only need to produce enough food using fewer resources such as land and labour but also do so with less negative impacts on the environment and humans. This motivated a team of researchers to find ways of harmonizing the coffee-banana farming systems with ecological systems in the ecologically fragile Mt. Elgon region. Findings from this study show that it is possible for farmers to increase their coffee and banana output through adoption of agroecological systems that blend agroforestry and good agronomy with less damage to the environment.

agroecological pathways. Adoption of an intensification pathway could be impeded by geographical location, wealth status in form of livestock, land and lack of credit access. We found the hypothesis that resource-rich farmers intensify by capital investments, while the resource-constrained farmers intensify through labour true for the conventional and agroecological intensification pathways respectively. The existence of intermediary pathways under the agroecological classification creates opportunities for interventions that target to increase yields while reducing degradation and negative environmental impacts of agriculture.

Subjects: Environment & Agriculture; Environmental Studies & Management; Food Science & Technology

Keywords: intensification; coffee; banana; principal component analysis; generalized linear model; Uganda

1. Introduction

Meeting future food demand will require the use of conventional and agroecological intensification technologies, such as embracing sustainable intensification and reducing extensification, especially in poorer countries (Garnett & Godfray, 2012; Tilman, Balzer, Hill, & Befort, 2011). These efforts may have huge environmental impacts which represents a considerable challenge. Up to date, few developing countries have managed a land use transition that simultaneously increased forest cover and agricultural production (Lambin & Meyfroidt, 2011). Conway (2012) indicated that, in a developing country context, sustainable intensification can be defined by: ecological intensification (e.g. conservation agriculture, agroforestry and integrated pest management), genetic intensification (plant and animal breeding) and market intensification (providing a socio-economic enabling environment). Rosegrant and Cline (2003) argued that despite agroecological approaches being promising for improving yields, food security in developing countries also depends on investing substantially in and reforming policies for the agricultural sector.

Monoculture farming systems in many cases depend on synthetic fertilizers and pesticides to increase yields but they are costly in addition to having negative impacts on the environment and human health (Bellamy et al., 2013). In Uganda's Mountain Elgon, coffee and banana are grown as intercrops, complementing each other in terms of shade and nutrient uptake. This makes the coffee-banana (and other crops in some cases) combination highly feasible and sustainable. Much as banana productivity has been found to be low in the organic and coffee-banana intercrop systems, research shows that the diversity of crops and tree species makes the intercrop system more sustainable due to reduced susceptibility to pests and more diversity of producer’s income sources (Lin, 2011; Tscharntke et al., 2011). Intensification of the coffee-banana system has been documented to be even more sustainable through the integration of different trees and crops to enhance soil fertility and biodiversity, reduce erosion, improve water quality,, increase aesthetics and Arabica coffee cupping scores, in addition to sequestering more carbon (Garrity, 2004; Nair, Mohan Kumar, & Nair, 2009; van Asten et al., 2015).

In fact, agroecological intensification of coffee-banana systems with shade trees has been found to be practically feasible and sustainable (Bellamy, 2013; Pretty et al., 2006; Pretty, Toulmin, & Williams, 2011; Siles et al., 2011; Soto-Pinto, Perfecto, Castillo-Hernandez, & Caballero-Nieto, 2000; Toledo & Moguel, 2012). The “sustainable intensification” (SI) approach is a policy goal for a number of national and international institutions that aim to enhance increase in food production from existing farmland in ways that exert far less pressure on the environment (Garnett et al., 2013). However, the concept is contested; Erb et al. (2013) and Shriar (2000) present the concept of sustainable intensification as a contradiction in itself with various approaches. However, this comes at a time when majority of farmers in Sub-Saharan Africa and many developing countries continue to rely on farming practices and systems that were developed in pre-industrial times, adapted to lower population densities (Pretty, 2008) yet 80% of African farms are less than 2 ha, without sufficient space for cropping and fallowing (Nagayets, 2005). Such farms are urged by researchers to intensify their agriculture in order to produce more food and feed (Gebreselassie, 2006; Pretty et al., 2011). However, there is growing concern about whether they should intensify using green revolution technologies such as inorganic inputs and machinery (Croppenstedt, Demeke, & Meschi, 2003; Kaliba, Verkuijl, & Mwangi, 2000) with its negative impacts on the environment (Pagiola, 2008; Snapp, Blackie, Gilbert, Bezner-Kerr, & Kanyama-Phiri, 2010) or intensify agroecologically (Bommarco, Kleijn, & Potts, 2013; Cassman, 1999; Karamura et al., 2013; Ochola et al., 2013; Tittonell, 2014; van Asten et al., 2015).

Majority of the farmers in East Africa, let alone Uganda, can hardly afford pesticides, advanced machinery and fertilisers. This in effect constrains the adoption of a conventional intensification pathway. At the same time, East African areas with high population densities are largely converted to farm fields, making biomass and manure more scarce inputs. This, again, limits the adoption of agroecological intensification pathways. The only way to avoid falling into a poverty trap is for farmers to find pathways which intensify the farming system through boosting the efficient use of existing resources, such as labour, off-farm nutrients and sunlight, in order to maintain or increase production while preserving the environment (Karamura et al., 2013; Ochola et al., 2013).

Uganda is a leading producer and exporter of coffee, only competing with Ethiopia for the top position (International Coffee Organisation [ICO], 2019). The country is also one of the leading producers and consumers of bananas in Africa (Van Asten, Wairegi, Mukasa, & Uringi, 2011). Coffee, like in many producing countries, is an important commodity in terms of both export earnings and generating income for smallholder farmers in Uganda (ICO, 2015). Banana on the other hand, is a key staple food for over 14 million people in Uganda (FAO, 2008). Many smallholder farmers in Uganda grow coffee and banana mainly as an intercrop under low-input farming systems, producing specialty coffee (Baffes, 2006; Bolwig, Gibbon, & Jones, 2009) which brings enormous yield and economic benefits to the farmers (Bagamba, 2007; Jassogne, van Asten, Wanyama, & Baret, 2013; Van Asten et al., 2011). Bongers et al. (2015) reported that while more than 50% of the coffee-banana farmers in Uganda agreed that they used external inputs, the actual input volumes used were far below the recommended levels. However, as the world population bulges and demand for food projected to double by 2050 (IFPRI, 2017; Misselhorn et al., 2012), Uganda's agricultural productivity, like in many Low Developing Countries is diminishing (Block, 2014; Fulginiti & Perrin, 1998). The decline in productivity is a result of poor farming practices, diseases, loss of soil fertility and emerging challenges of climate change (Craparo, Van Asten, Läderach, Jassogne, & Grab, 2015; Rosenzweig, Iglesias, Yang, Epstein, & Chivian, 2001; Van Asten et al., 2011).

In the Mt. Elgon, farmers are facing dwindling farm productivity, putting many at livelihood survival risks related to food and nutrition insecurity, resilience and sustainability of food systems (Irz, Lin, Thirtle, & Wiggins, 2001; Tendall et al., 2015). Arabica coffee and banana are commonly grown as an intercrop with a number of soil and water management practices undertaken by the growers. The agronomic practices include; manure application, mulching, pruning, de-suckering, weeding, fertilization, stumping and others.

Farming practices within the coffee-banana system in the Mt. Elgon have been investigated by several authors (Van Asten et al., 2011; Bongers et al., 2015; Rahn et al., 2018) who focussed on demonstrating that coffee yields vary with the type of intercropping done, either monocrop, banana intercrop or the forest type. However, these studies have neither done a systematic assessment of the different intensification strategies at the farming system level nor given more attention to banana too as a key food staple that shapes the farming systems, hence a bigger picture of trends in intensification pathways is missing. Therefore in this study, we draw from previous efforts by Tscharntke et al. (2012), Phalan, Balmford, Green, and Scharlemann (2011) and Phalan, Onial, Balmford, and Green (2011) to classify the current farming system's intensification pathways. In fact Van Asten et al. (2011) advised that developing recommendations on intercropping of coffee with banana in the Mountain Elgon would encourage production of both crops, which would contribute towards improved food security and increased family income. We therefore make use of production factors as surrogate indicators of intensification (Erb et al., 2013; Kleijn et al., 2008; Shriar, 2000; Smith, 2013; Temme & Verburg, 2011). This study focused on the coffee-banana cropping system to test the hypotheses that intensification pathways are shaped by household demography, farm characteristics and input availability and that resource-poor farms intensify by labour while richer ones intensify by capital through investment in equipment, machinery and improved inputs.

