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Crop diversification as a smallholder livelihood strategy within semi-arid agricultural systems near Mount Kenya

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ABSTRACT

Crop diversification is one strategy that smallholder farmers may employ to reduce their vulnerability in the face of global environmental change. Diversification not only expands the number of potential crop types for market, it also improves agroecosystem functioning by building redundancy into the agricultural system and allowing for innovation in areas exhibiting impacts of climate variability. While the driving forces behind and impacts of crop diversification have been extensively investigated, there are particular issues for the prospects of crop diversification to reduce household vulnerability within semi-arid agricultural systems. The decision to diversify crops is a particularly challenging one for farmers in semi-arid systems. Semi-arid systems can exhibit greater variability in annual precipitation in areas that are marginal for agricultural production. Changes to the timing of the growing season (onset of rains) and mid-season dry periods in particular pose significant challenges to farmers in semi-arid ecosystems. This paper examines the spatial diversification of crop types across an upland-lowland gradient on Mount Kenya's northwestern slopes. We perform regression analyses using household-level survey data collected during the summer of 2012 to investigate the factors contributing to varying levels of crop diversification and implications for crop production in a semi-arid irrigated agricultural system. We hypothesize that the study area locations at higher elevations will be able to grow a greater variety of crops due to climate suitability. Our analysis demonstrates that household-level income, field size, exposure to agricultural extension officers, and suitability of environmental conditions are related to the likelihood of smallholder crop diversification. More favorable growing conditions appear to outweigh limitations posed by inaccessibility and financial constraints, which has implications for adaptation to climate change in semi-arid ecosystems. We discuss the results in the context of challenges posed by global environmental change.

Introduction

Climate variability deeply influences livelihoods dependent on agricultural production.

In the semi-arid tropics (SAT), where 22% of the world's population resides, livelihoods are more susceptible to climate fluctuations due to the persistence of high levels of chronic poverty and inadequate food consumption (Falkenmark and Röckstrom, 2008). Surface hydrological dynamics additionally contribute to the vulnerability of smallholder farmers due both to rainfall variability and human- or climate-induced land and water degradation. In Africa, the proportion of arid- and semi-arid lands is expected to increase by 5–8% by the 2080s in large part due to depleted water resources (Collier et al., 2008). This is particularly concerning as the greatest impact of such depletion will be in agriculture, the sector that accounts for more than 60% of the African labor force (Collier et al., 2008). Further, it is projected that the area suitable for agriculture, the length of growing seasons, and the yield potential of agricultural lands will decrease. While such changes are expected to vary from country to country, yield reductions may be as high as 50% by 2020, with smallholder farmers being most vulnerable (Boko et al., 2007).

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Crop failure in semi-arid systems results from challenges such as pest outbreaks, insufficient rainfall, or in some cases excessive rainfall. When crop yields decline or fail, farmers adopt a variety of strategies to maintain their livelihoods. However, the adaptation opportunities available to semi-arid smallholder farmers are limited for a number of reasons. Dry spells may require some amount of irrigation to bridge to periods of higher rainfall. But in many locations, water harvesting strategies and irrigation infrastructure do not provide sufficient water to continue cultivation during dry periods. Household conditions including income and farm size may limit the ability to experiment with adaptation strategies such as growing market-oriented crops and diversifying income through off-farm employment given the household's inability to tolerate a failed endeavor. Finally, isolation from other villages and urban centers or poor infrastructure reduces connectivity to extension agents and may thereby diminish information flow concerning water conservation techniques and cultivation of drought-tolerant varieties. Challenges to semi-arid agriculture should therefore be recognized when exploring farmer adaptation strategies given the complex set of social and ecological conditions that influence the farmer decision-making process.

Crop diversification is one strategy households may employ to reduce their vulnerability to external stressors, such as climate change (Altieri, 2004; Baumgartner and Quaas, 2010; Lin, 2011). The term *vulnerability* should be understood as a function of three dimensions: *exposure* to social and/or environmental stresses, associated *sensitivities*, and related *adaptive capacities* (Polsky et al., 2007, p. 473). For example, from this perspective a community of smallholders could be equally *exposed* to a drought, yet household harvest *sensitivity* to the drought would vary depending on cropping strategies as soil moisture within monoculture fields has been shown to be lower compared to polyculture fields that make use of multi-storied crops and shade trees (Lin, 2007), translating to a relatively larger harvest from the polyculture system. Additionally, crop diversification provides access to multiple markets and may introduce farmers to new cultivation techniques thus improving *adaptive capacity* in the face of adverse market and/or climatic events. Taken together, growing a diverse array of crops can lessen household vulnerability to adverse conditions.

Examples of crop diversification include polycultures, agroforestry systems, and crop rotation systems, with diversity evident in form (e.g. genetic, species, structural), function (e.g. pest suppression, increased production), and scale (temporal and spatial) (Lin, 2011). One of the primary advantages of crop diversification is enhanced ecosystem functioning and resilience. Because different species occupy a multitude of niches while performing duplicative functions, redundancy is built into the system (Vandermeer et al., 1998; Lin, 2011). Such redundancies may allow for sustained ecosystem functioning over time, since species respond differently to environmental fluctuations, and the presence of multiple species performing similar functions better ensures that, if one species is unable to perform a specific role, another can be substituted. This benefit of diversification, linked to the insurance hypothesis, maintains that biodiversity provides a buffer against environmental fluctuations (Yachi and Loreau, 1999). The significance of on-the-farm crop diversification has additionally been extended to market-oriented smallholders (Bradshaw et al., 2004; Fraser et al., 2005). By growing a diverse array of crops and by maintaining links to multiple markets in a range of locations, a smallholder farmer is better able to ensure a marketable harvest and can buffer against adverse market events by, for example, taking a harvest to an alternative market if the initial market has been over-supplied with of particular crop.

Though crop diversification may reduce farmers' vulnerability to climate and market variability, dissimilarities in individual characteristics and social and biophysical conditions can impact the level of diversification across a landscape (Altieri, 1995). Land suitability, income level, risk avoidance, contact with extension officers, and social norms are potential determinants of crop diversification at a narrowed scope (Cutforth et al., 2001; Di Falco and Perrings, 2003). Across semi-arid upland-lowland environments, however, these determinants may change rapidly over short distances. Orographic lifting, for instance, creates disparities in precipitation levels (i.e. growing conditions) between relatively proximal locations. In the process, these dissimilarities may lead to varying income levels and livelihood activities, for example, as favorable growing conditions may spur successful cropping while individuals in drier regions may resort to less profitable alternatives. The rapidly changing abiotic factors across such environmental gradients often influence plant species diversity (Loreau, 1998; Loreau et al., 2001), with positive linear relationships between rainfall conditions and species diversity existing in some locations (Gentry, 1988).

