Agriculture, Ecosystems and Environment 263 (2018) 31–40

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

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

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ARTICLE INFO

Keywords:
Sustainable intensification
Ecosystem-based adaptation
Coffea arabica L.
Shade trees
Adoption
Uganda

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.

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https://doi.org/10.1016/j.agee.2018.04.019
Received 9 October 2017; Received in revised form 8 February 2018; Accepted 30 April 2018

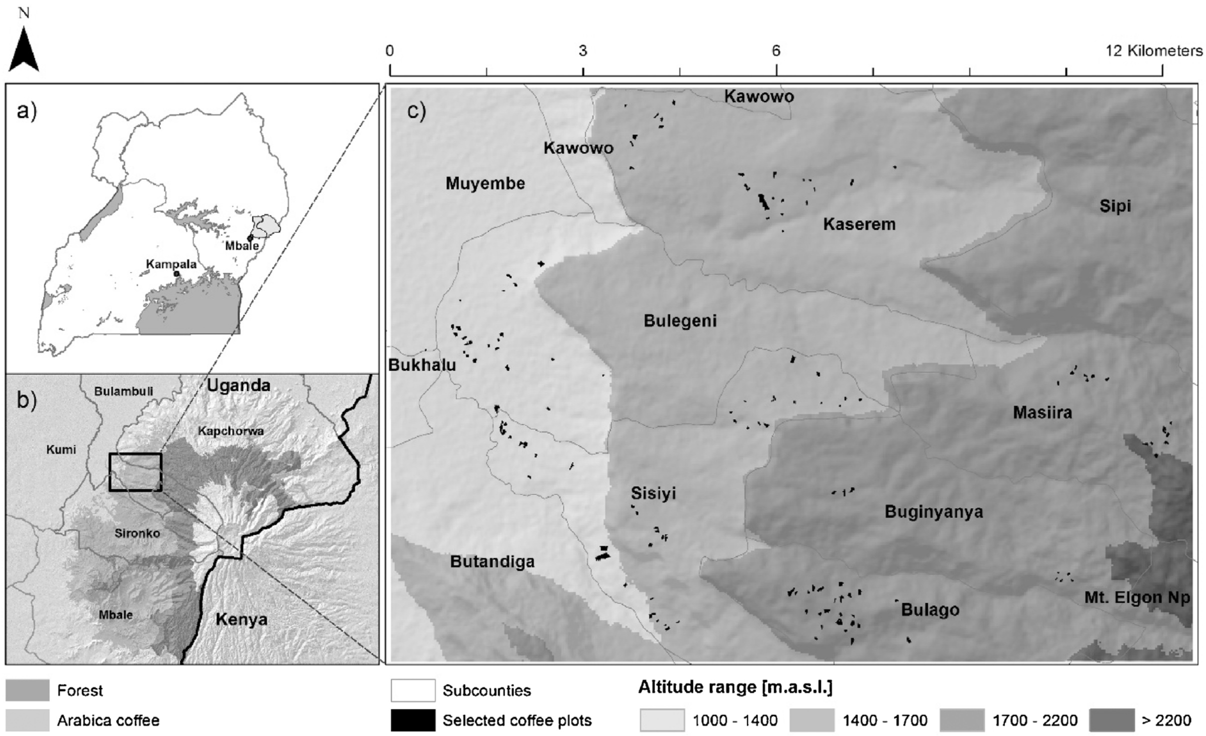

Fig. 1. a) Location of the study area within Uganda, Mt. Elgon area, b) Districts of study area (Bulambuli, Sironko, Kapchorwa), c) Study site with indication of three altitude ranges, sub-counties and sample plots.

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 and 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 and 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 and 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 and 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 and Ruf 2014; Vignola et al., 2015; Perfecto and 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 (Tittonell and Giller, 2013; Harris and 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