The paper attempts to highlight which intensification strategies are currently being followed using empirical results. It also tries to revisit the agroecology-conventional farming system dichotomy in the Ugandan context where cash and biomass scarcity intensely restrict intensification options for farmers in fragile ecosystems such as the Mt. Elgon.

2. Materials and methods

This study was conducted in two neighbouring districts of Sironko and Kapchorwa in the Mt. Elgon in Eastern Uganda, on the eastern border with Kenya. This area is part of an extinct volcano with a maximum altitude of 4,321 masl (Mugagga, Kakembo, & Buyinza, 2012a) and lies within 1°25′N and 34°30′E (Figure 1). The core ecosystem of this region is characterised by large montane forests surrounded by several protected areas adjacent to highly populated agricultural lands. More than 2 million people live on the foothills between 1000 and 2200 masl and depend on the surrounding forest for ecosystem services like construction materials, crop staking stems and biomass for fire wood (Sassen & Sheil, 2013; Sassen Sheil, & Giller, 2015; Sassen, Sheil, Giller, & Ter Braak, 2013).

Agriculture on the upper slopes is more intensive characterized by lush gardens of coffee, bananas, Irish potatoes and beans, while lowlands farming systems are more extensive, with maize, groundnuts, sorghum, millet, cotton, soya beans, sweet potatoes, sunflower and rice. The coffee-banana intercropping system is very popular among farms on the Mountain landscape (Kansiime, Wambugu, & Shisanya, 2013; Ministry of water and environment, 2013; Soini, 2007; van Asten et al., 2015; Wasige, 2009). The vegetation of the mountain Elgon consists of rainforest remnants found on the western part, most of which has been cleared for agriculture from the boundary up to the bamboo zone (about 2000 masl), the Afromontane forest on the north (at about 1500 masl), and bamboo (at >2200 masl) on the southern and Western Mountain slopes (White, Wanyama, & Obua, 2006). The Southern side of the Mt. Elgon forest was visibly extremely thin (encroached) with large areas within the Park or Forest Reserve are cleared. Rainfall is reported to vary by altitudinal gradients along the slopes of the mountain. Highlands in Sironko have denser tree

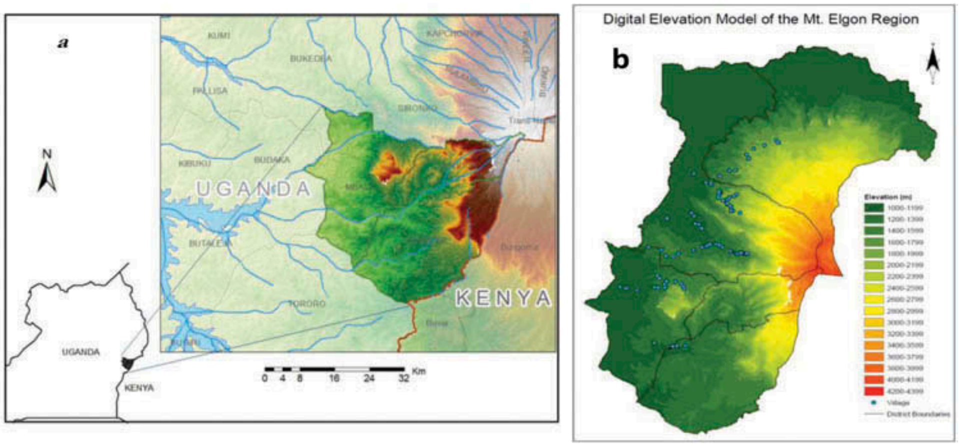


Figure 1. (a) Location of the study area in Uganda, Mt. Elgon region, (b) elevation map of the Mt. Elgon region and (c) land cover map of the Mt. Elgon region.

cover than any other farmland in the mountain area. The areas of 25–50% tree cover in the northern end of Sironko and patches in Kapchorwa are likely to be bushland (Soini, 2007).

2.1. Sample and data collection

Seven sub-counties from the two districts were purposively selected due to being the main coffee and banana producing areas in the study area. Altitude was a major criterion for site selection because of its documented role in shaping land use decisions and practices in Uganda (Mugagga et al., 2012a).

Based on the lists of coffee-banana farmers provided by the district, sub-county and the Uganda Coffee Development Authority (UCDA) personnel, we stratified the farmers into three groups based on elevation (low up to 1500 masl, middle between 1500 and 2000 masl and upper above 2000 masl). This was done at sampling stage because hypothetically we expected farmers at different elevations to have different intensification strategies. Within each stratum, a random sample was drawn using Tippett's random numbers to proportionately select the coffee-banana farmers' sample. We got three subsamples of 138, 270 and 92 respectively at the altitude levels and a total sample of 500 farms. However due to missing data, this analysis used data from 453 farms. Coffee yields, recorded as cherries or parchment, were later scaled to parchment for uniformity, by using the International Coffee Organisation Agreement (2007) standard conversion ratio of 0.8. Yield data were obtained through farmer harvest recall per plot for the two seasons between August 2015 and August 2016 when data were collected. Banana yields were calculated from bunches harvested in four annual seasons between August 2015 and August 2016. We used the modal banana bunch weight in kg as a unit of measure for its accuracy as used by Bagamba (2007). Outliers were identified using box-plots and scatter plots. In addition, other data on household assets, land use and land management practices, and input use were collected.

2.2. Data analysis

We used the quantitative data collected in a farmer survey. The data for this study that included household demography, assets, income base, farmland management, coffee and banana production data, soil and water conservation and labour use, etc. were collected in the last quarter of 2016, prepared and entered in SPSS 20.0 and analysed in Stata 14.0 software. Stata was used for all the analysis because of its superior power over SPSS in modelling. We used principal component and cluster analysis in the first stage to classify the main intensification pathways following careful selection of surrogate intensification indicator variables. Ruthenberg (1980) and Köbrich, Rehman, and Khan (2003) used similar approaches in the classification of tropical farming systems. Highly correlated variables were eliminated following factor analysis to avoid implicit weighting. Among the eliminated variables were; distance of farm from national forest reserve/park, household size and age of household head. Weighting for the selected variables prior to PCA and CA was done through averaging rather than omitting variables. This is a method proposed by Yuan, Bentler, and Kano (1997) for its ability to give better estimators and tests. Characterising farms, farming and land management systems are often exceedingly difficult because of the complexity and heterogeneity of the factors involved. The selection of factors that define farm typologies is guided by the purpose of the research. Farm typologies have been used to study appropriate fertilizer application (Tittonell, Leffelaar, Vanlauwe, Van Wijk, & Giller, 2006) and livelihood strategies (Tittonell et al., 2010) or resource use efficiency (Tittonell, Vanlauwe, De Ridder, & Giller, 2007; Zingore, Murwira, Delve, & Giller, 2007) and classification of cropping systems, land use and input use intensity (Lagemann, 1977; Ruthenberg, 1980).

3. Indicators of intensification

In this study, we used (sustainable) intensification indicators as spelt out by Delzeit et al. (2018), Haileslassie et al. (2016), Erb et al. (2013), Firbank, Elliott, Drake, Cao, and Gooday (2013) and Reig-Martínez, Gómez-Limón, and Picazo-Tadeo (2011). These included: inputs used (manure, fertilizer, labour), farming practices and systems (proportion of land under coffee and bananas, fallow and shade tree (soil and vegetation cover) and farmer commitment to agroecological practices (investment in soil and water conservation). Others were outputs of the production system (output per

Table 1. Selected variables for intensification land management pathway characterisation