Multiple studies have inspected how planting strategies and, accordingly, crop species diversity, are affected by farm-level abiotic conditions, such as rainfall, as well as socioeconomic conditions, household demographics, farmer experiences, and community-level characteristics (Napier and Camboni, 1993; Jarvis and Hodgkin, 2000; Neill and Lee, 2001; Ryan et al., 2003; Degrande et al., 2006). Further, a growing body of literature is concerned with understanding the management and improvement of agrobiodiversity in the context of changing conditions, such as mechanized monoculture farming, household member migrations, climate change, and development or alteration of irrigation systems (Zimmerer, 2010a, 2011; Khumalo et al., 2012). In this context, irrigation can improve agrobiodiversity by allowing crops with different maturation periods to be cultivated through extension of growing seasons (Zimmerer, 2014), yet a decrease in diversity as well as crop failures may also result if the governance or design of the irrigation infrastructure are unsatisfactorily altered for the needs of a community (Zimmerer, 2011). The area of study in our analysis has experienced significant change in the past century, including irrigation practices, which will be explained in 'Social and environmental conditions in the Upper Ewaso Ng'iro Basin' section. Social and ecological differences as well as varying trajectories of change throughout the study area have created a distinctly heterogeneous landscape in terms of biophysical and social traits. These local traits, upon which global forces of change operate, interact with agricultural management, on-the-farm biological diversity, and, in the process, smallholder vulnerability to fluctuating climatic and social conditions (Zimmerer, 2010b). We intend to explore crop diversification practices across this heterogeneous landscape, and in the process contribute to the growing body of literature inspecting social and ecological vulnerability in the face of global change pressures.

The purpose of this paper is to examine the crop diversification practices of households within a semi-arid upland-lowland system where biophysical conditions, social conditions, and features such as the capacity to irrigate vary. Irrigation presents an important capacity to support agricultural production in marginal environments, but there are diverse ways that farmers utilize this capacity at the farm level to maintain or enhance crop diversification. We focus on spatial rather than temporal crop diversity as the data employed in our analysis span a single growing season. The study takes place across a landscape spanning eight community irrigation projects on Mount Kenya's northwestern slopes. This study area is emblematic of semi-arid mountain environments exhibiting environmental gradients affecting land use suitability. A total of 315 households in eight community irrigation projects were surveyed to examine differences in crop diversification in the context of various social and environmental factors. The communities range from the lower slopes of Mount Kenya (2099–1805 m a.s.l.) to the Laikipia plateau (1799–1792 m a.s.l.) to the semi-arid to arid rangelands (1634–1617 m a.s.l.). By exploring crop diversity across a distinct semi-arid gradient, we will investigate the influence of varying social and biophysical conditions on cultivation strategies and, in the process, contribute to a growing research area concerning techniques to reduce vulnerability within irrigation systems. We hypothesize that the study area locations that are "upstream," or at a higher elevation, will have greater crop diversity levels due to more favorable biophysical conditions (i.e. higher potential annual precipitation and less reliance on irrigation to sustain adequate crop growth), and that, in easily accessible locations, frequent exposure to agricultural extension officers will increase diversification.

Background

Reduced vulnerability through crop diversification

Agriculturalists in the SAT face a number of sociopolitical and environmental challenges. Most notable among the environmental challenges are between and within season rainfall variability, low and deteriorating levels of soil organic matter, and high evapotranspiration rates (Ayuk, 2001; Rockström and Barron, 2007; Cooper et al., 2008). Crop diversification has the potential to enhance resilience in agricultural systems (Heal, 2000), particularly on lands considered marginal for production (Ewel, 1999). Resilience, here, refers to the capacity of a system to maintain structure and function following a perturbation, without necessarily returning to a particular reference state (Holling, 1973). Thus, a resilient agricultural system is one that continues to provide services, such as nutrient cycling and food production, despite the presence of external stressors, such as extreme climatic events or the presence of pests (Lin, 2011). Recent research has demonstrated that crop diversification practices help buffer microclimatic fluctuations (e.g. Holt-Giménez, 2002; Tengo and Belfrage, 2004; Lin, 2007; Philpott et al., 2008) and increase the suppression of pests and diseases (e.g. Mitchell et al., 2002; Perfecto et al., 2004), while also enhancing production stability and the provision of diverse livelihood benefits to farmers (e.g. Moguel and Toledo, 1999; Peeters et al., 2003; Méndez et al., 2007).

The resilience of diversified systems, such as polycultures and agroforestry systems,[1] to extreme climatic events is commonly linked to modifications in farm-level microhabitats. For example, in comparing the resilience of farms to hurricane impacts (e.g. Hurricane Mitch in 1998) in Nicaragua and Honduras, Holt-Giménez (2002) found that "agroecological" farms (or farms that used more sustainable land management practices, such as contour farming, intercropping, vegetative strips, and agroforestry) had more topsoil, higher field moisture levels, and lower economic losses than conventional farms following disturbance. Research by Philpott et al. (2008) in Chiapas, Mexico further demonstrates the importance of vegetative complexity in buffering against extreme storm and wind events. The authors examined the relative impact of topographic and biophysical characteristics (e.g. aspect, slope, elevation, canopy cover, vegetation structure) on predicting economic and landslide damage associated with Hurricane Stan in 2005. They found that reductions in farm-level vegetative complexity correlated with increased probability of landslides at the farm and landscape level.

Additional research by Lin (2007) demonstrates the importance of multistoried shade trees in producing microclimates that buffer temperature and humidity fluctuations, thereby improving growing conditions. In comparing the microclimate and soil moisture data of coffee systems with varying degrees of shade cover, Lin (2007) found that fluctuations in temperature, humidity, and solar radiation increased as shade cover decreased. The presence of shade trees helped control or limit climatic extremes, which enabled better management of plant physiological processes, including reduced loss of water through evapotranspiration. The positive impact of biodiverse systems relative to more modern, intensive agricultural systems was also demonstrated by Tengo and Belfrage (2004) in Sweden and Tanzania. The authors found that more traditional land management practices, particularly those that incorporated wild varieties suitable for local conditions, had a higher capacity to adapt to climatic extremes. Further, systems with greater spatial and temporal complexity, such as polycultures and intercropping systems, were shown to regulate pest outbreaks and enhance water conservation, which limited the impact of seasonal drought.

Finally, in the context of global change, the importance of crop biodiversity increases as commercial agriculture tends toward large, monoculture systems. These monoculture systems are generally associated with increased use of costly inputs for crop maintenance (e.g. irrigation, synthetic fertilizers, pesticides) and reduced diversity of crop varieties. Given losses of diversity, any major natural shock to the agricultural system may cause severe and irreversible damage to the system. Though crop diversification is not a panacea for reducing vulnerability to climatic variability, it has the *potential* to increase production and promote ecosystem stability on marginal or degraded lands. Additional to the benefits outlined above, diversified systems can aid in the cycling of water and nutrients. For example, intercropping with leguminous crops and trees has been shown to improve use of space, rooting ability and water use efficiency, and nutrient uptake on lands with poor soil quality (Morris and Garrity, 1993; Lithourgidis et al., 2011). Because inorganic fertilizers contribute to nitrate pollution and eutrophication (among other environmental consequences), intercropping with legumes can provide an alternative, sustainable way of introducing biological nitrogen fixation into the system (Fustec et al., 2010; Lithourgidis et al., 2011).

Crop diversity and agricultural innovation

Extensive attention has been given to agricultural innovation and adoption (e.g. Feder and Umali, 1993; Saha et al., 1994; Diederen et al., 2003; Knowler and Bradshaw, 2007; Shiferaw et al., 2009). This body of literature typically investigates farmer adoption of technological innovations or practices as a utility maximization process subject to micro-level and macro-level constraints (Feder et al., 1985). Factors affecting adoption can be grouped under four categories: human capital, structural, institutional, and environmental (D'Souza et al., 1993), with variables such as age and education grouped under *human capital* characteristics, farm size and off-farm employment under *structural* characteristics, participation in government programs under *institutional* characteristics, and rainfall and soil quality under *environmental* characteristics. These variables are then used to identify patterns of adoption behavior at micro- and macro-scales, and to verify or refute hypothesized relationships regarding new technology use and farm-level or firm-level (aggregate) characteristics.