Variable	Description	Extent of variable data collection and variable measurement
Total value of farm equipment (Shillings)	Value of farm investment in production equipment	Current value of farm equipment such as hand hoes, secateurs, forks, spades, wheel barrows was captured and valued in Uganda shillings
Total investment in water and soil conservation structures	Cost (Uganda Shillings) of constructing water and soil erosion conservation structures on the farm	Both annual hired and family labour used for making trenches, terraces, grass bunds, stone bunds, and mulching to prevent soil erosion and or increase fertility in the coffee banana garden were valued in Uganda shillings
Coffee output kgha^{-1}	Coffee yield	Coffee parchment was used as a standard measure of output. Red fresh cherries were converted to parchment equivalent in kg. This was converted to kgha^{-1}
Banana output kgha^{-1}	Banana yield	Modal banana bunch weight(Weight of majority of the bunches harvested in the last year) in kg as a unit of measure for its accuracy as used by Bagamba (2007) and Van Asten et al. (2011) were the measure of banana weight. Bananas harvested and converted to kgha^{-1}.
Rate of manure application (kgha^{-1})	Rate (kgha^{-1}) of poultry and or cow manure used in the last one year	Manure was captured as spades, wheel barrows and lorries that was converted to kg equivalents. It was later converted to kgha^{-1} as a unit area measure.
Rate of fertilizer application (kgha^{-1})	Rate (kgha^{-1}) of fertilizer used in the last one year	Total fertilizer used on coffee-banana plots was recorded and converted to kgha^{-1}
Total tropical livestock units	Total tropical livestock units (TLUs)	The standard TLU formulae was used for the owned livestock by the household on farm; Tropical livestock unit (TLU): sum of the animals with loading; cow = 0.7/goat = 0.1/chicken = 0.01/pigs = 0.2/sheep = 0.1.
Percentage of fallow land cover (%)	Percentage of total farmland area under fallow	Uncultivated fallow land within the coffee banana plantation was estimated from farmer recalls per plot and recorded in hectares. A percentage was then calculated from the total coffee-banana farmland.
Percentage of shade tree land cover (%)	Percentage of total farmland area under shade trees	The area of land under shade trees within the coffee banana plantation was estimated from farmer recalls per plot and recorded in hectares. A percentage was then calculated from the total coffee-banana farmland.
Farmer perception of soils and biodiversity conservation on the farm (index)	Farm index score on a scale of six questions related to intentional conservation efforts on the farm	Farm index score on a scale of six questions related to intentional conservation efforts on the farm were asked. An index was calculated as a ratio of the number of affirmative questions a farmer answers out of six. Questions scored included: whether a farmer Minimises environmental impacts on farm, Looks after the environment, Improves resource/land/soil condition/fertility, Conserves diversity of animals/plants and ecosystems on farm, etc.
Coffee output per man-hour of labour (family and hired) (kg/man-hr)	Family and hired labour productivity in coffee	Labour was recorded for all production activities in coffee per year. The total coffee output (kg) was later divided by the total labour (man-hours)
Banana output per man-hour of labour (family and hired) (kg/man-hr)	Family and hired labour productivity in banana	Labour was recorded for all production activities in banana production annually. The total banana output (kg) was later divided by the total labour (man-hours)

unit area, yield per unit labour man-hour) and technology level used (the value of farm equipment, tropical livestock units (TLUs) (Table 1). The key agroecological intensification indicators used were; rate of manure application, tropical livestock units, monetary investment in constructing on-farm water and soil erosion conservation structures and percentages of fallow and shade tree cover on the coffee-banana plantation. The others were: rate of fertilizer application, farmer perception of soils and biodiversity conservation on the farm and partly value of farm equipment.

Therefore, the observed values (Y) of components was explained through a linear combination of factors (B) and a residual (E). In mathematical terms;

$$Y_i = X_i B_i + E_i \tag{1}$$

The factors are common when they contribute to the variance for at least two observed variables or unique when their contribution is only towards one variable. The initial factors were extracted based on Principal Component Analysis (PCA). The goal of PCA was to find components that are linear combinations of the original variables that achieve maximum variance. The set of variables retained from PC analysis (Table 3) formed the basis of farmer's households' classification developed by hierarchical cluster analysis, using Ward's method and Euclidean distance to get at an appropriate cluster number that fit the data (Joffre & Bosma, 2009).

Twelve variables were divided into three categories, general farm and farmer related variables, input, and agroecological intensification variables. The Kaiser Meyer Olkin (KMO) measure of sampling adequacy and Bartlett's sphericity test were performed to address the question of independence and correlation of variables (Lattin, Carroll, & Green, 2003).

We further estimated a generalised linear model (GLM) to understand what factors influence intensification of the coffee and banana production system of Mt. Elgon (McCulloch, 2000). GLMs represent a method of extending standard linear regression models to incorporate a variety of responses such as count, binary, proportions and positive valued continuous distributions (Hardin, Hardin, Hilbe, & Hilbe, 2007; Hilbe, 1994). A Generalised Linear Regression based on a gamma distribution log link (Equation 2) were used to determine the effect of intensification and non-intensification factors on coffee and banana yields. The gamma distribution was used to account for the strictly positive data of coffee and banana yields and allow to meet all assumptions of normality of residuals and homogeneity. Since 47 farmers had missing data on many of these variables, we only analysed data from 453 farmers to avoid modelling errors. Three main coffee varieties are grown in the Mt. Elgon according to our data; SL14, SL28, KP162 and Bugisu local also known as Nyasaland. We, therefore, took SL14, the most recently released improved variety to be the base for comparison. We found no collinearity within the data since the independent variable had more than a threshold variance inflation factor (VIF) of 10.

The GLM model general equation was specified as in Equation 2;

$$G(E(Y)) = G(E(Y/X)) = \alpha + \sum_{k=1}^{K} \beta_k X_{ik} \tag{2}$$

Where $G(E(Y))$ is a function of the expected value of Y (Yield) and $Y \sim F$ with a gamma distribution. G is the link function, X are the independent variables and F is the function distributional family.

To understand the drivers of intensification pathway adopted, we estimated a multinomial logit model specified as in Equation 3;

$$P_i^h = \frac{exp\left\{\beta_{0i} + \sum_{k=1}^{k} \beta_k X_{ik}^h\right\}}{\sum_{j=1}^{j} exp\left\{\beta_{0j} + \sum_{k=1}^{k} \beta_k X_{jk}^h\right\}} \tag{3}$$

Where P_i^h is the probability that farmer h chooses intensification pathway i.

To estimate the model, we maximised the likelihood function (joint probability that the observed choices are generated by the model) with respect to the estimable coefficients β. Solving the $K + J$ equations in (4) simultaneously, we obtained all the elements of β; and this is an MNL model with k generic attributes and a full set of alternative-specific constants, all but one of which are identified.

Equation 3 was normalised to remove indeterminacy in the model by assuming that $\beta_0 = 0$ and the probabilities estimated as in Equation 4;

$$\frac{Prob(h_i = j)}{X_i} = \frac{exp\left\{\sum_{k=1}^{k} \beta_k X_{ik}^{h}\right\}}{1 + \sum_{j=1}^{j} exp\left\{\sum_{k=1}^{k} \beta_k X_{jk}^{h}\right\}}; j = 0, 1 \ldots J,\ \beta_0 = 0 \tag{4}$$

4. Results

4.1. Characterisation of intensification pathways

The KMO test for sampling adequacy and the Bartlett sphericity test were performed to check whether the 12 variables used in the PCA (Table 2) could be factored. Results from both tests showed that the overall KMO test was greater than 0.5 (at a value of 0.6), which is the lowest threshold recommended, while Bartlett's sphericity test was highly significant ($p < 0.001$). Therefore, the variables under study are related with high variance, justifying using principal component analysis.

4.2. Principal component analysis (PCA)

Table 3 shows the rotated factor (Varimax) matrix of independent variables with factor loadings for each variable. Further, variables with high factor loadings and high unexplained variation were considered from the rotated factor matrix (Harris, 2001). A total of 12 intensification indicator variables were included and the seven components retained because of having eigenvalues greater than one, cumulatively explained 70% of the total variability in the dataset. Principal Component 1 (PC1) was more correlated with investment in soil and water conservation, banana labour productivity, and banana output. PC2, with coffee labour productivity and coffee output, PC3 correlated with livestock and farm equipment (farm wealth) and PC4 was correlated with fallow land cover. PC5 was more correlated with manure applied, PC6 was correlated with fertilizer used per hectare and PC7 correlated with conservation perception.

4.3. Cluster analysis

The K-means method was employed with the four identified clusters. The analysis gave rise to the final four cluster centres as indicated in Table 4 using the seven PCs and hierarchical clustering through Euclidean distances. These final cluster centres help in the interpretation of what is typical of each particular cluster (Dauber et al., 2003). Figure 2 indicates a dendrogram with a cut-point of 0.5 Gower dissimilarity measure, and the four generated clusters of farms based on the pre-defined intensification criterion. The four clusters were determined using the hierarchical method where the k-cluster solution is formed by joining together two clusters from the $k + 1$ cluster solution (Hair, Black, Babin, Anderson, & Tatham, 2006; Lattin et al., 2003). We found that mineral fertilizer use, manure use, shade tree coverage, and fallow land coverage are the four variables most discriminating among the different intensification strategies and form the main basis for classification of the clusters. Table 4 showed that the four clusters had distinct ranges for these variables.