Studies investigating sustainable agricultural practices, such as crop diversification, have also utilized the technology adoption literature. While justifying their use of this literature in formulating an econometric model, D'Souza et al. (1993, p. 160) state that "the adoption of a sustainable agriculture system can be expected to be influenced by the same characteristics as those that influence adoption of conventional technologies." Similarly, studies inspecting adoption of sustainable agriculture techniques such as conservation tillage and no-till techniques (e.g. Gould et al., 1989; Pautsch

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[1] Polycultures are characterized by two or more crop species grown on the same field while agroforestry systems are characterized by the growing of trees and crops on the same field. In both systems, wide variability exists in the spatial and temporal arrangement of crops and trees (Lin, 2011).

et al., 2000; D'Emden et al., 2008), the use of cover crops (e.g. Neill and Lee, 2001), and the use of organic input or low-input practices (e.g. Saltiel et al., 1994; Clay et al., 1998; Parra López and Calatrava Requena, 2005; Genius et al., 2006) have assembled their analyses utilizing previous research on technology adoption. Likewise, we use the technology adoption literature to provide a framework for our analysis, a strategy applied less frequently in studying crop diversification compared to other sustainable agricultural practices.

We have chosen to conduct our study of crop diversification strategies within a semi-arid environment given the unique precipitation-related exposures present in these systems, and the role that these exposures may play in a household's ability to diversify. Additionally, our study takes place within an upland-lowland system to capture not only differences in climatic conditions and how these differences influence crop diversity levels, but also to better understand how differing social conditions influence crop diversification. Mount Kenya's environmental gradient, which captures varying biophysical conditions, as well as multiple socioeconomic levels, farming strategies, and ethnic groups, allows this to be achieved.

Social and environmental conditions in the Upper Ewaso Ng'iro Basin

Up to the early 1900s, Mount Kenya's Upper Ewaso Ng'iro Basin, which encloses on the mountain's northwest foot slopes and extends to the semi-arid plains of the Laikipia plateau before giving way to semi-arid and arid lowlands, was predominately occupied by Maasai and Samburu pastoralists (Wiesmann et al., 2000). During the colonial era, the lower slopes of Mount Kenya and the Laikipia plateau transitioned to large ranches and farms owned by white settlers. Following independence, many of the large agropastoral landholdings were subdivided into small plots of land where agropastoral systems persist. The basin has experienced a rapid increase in population since the colonial era as a population that stood at approximately 50,000 in 1960 rose to 500,000 in 2000 (Ngigi et al., 2007). This increase was largely driven by immigration from nearby densely populated areas, often people of Kikuyu or Meru origin from Kenya's Central Province seeking available farmland (Kunzi et al., 1998). The resulting social make-up of the once pastoral-centered Upper Ewaso Ng'iro Basin is as follows: densely settled smallholder and larger commercial operations with urban centers (populations ranging from 2500 to 30,000 people) on the lower slopes of the mountain, less densely settled smallholder farming operations on the Laikipia plateau, and pastoralists on the edge of the plateau as well as the more marginal arid lowlands (Wiesmann et al., 2000). Thus, a distinct "social gradient" exists in the basin from the upper slopes of Mount Kenya to the lowlands beyond the Laikipia plateau. This "social gradient" is characterized by variability in landholding density, landholding size, and ethnic groupings, among other qualities (as described in 'The study site: eight riparian communities' section).

Similarly, as is typical in an upland-lowland system, a strong precipitation gradient exists in the basin. At the peak of Mount Kenya (~5200 m a.s.l.), rainfall amounts to 2000 mm yr^{-1}, while at Archer's Post (862 m a.s.l.), the outlet of the Ewaso Ng'iro River in the north of the basin, rainfall may total only 200 mm yr^{-1} (Ngigi et al., 2007). Climatic zones thus progress from humid to semi-arid to arid with advancement first from the slopes of Mount Kenya, then to the Laikipia plateau, and finally to the northern lowlands. Average temperatures in the basin likewise range from 10 °C to 24 °C, with evaporation loss being a major obstacle to agriculture in the lowlands (Liniger et al., 1998).

Our analysis takes place in an upland-lowland social–ecological system embedded within the larger Upper Ewaso Ng'iro Basin system (Fig. 1). The study area exhibits social conditions and a climatic gradient not unlike the larger basin.

The study site: eight riparian communities

Fig. 1 identifies the eight riparian community irrigation projects surveyed for this analysis, as well as Nanyuki Town, the primary economic center within the study area. These irrigation projects encompass an area of approximately 1250 km^2 and are positioned along three major rivers of the Upper Ewaso Ng'iro Basin: the Likii, the Nanyuki, and the Ewaso Ng'iro. The upstream irrigation projects, those drawing their water from the Likii River, represent five of the nine projects occupying the Likii subcatchment (positioned within the larger Upper Ewaso Ng'iro Basin). These projects belong to the Likii Water Resource Users Association (Likii WRUA), which was established to allow for subcatchment-level management of water resources (LWRUA, 2009). Each of these irrigation projects has a single intake where water is then directed to users through a network of pipes. Within the Likii subcatchment, rainfall ranges from 1100 mm yr^{-1} in the humid areas to 750 mm yr^{-1} in the semi-arid locales at the foot of the subcatchment. The number of documented river water extraction points within the subcatchment more than doubled from 1997 to 2004, giving way to concerns of water scarcity (LRWUA, 2004). This has largely been driven by an increasing population as well as growth of the subcatchment's horticultural enterprises.

The Kikuyu and Meru ethnic groups are most prevalent within the Likii subcatchment, with Meru people mostly residing within the irrigation projects nearest Mount Kenya (i.e. Miarage A and Murimi). Landholdings are typically two acres in size and consist of several dwelling structures, a structure for livestock, and fields for cultivation. Some farmers with greater wealth may own additional acres; however, land redistribution and subsequent subdivisions following independence have resulted in landholdings of two acres as the norm within the Likii subcatchment. These farm units are being further subdivided as multiple generations inhabit a single household. This further strains the available land and water resources.

Many Meru and Kikuyu farmers in the Likii subcatchment are settlers from areas of higher agricultural potential, such as the lands surrounding Meru Town and Nyeri Town (personal correspondence). With them, they may bring a desire to cultivate crops more suitable to their previous residences, but most continue to grow the staple crops of maize, beans, and potatoes. These staple crops are first and foremost grown for consumption. A surplus may be taken to market, but aside from market crops such as cabbage, snow peas, and tomatoes, the familial unit consumes what is harvested.

Naibor represents the midstream irrigation project and is located along the Nanyuki River following its confluence with the Likii. Pastoralism is common here (Huho et al., 2012), but many sedentary farmers also exist. As opposed to the irrigation projects within the Likii subcatchment where a single intake acts as the source of river water for the community, river water extraction within the Naibor irrigation project is direct, meaning that individual farmers withdraw water from the Nanyuki River. Additionally, a collection of farmers receive water from the Kiburuti Dam, a dam project initiated by Kenya's Ministry of Agriculture, rather than the Nanyuki River. These farmers also directly withdraw water from the dam, typically through the use of fuel-powered pumps. Data provided by WorldClim (see Hijmans et al., 2005) suggests average yearly rainfall here to be between 700 mm and 715 mm and average temperature to be ~17 °C.

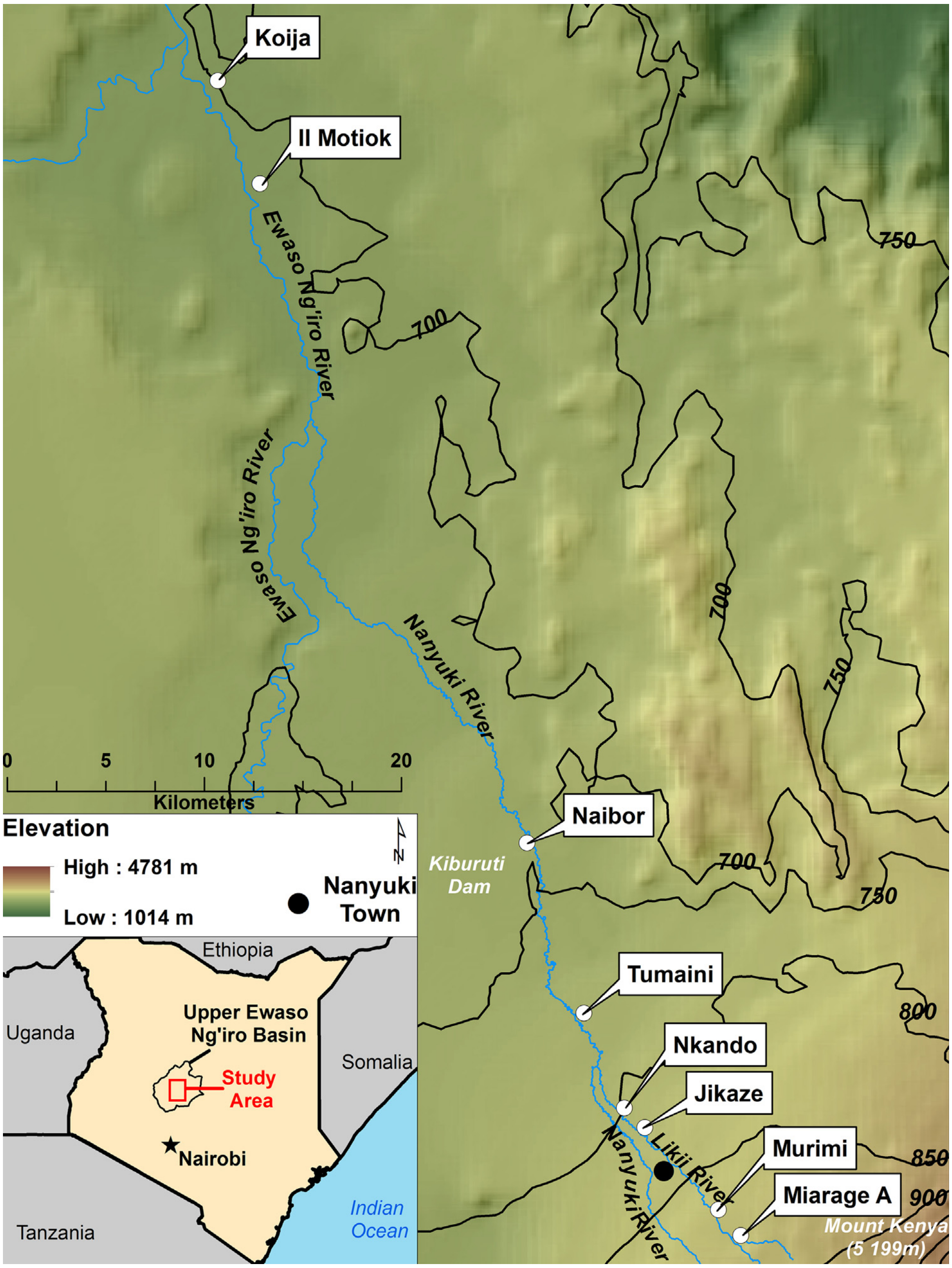

Fig. 1. Study area. *Note*: Isohytes, shown as black lines on the map, represent average yearly rainfall (mm) and are used to highlight the environmental gradient.

The Kikuyu tribe makes up the majority of sedentary farmers in Naibor. According to surveys conducted during the summer of 2012, which will be described further below, landholdings size, on average, are slightly greater than one acre. This reduction in size compared to landholdings within the Likii subcatchment is partly due to the small plots surrounding the Kiburuti Dam. Members of the Maasai tribe, while present in this area, were not interviewed unless their livelihood strategy was one of sedentary farming.

The downstream communities of Il Motiok and Koija are Maasai group ranches where farming operations only take place on the banks of the Ewaso Ng'iro River. Livestock herding is the chief livelihood practice in these communities with sedentary farming being a relatively recent phenomenon. Promotion and development of farming operations resulted through efforts by NGOs in 2010; however, farmers have expressed frustrations stemming from low rainfall, difficulties with wildlife, and the high costs associated with machinery and agricultural inputs (personal correspondence). River water extraction within these irrigation projects is performed by the individual and typically involves foot pumps, fuel-powered pumps, or simply abstracting water with buckets. Data provided by WorldClim suggests average yearly rainfall ranges from 685 mm to 715 mm, while average temperatures range from 18 to 19 °C.

Temporary dwellings are kept near the river to manage the fields and protect crops from wildlife, namely elephants and monkeys. Permanent *manyattas* (family compounds) are set back from the Ewaso Ng'iro River a distance of approximately 2–4 km. When visiting the Koija and Il Motiok sites during the summer of 2012, the authors witnessed several fields that had been abandoned – examples of the frustrations expressed concerning sedentary farming and coping with the challenges of developing a new livelihood practice. The 2012 fieldwork data revealed that riparian fields are, on average, one acre in size in Il Motiok and 0.50 acres in Koija.

Table 1
Attributes of community irrigation projects (CIPs).

	No. of surveys	No. of HH surveys conducted with tribe members traditionally practicing sedentary ag.	No. of HH surveys conducted with tribe members traditionally practicing pastoralism	CIP average size of household	CIP average change in land irrigated in past 5 years	Year CIP established	Range in elevation (m a.s.l.)
Miarage A	42	42	0	4.6	No change	1982	2099–2035
Murimi	47	47	0	4.4	No change	2001	2099–1981
Jikaze	18	15	3	4.8	Slight decrease	1997	1960–1923
Nkando	41	41	0	4.8	No change	2002	1920–1873
Tumaini	51	49	2	4.8	No change	2003	1860–1805
Naibor	57	49	8	5.0	Slight increase	~2006	1799–1792
Il Motiok	24	0	24	5.7	Slight increase	2010	1633–1619
Koija	35	0	35	4.9	Slight increase	2010	1624–1617

Methods

Data collection procedures and description of sample

Household-level and community irrigation project-level data were collected during the summer of 2012. Household surveys were administered to gather information regarding household-level demographics, water use, agricultural practices, reliance on irrigation, and attributes of the irrigation project to which the household belonged. These surveys had a duration of approximately 45 min. Irrigation project-level surveys were administered to the managers of the projects to better understand water rationing strategies, rules governing river water extraction, and relationships between other irrigation projects. The project-level surveys had a duration of 1 h. The analyses within this study employ only the household-level data; however, information obtained from the community irrigation project manager surveys helped to contextualize results.