4.4. Intensification pathways

The four clusters were characterised and named based on the intensification techniques (inputs, assets, investments and attitude and land use) and the outputs of the adopting farming systems. The intensity of input use was based on to classify the farm clusters as low-input, medium-input or high input conventional and agroecological farms depending on the type of inputs used.

Conventional-high output: Cluster C2 is the largest group of farms with 46% of the sampled farms. The intensification pathway undertaken in cluster C2 is characterised by the maximum use

Table 2. Summary statistics of independent variables used in PCA and cluster analysis

	Clusters (Mean (Std. dev))				
Variable	**Pooled sample (*n* = 453)**	**C1 (*n* = 120)**	**C2 (*n* = 210)**	**C3 (*n* = 48)**	**C4 (*n* = 75)**
Total value of farm equipment (Uganda shillings)	134,256.98 (126,180.57)	113,238.07^{***C2} (68,764.79)	237,108.04^{***C4} (244,458.09)	117,380.65^{***C2} (71,260.59)	157,694.12^{*C4} (167,777.86)
Total investment in water and soil conservation structures (Uganda shillings)	88,648.13 (84,340.51)	84,977.23^{**C3} (87,215.64)	95,588.75 (69,431.46)	134,526.55^{*C4} (90,337.83)	65,157.90 (48,607.29)
Coffee output (kgha^{-1})	2,353.16 (5,137.19)	1,157.59^{***C4} (272.01)	2,337.58^{***C4} (1,732.20)	1,523.32^{***C4} (1,600.89)	9,606.10 (12,286.57)
Banana output (kgha^{-1})	6,344.41 (5,342.80)	6,175.50 (5,258.43)	7,719.79 (5,642.12)	6,106.27 (5,144.91)	5,940.98 (5,581.18)
Rate of manure application (kgha^{-1})	1,249.235 (1,267.338)	1,124.77^{**C3} (1,118.72)	1,502.74 (1,416.07)	1,990.49 (1,804.05)	1,151.63 (1,402.17)
Rate of fertilizer application (kgha^{-1})	123.29 (152.67)	70.47^{***C2} (65.1292)	273.28^{***C3} (229.04)	76.13 (48.57)	91.07^{***C2} (82.15)
Total tropical livestock units	3.82 (3.66)	1.58^{***C2} (1.49)	7.10^{***C3} (13.84)	2.00 (1.53)	1.78^{***C2} (1.98)
Percentage of fallow land cover (%)	7.24 (8.03)	2.66^{***C3} (2.37)	5.49^{***C3} (5.46)	17.48^{***C4} (7.19)	6.67^{*C1} (8.55)
Percentage of shade tree land cover (%)	2.22 (1.99)	2.14 (2.02)	2.25 (1.82)	2.59 (2.65)	2.46 (1.41)
Farmer perception on soils and biodiversity conservation on farm (index)	0.66 (0.33)	0.66 (0.37)	0.66 (0.21)	0.72 (0.19)	0.65 (0.29)
Coffee output per man-hour of labour (family and hired) (kg/man-hr)	0.84 (0.99)	0.54^{***C2} (0.59)	1.11^{***C4} (1.08)	0.95^{**C1} (0.73) ^{***C4}	3.18^{***C1} (1.04)
Banana output per man-hour of labour (family and hired) (kg/man-hr)	8.15 (7.58)	7.61 (7.50)	9.94 (8.13)	8.15 (9.33)	9.69 (6.03)

Significance:*10%, **5%, ***1%.
Tropical livestock unit (TLU): sum of the animals with loading; cow = 0.7/goat = 0.1/chicken = 0.01/pigs = 0.2/sheep = 0.1.; 1US$ = 3,342 Uganda Shillings (20 September 2016) at time of this study survey

Table 3. Principal components analysis Verimax rotated components

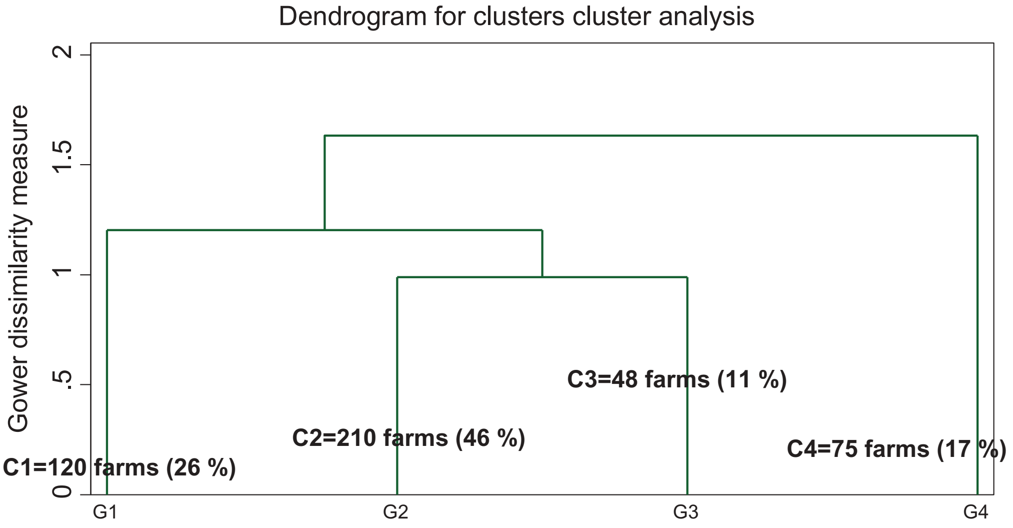
Variable	**Comp1**	**Comp2**	**Comp3**	**Comp4**	**Comp5**	**Comp6**	**Comp7**	**Unexplained**
Tropical livestock units (TLU)	0.012	0.031	0.646	0.169	0.319	−0.107	0.023	0.336
Total investment in soil and water conservation (Uganda shillings)	0.572	−0.065	0.101	0.143	−0.040	0.133	0.058	0.400
Percentage of shade tree land cover	−0.001	0.001	−0.002	0.004	0.002	−0.004	−0.002	0.001
Percentage of fallow land cover	0.005	−0.013	0.028	0.893	0.050	0.007	−0.004	0.124
Farmer perception on the conservation of soils and biodiversity on the farm (index)	−0.003	−0.001	−0.007	−0.002	−0.000	−0.003	0.990	0.011
Coffee output per man-hour of labour (family and hired)	−0.090	0.686	−0.051	0.200	−0.000	−0.019	0.022	0.325
Banana output per man-hour of labour (family and hired)	0.613	0.013	−0.111	−0.001	0.068	−0.078	−0.101	0.347
Coffee output (kgha^{-1})	0.079	0.721	0.048	−0.195	−0.010	0.033	−0.021	0.291
Banana output (kgha^{-1})	0.531	0.063	0.014	0.220	−0.050	−0.053	0.063	0.386
Total fertilizer (kgha^{-1})	−0.002	0.007	−0.002	0.005	0.025	0.977	−0.004	0.033
Total manure (kgha^{-1})	0.000	−0.007	−0.027	0.053	0.913	0.036	−0.002	0.121
Total farm equipment value (Shillings)	−0.018	−0.016	0.744	0.156	−0.228	0.065	−0.031	0.267
Eigenvalues	1.955	1.307	1.278	1.063	1.004	1.003	1.002	
Cumulative explained Variance	14%	25%	35%	44%	53%	61%	70%	

The Kaiser-Meyer-Olkin measure of sampling adequacy for this data was 0.60

Table 4. Final cluster centres for four clusters identified through K-means clustering

		Cluster			
Principal components	**Description**	**1 (Low agroecological)**	**2 (highly conventional)**	**3 (highly agroecological)**	**4 (mildly agroecological)**
PC1	Soils and banana output	−0.219	0.447	1.436	−0.126
PC2	Coffee labour and output	−0.367	−0.059	−0.126	2.354
PC3	Farm equipment and livestock)	−0.225	1.212	−0.08	−0.144
PC4	Land fallow coverage (%)	−0.290	−0.080	2.769	0.160
PC5	Manure and shade trees	−0.184	0.958	0.252	−0.271
PC6	Fertilizer	0.001	0.016	0.174	−0.131
PC7	Soil and water conservation on farm	−0.253	1.334	−0.233	−0.042
Variable ranges	Mineral fertilizer range (min-max/$kgha^{-1}$)	0.627–286.622	6.351–1,093.344	14.074–173.883	5.810–361.705
	Manure range (min-max/$kgha^{-1}$)	1.555–8,465.608	2.045–39,950.060	2.524–12,012.010	2.263–5,198.181
	Shade tree coverage range % (min-max)	0.017–21.667	0.050–15.00	0.333–14.167	0.500–20.00
	Fallow land range % (min-max)	0.033–10.000	0.033–16.667	5.000–45.555	0.833–33.33

Figure 2. Dendrogram of clusters of coffee-banana farms based on intensification.



for mineral fertilizer of 1,093 kgha^{-1} (Table 4). This conventional pathway is implemented by wealthier farms that have more equipment and invest more in soil and water conservation, livestock and fertilizer. This cluster is therefore characterised by technology intensity, fertilizer and manure intensity, livestock stocking intensity and higher coffee and banana returns to labour.