In all irrigation projects, selection of households was done in such a fashion that after completing a survey, the next two homesteads would be skipped before stopping at the third homestead to conduct the next survey. This was done to obtain a more representative sample of households within the community irrigation projects. A total of 315 surveys were administered. Table 1 provides attributes of surveyed households as well as the irrigation projects themselves, with information grouped by irrigation project.

A representative sample of at least 35 households per project were visited in the larger irrigation projects. In the smaller projects of Jikaze and Il Motiok, 18 and 24 households were visited, respectively. This represented more than 50% of total members in both of these irrigation projects. All households were located near one of the main rivers within the study area (i.e. the Likii, Nanyuki, or Ewaso Ng'iro River), or in the case of the Kiburuti Dam, households were located near the dam. Within the two downstream communities of Il Motiok and Koija, temporary dwellings were kept near the riparian fields, while permanent *manyattas* were set back several kilometers from the river, as mentioned in 'The study site: eight riparian communities' section. To get a representative sample within these two communities, one surveying group visited the permanent homesteads while two other surveying groups visited the temporary riparian dwellings.

Variables for analysis and hypotheses

Whether spatial crop diversity is studied at the genetic or species level, the outcome of reduced vulnerability from greater diversity remains since redundancy is built into the agricultural system through various levels of diversity (Vandermeer et al., 1998). The household-level surveys only collected information on the crop species grown, not the genetic variety of crops. As a result, attention is given to the species level. The crops grown in the study area offer many agroecological benefits when grown together (see Table 2), and the dependent variable *CropType* was constructed to capture these benefits of diversification at the household level.

To construct the *CropType* variable, a homestead's crops were grouped into one of eight categories: cereal, legume, root vegetable, fodder grass, fruit/fruit tree, leafy green vegetable, stimulant/hallucinogen, and sugar-rich grass. One point was awarded

Table 2
Agroecological benefits by crop type and qualities of crops associated with the study area.

Crop type	Crops grown in study area	Benefit
Grain	Maize, sorghum, rice, millet, wheat	Intercropped with nitrogen-fixing crops to increase production; large biomass producing cover crop; extensive rooting structure; *staple food crop*
Legume	Groundnut, soybeans, mixed beans, Bambara nuts, cowpeas, velvet beans, peas	Contribute to nitrogen fixation; used as cover crop to reduce water loss; pest suppression properties; *staple food crop*
Root vegetable	Irish potatoes, sweet potatoes, cassava, onions, carrots	Efficient use of space – food source and rooting structure are one and the same; *staple food crop*
Stimulant/hallucinogen	Tobacco, miraa	Provides temperature regulation and reduces water loss by providing shade in the case of miraa; commercial crop
Fodder grass	Hay, napier grass, Rhodes grass	Used frequently in mulching to improve soil cover; reduces soil erosion and acts as a windbreak when planted on field perimeter; promotes pest regulation; *critical component of integrated livestock-agricultural systems*
Sugar-rich grass	Sugarcane	Some varieties capable of fixing nitrogen; *grown in small quantities for domestic consumption*
Fruit tree/fruit shrub/fruit	Tangerine, orange, banana, guava, pawpaw, avocado, watermelon, mango, tomatoes	Provides temperature regulation and reduces water loss by providing shade; extensive rooting structure; *some crops provide large economic returns, particularly tomatoes*
Leafy green vegetable	Cabbage, spinach, kales	Improved yields from integration into intercropped systems; efficient use of space; *cabbage is often grown for market*

Note: Information in italics pertains specifically to the study area, although the information may also be consistent with other locations.

Table 3
Summary of variables used for analysis.

Variable	Variable description	Variable type	Max	Min	Avg
CropType *(Dependent variable)*	Number of different crop types grown by the household. See 'Variables for analysis and hypotheses' section for further information regarding construction of this variable.	Ratio	6	0	2.936
FrequencyGrown *(Dependent variable)*	Number of different crops grown by the household. See 'Variables for analysis and hypotheses' section for further information regarding construction of this variable.	Ratio	8	0	2.168
Precip	The average annual precipitation at the location of the homestead unit as provided by World Resources Institute (in millimeters).	Ratio	886	685	791.15
HH12yr	The number of members within the household who are 12 years old or older.	Ratio	9	1	3.55
Income	The total yearly income summing the incomes of all members of the household (in Kenyan shillings).	Ratio	1,428,000	0	167,431
Age	The age of the household head as identified through the survey.	Ratio	92	16	46.2
Loc	The number of years that the household head has been farming at the current location.	Ratio	53	1	15
Extension	Whether or not a member of the household met with or attended workshops with an agricultural extension officer within the previous year.	Binary	1 (yes)	0 (no)	0.29
Edu	The highest level of education obtained by the household head categorized by *no education*, *some primary education*, *completed primary*, *some secondary*, *completed secondary*, *certificate level*, and *some college/university*.	Ordinal	6 (some college)	0 (none)	2 (finished primary school)
Offfarm	The number of household members who derive their income from an off-farm source.	Ratio	3	0	0.58
Fldsize	The sum of the acreage of all the fields possessed by the household that were being cultivated at the time of the interview or were fallow either at the time of the interview or the previous year (in acres).	Ratio	7.25	0.25	1.35

for each crop type grown, which resulted in a variable ranging from 1 (a farm growing one crop or one crop type) to 8 (a farm growing at least one of each crop type). Thus, a homestead growing onions, carrots, maize, mixed beans, and bananas would have a score of 4 (*root vegetable*: onions and carrots; *legumes*: mixed beans; *cereal*: maize; *fruit*: banana trees). After grouping all crops into the eight categories, household fields that were less than or equal to 0.125 acres were removed from the analysis to avoid capturing the smallest gardens (i.e. kitchen gardens). This resulted in 16% of the initial 1181 fields being dropped from the analysis. While kitchen gardens are important to maintaining livelihoods, our analysis seeks to examine the fields that impose a greater demand on labor and agricultural inputs.

The *CropType* variable is, in essence, a measure of farm-level species richness during a single growing season with species grouped by type to emphasize agroecological benefits. A second representation of species richness is captured by an additional dependent variable, *FrequencyGrown*. Of the households surveyed, maize, potatoes, and mixed beans accounted for more than 60% of all crops grown. This variable groups maize, potatoes, and mixed beans together and awards only one point for growing one, two, or all three of these crops. These three crops are grouped since each is a staple food item and, we believe, each yields similar (i.e. minimal) market opportunities. Therefore, the vulnerability-reducing capacity of each of these three crops likely remains similar whether a household grows one, two, or all three crops. An additional point is awarded for each less commonly grown crop. Therefore, an agricultural system consisting of maize, mixed beans, tomatoes, mangoes, and spinach would have a species richness value of 4, since maize and mixed beans, together, are counted only once. Like *CropType*, the smallest fields, those less than or equal to 0.125 acres, were eliminated when constructing the *FrequencyGrown* variable.

A metric of species richness offers an adequate alternative to proportional abundance measures of diversity, such as the Shannon or Simpson indices of diversity, but detail is compromised using a richness index. The two separate dependent variables were constructed to mend this by examining diversity from two perspectives: an agroecological perspective and a more straight-forward count of the different species grown. The independent variables used in the analysis, as well as the hypotheses, remain the same regardless of the dependent variable.