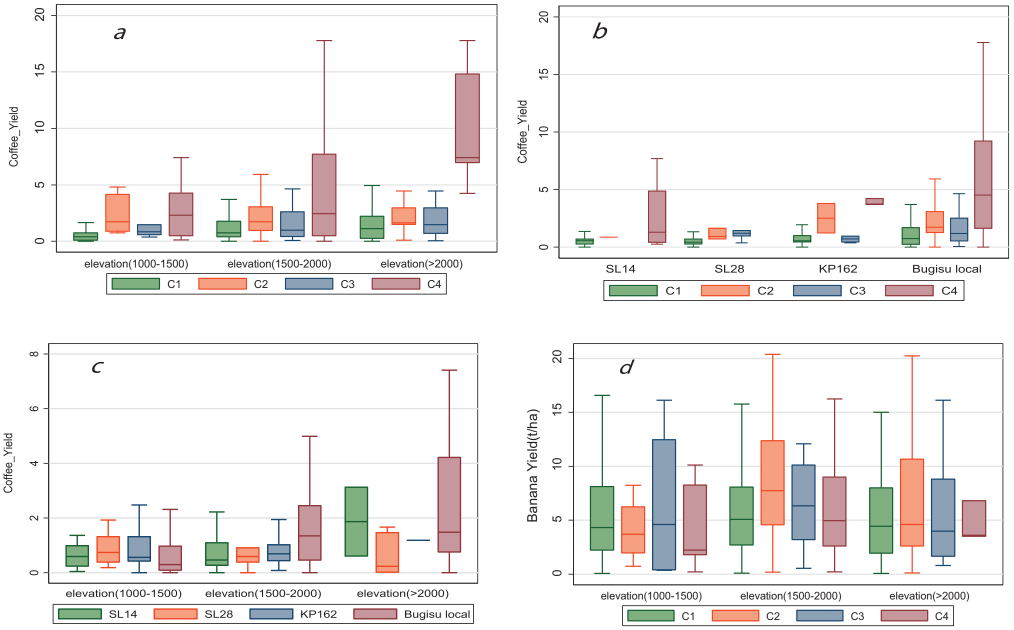
The low-to-medium input agroecological clusters 1, 3 and 4 were typical of subsistence farming systems where farmers focus on banana and other food crops usually grown under difficult ecological conditions. Cluster 3, farms used the highest amounts of manure at a maximum of about 12,000 kgha^{-1} and ranked first in terms of shade trees and fallow coverage on coffee-banana farmlands. The combined use of both manure and mineral fertilizers in agroecological systems were termed “split fertilization” by Wezel et al. (2014) and credited by Zebarth, Drury, Tremblay, and Cambouris (2009) for reducing fertilizer use on farms while increasing crop uptake efficiency. This kind of input intensification applies particularly to cluster C2, which combines high levels of manure and fertilizers. The fertilizer use rates in the case of clusters C2 and C3 are negligible though in terms of capacity to catalyse productivity.

Table 4 indicates that cluster 2, the highly conventional pathway is implemented by wealthier farms that have more equipment and invest more in soil and water conservation, livestock and fertilizer. This cluster is therefore characterised by technology intensity, fertilizer and manure intensity, livestock stocking intensity and higher coffee and banana returns to labour. Clusters 1, 3 and 4 on the other hand, have agroecological production characteristics such as more shade tree and fallow intensity on agricultural lands, more investment in soil and water conservation and high coffee and banana yields especially cluster 4. This confirms our hypothesis that resource-rich farmers intensify by capital investments, such as using fertilizers while the resource constrained farmers intensify through labour (applied in agroecological labour-intensive agronomic practices).

4.5. Intensification pathways comparison

The difference between C1 “low agroecological” and C4 “mildly agroecological” is very narrow and can be in terms of coffee output and level of technology used in terms of farm equipment. C1 farms produce significantly more coffee and bananas per unit area with lower-value equipment than C4 farms (Table 2). Labour returns (output per man-hour of labour applied) in the low-input system (C1) and the agroecological system (C3) in coffee were found to be significantly lower than in the conventional system and low-input/coffee system (C2 and C4). We however found no significant differences between the two systems in terms of banana labour returns (Table 2).

Figure 3. Boxplots showing: (a) Coffee yield variation by elevation and cluster, (b) coffee yield by variety and cluster, (c) coffee yield by elevation and variety and (d) banana yield by elevation and cluster.



Results in Figure 3(a) showed that intensification pathway C4 had the highest coffee yield variability at all the three altitude ranges but more at the highest altitude (<2,000 masl) followed by pathway C2 (conventional). Figure 3(b) indicated that in terms of coffee genotypes (varieties), pathway C4 and C2 had more variability for three of the four varieties grown in the study area; SL14, KP162 and Bugisu local.

Figure 4 indicates that cluster C1 (low-inputs/low-output) is present across the mountain landscape with 21% of farms at >2000 masl and 7% of the farms at 1000–1500 masl. The majority of the farms belonging to Clusters 2 (conventional), 3 (agroecological) and 4 (low-input-coffee) were found at the highest altitude range above 2000 masl. Figure 5 also shows that by study site, cluster 1 (low-input/low-output) pathway has the majority of the farmers in Kapchorwa and Sironko. However, Kapchorwa has a higher percentage of the highly conventional (C2) and mildly agroecological (C4) farms than Sironko. Figure 6 showed that farms taking a conventional intensification (C2) in Kapchorwa district are very near to the protected area compared to Sironko district. The opposite is true in the case of the low-input-coffee producing farms (C4). Banana yields were more variable within cluster 2 (highly conventional) and cluster 3 (mildly agroecological) at altitude ranges above 1,500 masl, with maximums of

Figure 4. Authors' illustration of the distribution of the SI land management clusters on the mountain landscape at three altitude ranges.

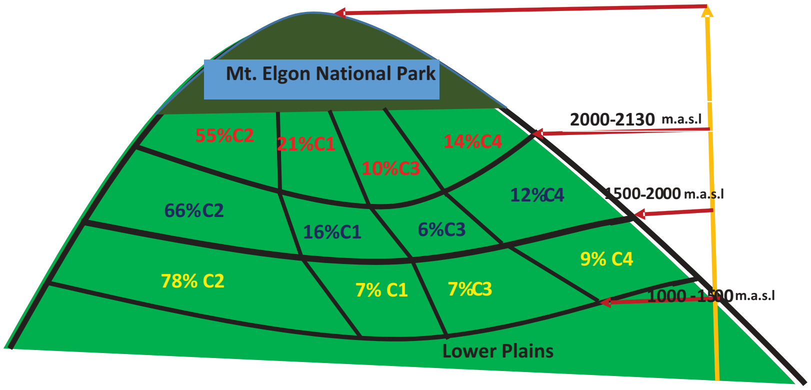
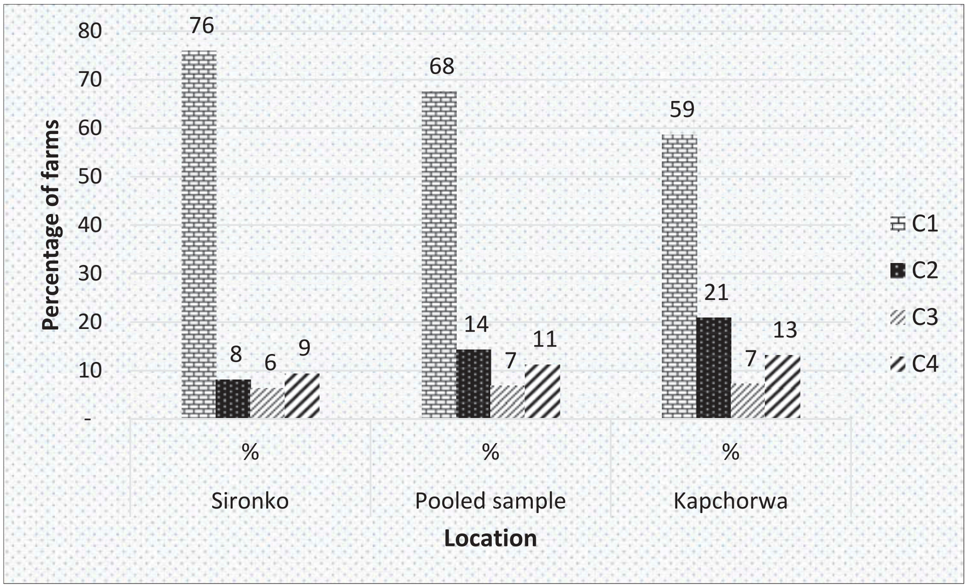


Figure 5. Percentage of farms in each cluster by study sites.



17–21 tons/ha/year (Figure 3(d)). Cluster 1 was more variable in banana yield at the lower altitude range of 1,000–1,500 masl.

4.6. Coffee and banana intensification and yield variability

A two-way interaction between elevation and genotype (coffee variety) as assessed by a GLM explained the variability of the Arabica coffee yield (Table 5). Coffee yield was significantly affected by elevation ($p < 0.01$), fertilizer rate, genotype ($p < 0.05$) and fodder tree intercropping in coffee and banana ($p < 0.10$). Further analysis of coffee yields indicated that the highest yields were obtained by farms at elevation above 2,000 masl with 1,991 kgha^{-1} followed by elevation 1,500–2,000 masl (1,488 kgha-1). Farms in the lower elevation range of 1,000–1,500 masl obtained coffee yields of about 968 kgha-1 (Table 5). We also found that coffee yields increased with increasing elevation and fertilizer intensification. Reduction in manure intensity and farm equipment value (level of technology) at higher elevation (>2,000 masl) did not lead to a subsequent reduction in coffee yields (Table 9).

Figure 6. Location of clusters by the distance from the national park boundary.

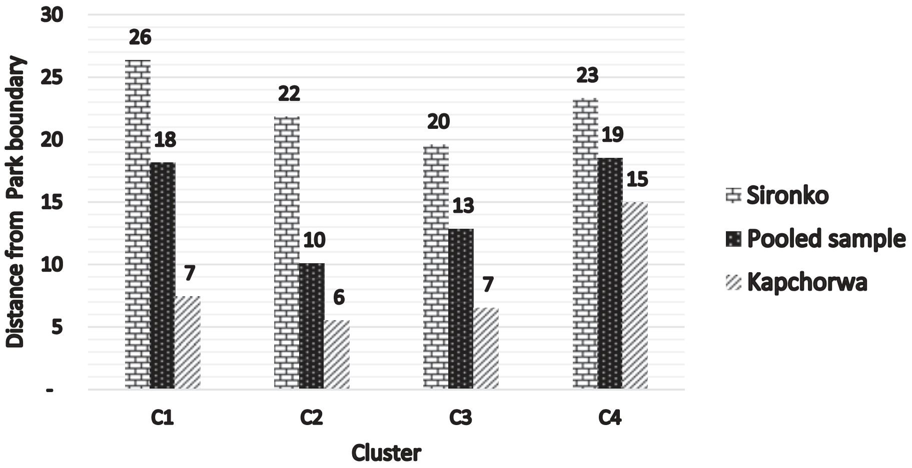


Table 5. Intensification factors affecting coffee yield based on gamma distributed GLM with log link

	Estimate	Std. Err.	z	*p* value
Intercept	0.70	1.90	0.37	0.71
Total fertilizer (kgha^{-1})	0.0019	0.00084	2.29	0.02
Total manure (kgha^{-1})	0.000011	0.000028	0.37	0.71
Percentage of shade tree land cover (%)	0.0041	0.028	0.15	0.88
Percentage of fallow land cover(%)	−0.02	0.017	−1.09	0.28
Tropical livestock units (TLU)	−0.00072	0.011	−0.07	0.95
Coffee output per man-hour of labour (family and hired)	0.04	0.038	1.02	0.31
Clusters				
2 (highly conventional)	0.022	0.22	0.11	0.92
3 (highly agroecological)	0.27	0.44	0.61	0.54
4 (mildly agroecological)	1.03	0.33	3.11	0.002
Coffee variety				
SL28	5.47	2.46	2.23	0.03
KP162	7.55	6.74	1.12	0.26
Bugisu local	4.82	2.07	2.33	0.02
Farmer inter-planted fodder trees in banana and coffee (dummy)	0.30	0.18	1.69	0.09
Elevation	0.0039	0.0012	3.11	0.002
Elevation: variety SL28	−0.0036	0.0016	−2.33	0.02
Elevation: variety KP162	−0.0049	0.0045	−1.1	0.27
Elevation: variety Bugisu local	−0.0029	0.0013	−2.24	0.03

Coffee yields by elevation**: Elevation_1(1000–1500 masl)^{2,3} (mean = 967.51, sd = 1,132.03); elevation_2(1500–2000 masl)(mean = 1,488.40,sd = 1,409.61); elevation_3(>2000 masl)(mean = 1,991.27, sd = 1,659.37)**^{2}**: Bonferroni one way test** significance between two elevations; ** = 5%, *** = 1%*

Null deviance is 91.81 on 138° of freedom & the residual deviance is 82.60 on 121° of freedom; AIC = 17.51; BIC = −505.26; sd = standard deviation

Manure application rate, shade tree cover and livestock intensity (TLUs) did not affect coffee yield (Table 5). Coffee yield was, however, positively and significantly ($p < 0.01$) associated with land management pathway C4 (low-input-coffee). These findings indicated that coffee yields are partly driven by fertilizer, labour, genotype and agroecological management practices.

Banana yields were found to be significantly affected by shade tree cover and elevation ($p < 0.01$) as well as labour intensity, and fodder tree intercropping in relation to elevation ($p < 0.05$) (Table 6). In comparison to pathway C1 (low-input/low-output), yields were significantly higher in pathways C3 (agroecological) and C4 (low-input-coffee) ($p < 0.01$) (Table 5). Table 9 further indicated that banana yields increased with increasing intensification of fertilizer, manure and farm equipment between 1,000 and 2,000 masl but reduced beyond that. From these findings, banana yields seem to be driven by labour, shading intensity and elevation.

A Spearman's correlation matrix showed that tropical livestock units were positively ($p < 0.05$) correlated with a farmer planting windbreaks ($r = 0.11$) at their farm boundary (Table 7). The number of plots correlated with annual hired labour ($p < 0.05$, $r = 0.35$) while tropical livestock units correlated positively and significantly with household size ($p < 0.05$, $r = 0.34$) and age of household head ($p < 0.05$, $r = 0.17$). Credit access correlated negatively with age ($p < 0.05$, $r = 0.10$).

Table 8 shows the results of the multinomial logistic regression showing that altitude/elevation, number of plots and TLUs have opposite effects on adoption of the coffee-banana intensification pathways in C1 (low-input/low-output) and C2 (conventional). Increasing altitude, plots under coffee and banana and TLUs significantly ($p < 0.01$) favoured adoption of pathway C2 but the odds of adopting pathway C1 reduced.

Relative to pathway C1 (base), increasing access to credit and number of plots increased the odds of adopting pathway C3 (agroecological) ($p < 0.01$). The odds of adopting pathway 4 (low-input-coffee) were augmented by increasing altitude relative to cluster C1 ($p < 0.05$) and reduced with increasing TLUs relative to pathway C2 ($p < 0.01$). These results indicated that altitude, credit access, and livestock are key factors in promoting intensification of coffee and banana production systems in the Mt. Elgon.

5. Discussion

This study defines sustainable intensification in both conventional and agroecological terms. Conventional sustainability is when a coffee-banana farm is able to apply inputs such as fertilizer and agrochemicals to such levels that have minimal effect on the environment and biodiversity within their ecosystem and beyond. Agroecological sustainable intensification on the other hand is where a farm uses more of agroecological practices but in some cases can use small doses of fertilizer and agrochemicals to produce enough food (bananas) and generate enough household income (by selling coffee and bananas) to sustain the family throughout the year in the medium and long term.