The independent variables listed in Table 3 were chosen based on a review of studies inspecting agricultural innovation and adoption of agroecological practices, namely Ghadim and Pannell (1999), Pannell et al. (2006), and Knowler and Bradshaw (2007). These variables are consistent with the technology adoption literature, since adoption of sustainable agricultural practices can be expected to be guided by the same factors as those influencing adoption of technologies in agricultural systems (D'Souza et al., 1993). Because we are motivated by the distinct and differing conditions across the study area's gradient, the variables have also been summarized by community irrigation project (Table 4). Aside from the precipitation variable, all variables were derived from the household survey. Precipitation data were obtained from WorldClim (see Hijmans et al., 2005).

Table 5 provides the predicted relationships between the dependent variables and the independent variables, as well as explanations for these relationships. In the case of both dependent variables (i.e. *CropType* and *FrequencyGrown*), the expected

Table 4
Average value of variables by community irrigation project.

	Miarage A	Murimi	Jikaze	Nkando	Tumaini	Naibor	Il Motiok	Koija
CropType (*Dep. Var*)	3.462	3.333	3.187	3.342	3.021	2.189	2.500	2.600
FrequencyGrown (*Dep. Var*)	2.513	2.250	2.375	2.711	1.896	1.887	1.800	2.000
Precip	882.72 mm	874.14 mm	809.25 mm	803.16 mm	775.56 mm	737.57 mm	714.40 mm	718.50 mm
HH12yr	3.5	3.3	4.1	3.7	3.9	3.5	3.2	3.4
Income	182,789 Ksh	171,794 Ksh	309,962 Ksh	236,096 Ksh	133,516 Ksh	149,422 Ksh	139,060 Ksh	84,226 Ksh
Age	47.9	47.7	48.3	45.3	55.7	42.0	35.4	38.9
Loc	18.7 years	12.5 years	17.4 years	15.3 years	25.5 years	15.4 years	2.1 years	2.0 years
Extension (% of homes visited by extension officers)	28.2%	19.4%	0%	36.3%	44.9%	29.4%	16.2%	10.9%
Edu	Some secondary school	Finished primary school	Finished secondary school	Some secondary school	Finished primary school	Finished primary school	No education	No education
Offfarm	0.41	0.53	1.13	0.89	0.63	0.64	0.30	0.20
Fldsize	1.92 acres	1.28 acres	1.44 acres	1.36 acres	1.68 acres	1.14 acres	1.18 acres	0.54 acres

relationships with the independent variables are thought to be identical.

Analysis

To analyze the effects of the independent variables on both *CropType* and *FrequencyGrown*, two sets of regression models were run, one for each dependent variable. Other than this, the models were identical. Each model included all independent variables mentioned previously to create the following equations (see Table 3 for variable descriptions):

$$\begin{aligned} CropType_i = {} & \beta_0 + \beta_1 Precip + \beta_2 HH12yr_i \\ & + \beta_3 Income_i + \beta_4 Age_i + \beta_5 Loc_i + \beta_6 Extension_i \\ & + \beta_7 Edu_i + \beta_8 Offfarm_i + \beta_9 Fldsize_i + \varepsilon_{it} \end{aligned} \quad (1)$$

$$\begin{aligned} FrequencyGrown_i = {} & \beta_0 + \beta_1 Precip + \beta_2 HH12yr_i \\ & + \beta_3 Income_i + \beta_4 Age_i + \beta_5 Loc_i + \beta_6 Extension_i + \beta_7 Edu_i \\ & + \beta_8 Offfarm_i + \beta_9 Fldsize_i + \varepsilon_{it} \end{aligned} \quad (2)$$

Both ordered logistic and standard ordinary least squares were used to estimate the models, and similar results were produced with each technique (only the results of the OLS models are presented). Diagnostic tests following the regressions did not reveal any large problems with the data. Several outliers were identified in the *FrequencyGrown* model and there was evidence for heteroskedasticity in both models, but correcting for these possible problems did not substantively change the results of the models.

Results and discussion

Results

Table 6 shows the results of the OLS regressions for both models. For the model with *CropType* as the dependent variable, the only independent variable that was significant was the *Precip* variable, which was extremely significant. The direction of this variable was also as predicted, with more precipitation associated with increased crop diversity. On average, an increase in one standard deviation of this variable led to a 0.42 increase in the *CropType* variable (or 37.5% of its own standard deviation). Considering that the average of the *CropType* variable is 3 (with a range from 0 to 6), we judge the *Precip* variable then to have a moderate effect size. The rest of the variables were not significant at the 5% or 10% levels, nor were any of them close to either threshold.

For the *FrequencyGrown* model, the *Precip* variable was highly significant as was the *Fldsize* variable. The *Income* and *Extension* variables were also significant at the 5% and 10% levels, respectively. The p values of the *HH12yr* and *Offfarm* variables were also much closer to the threshold for significance than either were in the *CropType* model. The effect size for the *Precip* variable was smaller in this model (with its standard deviation change associated with an average 22% of a standard deviation change in the *FrequencyGrown* variable). The effect sizes of the other significant variables were moderate to small: using the same formula, one standard deviation

Table 5
Hypothesized relationships.

Variable	Hypothesized relationship with dependent variables	Explanation
Precip	+	Locations with higher rainfall levels represent locations where environmental conditions support more numerous plant species (Gentry, 1988)
HH12yr	+	If a household has additional family members capable of working on the farm, the risk of trying new techniques, including new crops and agroecological techniques, will decrease (Schmitt, 1991; Ghadim and Pannell, 1999)
Income	+	The adoption of new techniques requires sufficient financial security (Somda et al., 2002)
Age	–	Increasing age may cause farmers to become more risk averse against new techniques (Clay et al., 1998)
Loc	+	The experience of the homestead with the local farming conditions will increase willingness to try new techniques (Knowler and Bradshaw, 2007 for summary of viewpoints)
Extension	+	Exposure to new ideas, training, technical support, and logistical support will put farmers in a better position to adopt new crops and techniques (Rahm and Huffman, 1984)
Edu	+	Education reduces risk aversion and leads to household heads being more inclined to adopt new farming strategies (Knight et al., 2003)
Offfarm	–	Less labor available on the farm will discourage farmers from adopting new strategies since human capital will be drawn down (Knowler and Bradshaw, 2007 for summary of viewpoints)
Fldsize	+	Larger landholdings may be indicative of a farmer's willingness to take on the risks of investing in new techniques and new technologies (Nkonya et al., 1997)

Table 6
Ordinary least squares regression results.

	CropType model	FrequencyGrown model
Precip	0.007 [a]	0.004 [a]
	(0.001)	(0.001)
HH12yr	0.057	0.071
	(0.044)	(0.047)
Income	0.002	0.008 [b]
	(0.003)	(0.004)
Age	−0.004	0.000
	(0.005)	(0.006)
Loc	0.003	−0.004
	(0.007)	(0.007)
Extension	0.166	0.277 [c]
	(0.156)	(0.164)
Edu	−0.015	−0.021
	(0.047)	(0.049)
Offfarm	−0.072	−0.162
	(0.107)	(0.112)
Fldsize	0.042	0.186 [a]
	(0.062)	(0.065)
N	265	265
***R*^{2}**	0.165	0.147

Note: OLS estimates shown for each variable, with standard errors given in parentheses for each variable.