5.1. Farm intensification pathways

Study results indicated that there are four distinct coffee-banana intensification pathways for farmers in the Mt. Elgon. The farm classification showed that pathway C1 was a low-input/low-output pathway with characteristics typical of a subsistence farm where the farmer's main focus is on producing food (banana). Little investments under this pathway are made by farmers to enhance fallow/cover trees. This finding is a pointer to the fact that such farms are constrained by soil degradation given the topography of the Mt. Elgon with intensive rains resulting in soil erosion and wild landslides, making agricultural intensification production systems a big necessity (Knapen et al., 2006; Mugagga, Kakembo, & Buyinza, 2012b) and more especially intensification of shade trees (Kobayashi & Mori, 2017). In addition, Wang et al. (2015) recommended that improvement of soil fertility in the Mt. Elgon can be fulfilled by farmers taking up the integrated soil fertility management (ISFM) approach that includes the application of organic and inorganic fertilizers.

Table 6. Intensification factors affecting banana yield based on gamma distributed GLM (log link)

	Coef.	**Std. Err.**	**z**	***p* > z**
Intercept	6.81	0.70	9.72	0.00
Total fertilizer (kgha^{-1})	0.00071	0.00057	1.24	0.22
Total manure (kgha^{-1})	0.000015	0.00002	0.75	0.45
Banana output per man-hour of labour (family and hired)	0.0029	0.0014	2.09	0.037
Percentage of fallow land cover	−0.01	0.017	−0.60	0.55
Percentage of shade tree land cover	0.045	0.017	2.68	0.01
Tropical livestock units (TLU)	0.028	0.019	1.46	0.14
Cluster				
2 (highly conventional)	0.18	0.21	0.83	0.41
3 (highly agroecological)	1.84	0.33	5.62	0.00
4 (mildly agroecological)	0.58	0.18	3.13	0.002
Farmer inter-planted fodder trees in banana and coffee(dummy)	1.70	0.86	1.99	0.047
Elevation	0.0011	0.0004	2.74	0.006
Elevation: farmer inter-planted fodder trees in banana and coffee	−0.00105	0.0005	−2.1	0.035

Null deviance is 517.20 on 452° of freedom and the residual deviance is 554 on 440° of freedom; AIC = 20.31; BIC = −2173.79

Table 7. Spearman's correlation matrix

	Household size	Elevation	Age of household head	Farmer sex (1 = male,0 = female)	Credit access (dummy)	Number of coffee and banana plots	Farmer has an off-farm job	Farmer has planted windbreaks on farm (dummy)	Tropical Livestock units(TLU)	Total annual hired labour (man-hours)
Household size	1.00									
Elevation	0.13*	1.00								
Age of household head	0.20*	−0.13*	1.00							
Farmer sex (1 = male, 0 = female)	−0.01	−0.05	−0.02	1.00						
Credit access (dummy)	0.06	0.02	−0.10*	0.01	1.00					
Number of coffee and banana plots	0.14*	−0.06	0.06	0.16*	0.08	1.00				
Farmer has an off-farm job	0.01	0.05	−0.07	−0.07	−0.03	−0.08	1.00			
Farmer has planted windbreaks on-farm	0.07	0.08	0.00	−0.00	0.02	0.23*	−0.04	1.00		
Tropical livestock units (TLU)	0.34*	0.07	0.17*	0.02	−0.07	0.07	0.02	0.11*	1.00	
Total annual hired labour (man-hours)	0.03	0.17*	0.04	−0.01	−0.05	0.35*	−0.06	0.09	0.04	1.00

Significance: *5%

Table 8. Estimates for the adoption of coffee-banana intensification pathways by multinomial logistic regression

	C2 (highly conventional)			**C1 (low agroecological)**			**C 3a (highly agroecological)**		
Variables	**β**	**Std. error**	***z* value**	**β**	**Std. error**	***z* value**	**β**	**Std. error**	***z* value**
Household size	−0.100	0.064	−1.580	0.100	0.064	1.580	0.036	0.067	0.540
Elevation	0.003***	0.001	3.760	−0.003***	0.001	−3.760	0.001	0.001	1.480
Age of household head	−0.011	0.012	−0.910	0.011	0.012	0.910	0.024	0.016	1.540
Farmer sex (1 = male, 0 = female)	0.187	0.326	0.570	−0.187	0.326	−0.570	−0.395	0.414	−0.950
Credit access (dummy)	−0.140	0.324	−0.430	0.140	0.324	0.430	1.066**	0.423	2.520
Number of coffee and banana plots	0.134**	0.053	2.530	−0.134**	0.053	−2.530	0.160***	0.055	2.930
Farmer has an off-farm job	0.404	0.318	1.270	−0.404	0.318	−1.270	−0.012	0.406	−0.030
Farmer has planted windbreaks on farm	−0.431	0.343	−1.250	0.431	0.343	1.250	0.230	0.465	0.500
Tropical livestock units (TLU)	0.372***	0.068	5.460	−0.372***	0.068	−5.460	0.070	0.104	0.670
Total annual hired labour (man-hours)	−0.000	0.000	−0.010	0.000	0.000	0.010	−0.000	0.000	−0.530
Intercept	−6.561***	1.531	−4.290	6.561***	1.531	4.290	−7.295***	1.939	−3.760
	C3^b			**C4^a (mildly agroecological)**			**C4^b**		
	β	**Std. error**	***z* value**	**β**	**Std. error**	***z* value**	**β**	**Std. error**	***z* value**
Household size	0.137	0.086	1.590	−0.070	0.063	−1.110	0.030	0.082	0.370
Elevation	−0.001	0.001	−1.340	0.001**	0.001	2.010	−0.001	0.001	−1.530
Age of household head	0.035*	0.019	1.890	−0.014	0.012	−1.210	−0.003	0.015	−0.220
Farmer sex (1 = male, 0 = female)	−0.582	0.495	−1.180	0.164	0.315	0.520	−0.023	0.413	−0.060
Credit access (dummy)	1.206**	0.498	2.420	0.024	0.312	0.080	0.164	0.408	0.400
Number of coffee and banana plots	0.026	0.057	0.460	0.052	0.065	0.800	−0.082	0.072	−1.140
Farmer has an off-farm job	(0.416)	0.480	−0.870	0.025	0.313	0.080	−0.379	0.405	−0.940
Farmer has planted windbreaks on farm	0.661	0.544	1.210	−0.478	0.326	−1.470	−0.047	0.427	−0.110
Tropical livestock units (TLU)	−0.302***	0.107	−2.810	0.107	0.089	1.200	−0.265***	0.091	−2.930
Total annual hired labour (man-hours)	−0.000	0.000	−0.530	−0.000	0.000	−0.260	(0.000)	0.000	−0.230
Intercept	−0.734	2.330	−0.310	−3.157**	1.378	−2.290	3.404*	1.901	1.790

Significance:*10%,**5%, ***1%.; Hausman test rules out a violation of IIA.
a The reference cluster is C1, **b** The reference cluster is C2(LR chi2(30) = 114.41; Prob>chi2 = 0.000)

Table 9. Effect of elevation on the independent variables used in PCA and cluster analysis

	Altitude range (masl)								
	Elevation (1,000–1,500)			Elevation (1,500–2,000)			Elevation (>2,000)		
	Mean	sd	Max	Mean	sd	Max	Mean	sd	Max
TLU	1.795	2.327	17.860	2.850	7.212	101.000	2.054	3.797	25.540
Total investment in soil and water management	119,914.300	181,658.100	1,207,525.000	173,313.400	322,606.800	2,643,000.000	149,918.000	208,366.100	1,037,000.000
Percentage shade tree land coverage	3.438	4.322	21.667	2.958	3.594	20.000	2.643	2.927	18.833
Percentage fallow land coverage	8.281	6.470	18.333	6.353	7.953	33.333	8.432	9.516	45.555
Farmer perception on soils and biodiversity conservation on farm (index)	0.661	0.240	1.000	0.657	0.395	5.500	0.672	0.203	1.000
Coffee output per labour man-hour	0.804	1.282	6.714	1.378	2.578	21.900	1.390	2.659	20.000
Banana output per labour man-hour	21.072	42.429	229.839	25.628	68.693	487.500	19.440	63.538	412.500
Coffee output (kgha^{-1})	1,021.177	1,271.348	7,407.407	2,595.009	5,844.963	59,259.260	3,943.721	6,193.929	29,629.630
Banana output (kgha^{-1})	10,900.880	27,076.060	204,360.500	12,032.400	21,136.370	231,604.900	11,435.670	15,423.170	87,481.480
Fertilizer rate (kgha^{-1})	107.464	159.655	750.361	124.094	157.913	1,093.344	140.776	126.315	417.319
Manure rate (kgha^{-1})	1,341.769	3,101.499	29,126.790	2,041.186	4,713.828	39,950.060	971.211	1,742.840	9,413.895
Total value of farm equipment (Uganda shillings)	100,772.900	59,153.550	400,000.000	212,857.300	455,772.200	4,728,000.000	193,123.900	271,935.800	1,602,000.000

The second pathway (cluster C2) is characteristic of conventional farming. It is characterised by higher investments in conventional inputs such as fertilizer that result into higher returns to labour in form of high coffee and banana yields. Pathways C3 (agroecological) farms make use of ecological practices such as shading tree incorporation in the production system in higher proportions than C1 and C2. Despite pathway C3 having more investment in farm soil and water conservation, manure and more fallow and shade tree coverage than C4, the latter had a significantly higher coffee yield. This can be explained by higher investments in farm equipment, fertilizer, manure and a fair balance between fallow land, shade tree cover and cropland.