[a] Statistical significance indicated at the 0.01 level.

[b] Statistical significance indicated at the 0.05 level.

[c] Statistical significance indicated at the 0.10 level.

change in the *Income*, *Fldsize*, and *Extension* variables on average led to 14%, 17.5%, and 10% of a standard deviation change in the *FrequencyGrown* variable, respectively. For each of these variables, the direction of the relationship was as hypothesized (positive).

Discussion: understanding crop diversification in a semi-arid agricultural system

Strategies for adopting cropping practices are manifold. Benefits such as increased productivity, market returns from innovation, ability to cope with adverse climatic and market events, food security, and maintaining traditional practices all may influence crop choices.

Maize, beans, and potatoes are staple crops within Kikuyu and Meru diets, so it was not surprising that these three crops accounted for more than 60% of all crop observations within the study area. In Il Motiok and Koija, where the Maasai have traditionally led a subsistence lifestyle centered on pastoralism, the recent emphasis on sedentary farming has increased the presence of maize, beans, and potatoes here as well. In all locations, more than anything else, the presence of the three staple crops results from a desire to achieve food security and, in the upstream communities, to maintain a traditional diet. No farmers stated that these three staple crops were being grown solely for market.

Tengo and Belfrage (2004) found that smallholder farmers adjusted their management practices in accordance with ecological conditions and to account for recurrent climatic disturbances. Conversations with farmers surveyed in this study revealed a range of considerations for ecological conditions. For example, when describing the rationale for intercropping, some farmers expressed the ecological benefits of pest management, and improved soil quality, as well as efficient use of space. However, others who were also intercropping expressed a desire to move away from the practice in favor of monocropping, and that they were intercropping simply because that was the traditional practice used in the area. Therefore, deployment of agroecological practices, such as crop diversification, was not solely the outcome of consciously seeking stability in the face of adverse conditions. In some cases, the decision was made due to the choices of neighbors, friends, or family members. In other cases, such as the one described above, the farmer may eventually transition away from some agroecological practices if it is believed that a different agricultural management scheme may yield better results. These scenarios demonstrate that agroecological management decisions arise from consideration of multiple factors, which must be kept in mind when interpreting the study results. Additionally, directionalities of the relationships from our analysis have not been thoroughly defined. In this section, we show and posit explanations for relationships, however, we leave more rigorous testing of causal relationships to future work where we also intend to employ a longitudinal data set to better understand spatial as well as temporal semi-arid agricultural practices.

Both the *CropType* and the *FrequencyGrown* models explain roughly the same amount of variation within their respective dependent variables. As mentioned in ‘Results’ section, the *FrequencyGrown* model found significant relationships with four of the independent variables, while the *CropType* model found only one significant relationship. This may reflect the fact that the dependent variable in the *FrequencyGrown* model is a much more conventional measure of crop diversity, or that using the technology adoption literature to guide selection of independent variables is more appropriate when the response variable is a conventional measure of crop diversity. Studies such as Isakson (2007) have used strict richness measures when the data did not lend themselves to a measure of proportional abundance (e.g. Simpson or Shannon indices of diversity). To our knowledge, a richness measure that also attempts to account for agroecological function by grouping crops by type (i.e. the *CropType* model) has not been used previously. Had the results of the *CropType* model been more notable, or had the model clearly outperformed *FrequencyGrown*, evidence may have existed that farmers were considering the interrelatedness of crop functions in their cultivation practices. It certainly remains a possibility that farmers do consider these agroecological functions when making cultivation decisions, but it is not being captured by grouping crops by type. Given that the *FrequencyGrown* model performed better in terms of identifying significant relationships, we focus our remaining discussion on this model.

All significant independent variables for the *FrequencyGrown* model were in the hypothesized direction, as shown in Table 5. As mentioned in ‘Crop diversity and agricultural innovation’ section, the technology adoption research (e.g. Feder, 1982; Feder et al., 1985; Rogers, 1995) has been used in the study of multiple sustainable agricultural practices; a similar level of effectiveness in explaining the farm-level characteristics contributing to crop diversification was found when applying the technology adoption literature. The *Precip* variable was highly significant and indicated that increasing precipitation resulted in greater crop diversification. This was not surprising as suitability of growing conditions in the study area improves with increased rainfall. Smallholder farmers in locations with higher precipitation levels may need to rely less on irrigation infrastructure and water harvesting practices since dry spells may be less frequent and less severe. It should also be recognized that the precipitation variable is acting as a proxy for other environmental conditions, an observation that was made by Samberg et al. (2010) in their study of the diversity of crop species and crop varieties in Ethiopia’s highlands. Elevation and temperature would both likely produce a comparable effect as, similar to precipitation, both show a continuous, steady, unidirectional trend with advancement along the mountain slopes. Thus, the precipitation variable is capturing Mount Kenya’s leeward environmental gradient.

Household income had a small but positive effect on crop diversity levels. Wealthier farmers may deem the practice of growing a diverse array of crops, some crops less commonly grown than others, a less risky endeavor compared to farmers with relatively low income. This is due to the ability of a wealthier farmer to better absorb the consequences of a failed cultivation venture since investment in the uncertain endeavor constitutes a smaller proportion of overall wealth. Farmers with greater wealth can additionally invest in new equipment and labor that facilitates planting and maintaining multiple crop types. For example, drip irrigation kits are commonly used when growing tomatoes in the study area. The cost of these kits and the additional labor needed to maintain intensive horticultural endeavors may preclude some farmers from cultivating tomatoes. The household surveys reveal that the average income of farmers who have at least one field in which tomatoes are grown is 183,000 Ksh, while the average income of farmers growing sweet potatoes, a less capital-intensive crop, is 152,000 Ksh. If not for some small-scale growers of tomatoes, this disparity would be much greater due to the presence of several wealthier farmers with large greenhouses dedicated to tomato production.

In the case of interactions with agricultural extension officers, the relationship is also consistent with much of the findings from the technology adoption literature, since it suggests that exposure to new techniques and strategies provided by extension officers will lead to a greater diversity of planted crops. Here, accessibility may be an influencing factor. Extension officers are more likely to visit locations made more accessible via better road networks or proximity to economic centers. The more accessible community irrigation projects are those located in the middle and lower zones of the Likii WRUA (i.e. Jikaze, Nkando, and Tumaini), as well as Naibor. A closer inspection of the agricultural extension variable indeed reveals that the more accessible Nkando, Tumaini, and Naibor irrigation projects were more consistently visited by extension officers (36% of surveyed households in Nkando, 45% in Tumaini, and 29% in Naibor). Surprisingly, the Jikaze project, which is located closer to Nanyuki Town than any other irrigation project, recorded zero visits by extension officers. One possible explanation for this is the disproportionate number of civil servants within the Jikaze project, which leads to many Jikaze members being financially better-off when compared to members of other irrigation projects. Extension services therefore are possibly being directed away from Jikaze toward other irrigation projects in greater need of these services. Of the households surveyed in the remote downstream irrigation projects of Il Motiok and Koija, 16% of households in Il Motiok and 11% of households in Koija had been visited by an extension officer within the previous year. These were the lowest values aside from the value recorded for Jikaze. For farmers in these two irrigation projects, low exposure to extension officers further challenges the smallholders since sedentary farming was only widely adopted in 2010 and assistance is likely needed in order to inform farming decisions.