Related to this study findings, Van Asten et al. (2011) reported that 71% of the farmers growing Arabica coffee as a monocrop in the Mt. Elgon had applied manure while 77% of those intercropping it with banana applied the manure. The same study found that 60% of the farmers had de-suckered or pruned their banana and coffee respectively. Bongers et al. (2015) described a diversity of coffee-banana farms in Uganda including the “diversified” type where 53% of household income came from coffee and 16% from banana. In addition, the study also classified a typical “banana-coffee farm” that earned 21% of its annual income form coffee and 44% from banana. This indicates that generally coffee-banana farmers tend to prioritize one of the two crops in their production system.

The yields obtained in this study however, are comparable to those obtained by Van Asten et al. (2011) who found banana yields of 20,000 kgha^{-1}/year in the same study area for Arabica coffee-banana intercrops and 15,000 kgha^{-1}/year of banana for banana monocrops. The yields obtained in this study which only studied the coffee-banana intercrop are slightly lower than the coffee yield estimates by Wairegi, van Asten, Tenywa, and Bekunda (2010) who found that the potential yield in Arabica coffee is >2,500 kgha^{-1}/year in a monocrop and >4,400 kgha^{-1}/year in a banana intercrop. Van Asten et al. (2011) obtained comparatively similar coffee yields in the same study area where we carried out this study while Nzeyimana, Hartemink, and Geissen (2014) using GIS, obtained almost similar Arabica coffee yield results in the highlands of neighbouring Rwanda, a region with similar topography with the Mt. Elgon. Van der Vossen (2005) and Rahn et al. (2018) indicated that cropping systems in Africa and in the Mt. Elgon, in particular, mix organic and inorganic inputs and soil and water conservation. This has been further made indispensable by the change in the climate of the area making intensification of the production systems an essential means for climate change adaptation (Campbell, Thornton, Zougmoré, Van Asten, & Lipper, 2014; Jiang, Bamutaze, & Pilesjö, 2014; Kervyn et al., 2015).

5.2. Intensification factors affecting coffee and banana yields

Elevation on the mountain landscape, fertilizer applied per unit area and coffee genotype (variety) came out strongly to explain coffee yield variability among intensification pathways. Supporting evidence from Bolwig et al. (2009) indicated that elevation and use of organic practices were drivers of coffee yield per tree in the Mt. Elgon. Cerda et al. (2017) also found strong evidence that elevation, shade cover and management intensity interact well to create an ecosystem that supports sustainable coffee yields. Van Asten et al. (2012) found that the suitable elevation for bananas and Arabica coffee are <1,900 masl and 1,400–2,300 masl respectively. We also found a strong effect of the interaction between elevation and genotypic intensification on coffee yield. It is worth noting that improved coffee genotypes are more capital intensive requiring more fertilizers and manure in addition to skills to manage them. However, Okoboi and Barungi (2012) identified high cost of both inorganic and organic fertilizers as a major limitation to fertilizer use coupled with lack of information and technical advice due to inadequate extension services in Uganda. Banana yields were found to be enhanced by labour, elevation and shading intensification. This finding is in tandem with Van Asten et al. (2011) and Van Asten et al. (2012) who found that banana systems under coffee and tree intercrops gave higher yields than the monocrops. Ajayi, Akinnifesi, Sileshi, and Kanjipite (2009) also found that non-conventional agricultural production systems had lower returns to labour compared to conventional ones. Despite their lower returns to labour, other studies have indicated that agroecological systems require 15%–35% more labour than conventional ones (Granatstein, 2003; Pimentel, Hepperly, Hanson, Douds, & Seidel, 2005).

5.3. Drivers of adoption of intensification pathways

This study reveals that intensification of coffee and banana production in the highlands is highly related to altitude, land size and livestock. The altitude, in this case, determines the extent of soil erosion and land degradation given a particular land management system. Magrach and Ghazoul (2015) noted that with increasing climate change and variability, the production of coffee is geographically shifting to cooler and higher altitude areas. Davis, Gole, Baena, and Moat (2012) earlier predicted 65%–100% possible loss of Arabica coffee indigenous species due to climate change and biome shifts. These findings seem to agree with the results in this study because altitude has prominently come up as a key factor for adoption of sustainable intensification management systems.

Livestock acts as a risk buffer in smallholder farming systems while access to credit is key in unlocking input and output markets. However, results showed that older farmers are less likely to access credit yet they are more likely to have more livestock (TLU) and land that would act as collateral for loan acquisition. Therefore, for sustainable intensification to succeed, biophysical as well as social economic constraints have to be addressed. Livestock heavily depends on crop production and a balance between the two can bring about sustainable benefits (Tilman, Cassman, Matson, Naylor, & Polasky, 2002). The integration of livestock in cropping systems has been noted to have the capacity to increase production and economic returns (Herrero et al., 2010; Lemaire, Franzluebbers, de Faccio Carvalho, & Dedieu, 2014). In addition, a functioning rural financial system that enables the rural poor to access savings and credit services is key in unlocking their potential to move out of low-return and high-risk livelihood strategies(Barrett, Reardon, & Webb, 2001; Reardon, Berdegué, Barrett, & Stamoulis, 2007).

From these findings, the hypothesis that intensification pathways are shaped by household demography, farm characteristics and input availability can be true to a limited extent. This is because our findings showed similarities in factors driving both the conventional and agroecological pathways. The hypothesis was however true for location of the farm (elevation), number of plots (wealth) and Tropical Livestock Units (livestock wealth) where these were key drivers of the high conventional intensification pathway but were bottlenecks in the low agroecological pathways.

6. Conclusions

This study investigated the available agricultural intensification pathways in the coffee-banana farming system and the drivers of their adoption in volatile and fragile ecosystems such as those in the Mt. Elgon highlands in Uganda. Results revealed four diverse and distinct coffee-banana intensification pathways, one of which is conventional in nature while the other three are agroecological at various levels on the continuum. Intensification of coffee yields is driven by higher inorganic fertilizer application rates, genotype (variety) of the coffee grown and intensification system relative to altitude. Our earlier hypothesis that coffee-banana intensification pathways are shaped by household demography, farm characteristics and input availability were found to be true to a limited extent though it was true for location of the farm (elevation), number of plots (wealth) and Tropical Livestock Units (livestock wealth), found to be key drivers of high conventional intensification pathway but not for the low agroecological pathway.

Farmers at different locations on the mountain are influenced by different factors to adopt a particular intensification pathway. However, the importance of livestock in the farming system and access to and affordability of functional credit cannot be overemphasised. The livestock plays a key role in providing manure that powers agroecosystems on one hand and as a safety net against production risks. The credit and savings play a crucial role in asset and capital accumulation as well as smoothening consumption and input access.

Pathways that blend both conventional (capital intensive) and agroecological (labour intensive) production strategies are found in this study to have higher returns to labour as well as to overall investment in farming through yields. Conventional farms hired more labour while agroecological ones used more of family labour. Based on this, we accepted the earlier study hypothesis that resource-rich farmers intensify by capital investments, while the resource-constrained farmers intensify through labour (applied in agroecological labour-intensive agronomic practices).We therefore conclusively assert that for agricultural intensification to meet both production and conservation objectives, that is to be sustainable, in this and coming decades, there will be a need for farmers to adopt sustainable intensification pathways that strike a conventional and agroecological balance to increase yields.

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Competing Interests
The authors declare that they have no competing interests.

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