Finally, field size had a positive relationship with *Frequency-Grown*. Feder et al. (1985) point out that the relationship between farm size and adoption of practices is less distinct than is the case with other farm-level characteristics, since landholdings, in actuality, may act as a surrogate for such factors as access to credit, risk aversion, access to scarce inputs, and access to information, thereby clouding the relationship. Studies such as Clay et al. (1998) have in fact found a negative relationship between field size and adoption of new practices. One possible explanation for the positive relationship found in our study is that farmers with larger landholdings may have more cultivatable space to experiment with new crops. Thus, if the area dedicated to a new crop is a relatively small proportion of the overall landholding size, the household is better able to withstand failed experimentation if much of the land continues to yield a harvest from other reliable, commonly grown crop species. This explanation clearly links size of landholdings with ability to tolerate risk.

Discussion: crop diversification trends across both the upland-lowland gradient and in the context of changing conditions

Our analysis aimed to capture information about crop diversification practices across a heterogeneous biophysical and social landscape to both investigate influencing factors to crop diversification in general and to further the understanding of practices aimed at reducing vulnerability in semi-arid agricultural irrigation systems experiencing significant change. The study area encompassed multiple agroclimatic zones: the Miarage A and Murimi irrigation projects exist near the *semi-humid* and *semi-humid to semi-arid* interface; Nkando and Jikaze are located within the *semi-humid to semi-arid* zone; Tumaini is positioned at the interface with the *semi-arid* zone; and Naibor, Il Motiok, and Koija are located within the *semi-arid* zone, with the latter two approaching the *arid* agroclimatic zone. Additionally, the study incorporated multiple ethnic groups with different socioeconomic levels. Finally, by conducting the study within a semi-arid environment where rain-fed agriculture is practiced and irrigation needed during dry periods, we gain insight to crop diversification strategies in regions of fluctuating rainfall potential. By incorporating these features, the following trends were identified.

First, wealth, which had a positive influence on crop diversity, not surprisingly appears to be influenced by opportunities for employment. The wealthiest irrigation projects (i.e. Jikaze and Nkando) are both located near Nanyuki Town. Miarage A and Murimi suffer from road infrastructure that is virtually impassable during the rainy season, which reduces market access, and Il Motiok and Koija have very limited access to paid employment opportunities and educational services due to their isolation. So, while crop diversity is influenced by wealth, cultivation decisions may more broadly be a product of accessibility to markets as well as employment and educational opportunities. With improved accessibility comes increased income, which allows farmers to experiment with crop diversification strategies. Second, as mentioned earlier, visitations from extension officers (or lack thereof) may similarly be a product of accessibility. This was a major advantage of conducting the analysis across irrigation projects ranging from very accessible to minimally accessible, since the survey data bear out this pattern nearly perfectly. As evident in Table 4, the irrigation projects near Nanyuki, aside from Jikaze (to which a hypothesis was offered in ‘Discussion: understanding crop diversification in a semi-arid agricultural system’ section), had the greatest percentage of households visited by extension officers, while Il Motiok and Koija had few visitations. Miarage A and Murimi, however, are much closer to Nanyuki than both Tumaini and Naibor, yet a smaller percentage of households were visited in these two projects, especially in the case of Murimi. This again lends itself to the role accessibility plays in crop diversity outcomes since Tumaini and Naibor, despite being further from the primary economic center, are more reachable for extension officers given the relatively well-maintained road along which they reside. Third, despite the poor infrastructure and relative inaccessibility within the uppermost irrigation projects of Miarage A and Murimi, some of the highest crop species richness counts were found in these areas. Employment opportunities and accessibility cannot alone be explaining diversity. This seems to suggest that even with limited market access, comparably fewer employment opportunities, and less frequent visits by extension officers, favorable growing conditions (as exhibited by higher potential precipitation in these projects) outweigh potential disadvantages that arise from inaccessibility. Fourth and finally, aside from Tumaini, the other irrigation projects within the Likii WRUA (i.e. Miarage A, Murimi, Jikaze, and Nkando) had the greatest levels of crop diversity within the study area (Table 4). Admittedly, these irrigation projects experience more favorable growing conditions than the projects outside of the Likii WRUA, but the attention given to irrigation infrastructure within the WRUA (see 'The study site: eight riparian communities' section) may also be influencing crop species diversity as the well-maintained irrigation infrastructure within the WRUA allows smallholders to better tolerate dry periods. This ability to bridge to wet periods by irrigating during dry spells is an important element in semi-arid agriculture. This will be explored further in future research.

Smallholder farmers therefore are influenced by income levels and extension officers when making cultivation decisions, but greater levels of crop diversification appear to take place irrespective of these influences when biophysical conditions, and possibly irrigation infrastructure, allow. In Il Motiok and Koija, relative inaccessibility and limited employment opportunities coupled with unfavorable growing conditions led to lower crop diversity. These two irrigation projects also represent a collection of relatively new agriculturalists, which may lead to conservative cropping strategies (e.g. cultivating only maize, beans, and potatoes). The heterogeneity of conditions therefore suggests the importance of accessibility and climatic conditions in crop diversification, with favorable climatic conditions capable of outweighing limitations posed by poor road networks and isolation (i.e. separation from villages and towns capable of providing opportunities not offered in a smallholder's home village).

Zimmerer (2014) inspected agrobiodiversity of smallholder farmers facing changes to their "cultural landscape" presented by proximate and more distant forces, such as decision-making regarding irrigation infrastructure, peri-urban influences, and outmigration to different regions and countries. Farmers within the Mount Kenya upland-lowland irrigated agricultural landscape similarly face challenges from a variety of sources when seeking to reduce vulnerability through crop diversification strategies. The reliable provision of water likely played a role in the higher levels of crop diversity within the Likii WRUA (aside from Tumaini). However, even within the Likii WRUA irrigation projects there is great variability in the quantity of water supplied to households; a source of frustration for some members. This, to a certain extent, is the result of a mostly one-size-fits-all approach taken in WRUA development and in the formal recognition of WRUAs by Kenya's Water Resources Management Authority. Overreaching of outside forces in irrigation system development has been shown to influence not only overall performance of an irrigation system (Lam, 1996), but also agrobiodiversity outcomes (Zimmerer, 2011). Future work will inspect the institutions governing water use and provision in the study area and the fostered outcomes, but preliminary assessment indicates limited tailoring of irrigation project decision-making to local conditions.

Population growth, as discussed in 'Social and environmental conditions in the Upper Ewaso Ng'iro Basin' section, has also played a role in altering the social–ecological setting and, in the process, potential diversification levels. For example, sensing an inability to reliably provide farmers with water, irrigation projects may limit the number of total members (as Jikaze has done). For those who are not members at the time of this decision, and who are unable to receive service from another irrigation project, irrigation opportunities become much less certain. Under these occasions cultivating a diverse array of crops may no longer be possible due to an inability to span dry periods or extend the growing season.

While a more exhaustive list of proximate and distal causes of change within the studied landscape certainly exists, the two previously mentioned (i.e. WRUA development and population growth) provide examples of the pressures faced by smallholder irrigated agricultural systems in maintaining and improving agricultural outcomes, such as crop diversity.

Conclusions

This research demonstrated the influence of income, exposure to extension officers, field size, and precipitation on crop diversity levels in semi-arid farming systems. It was then followed by a discussion that included acknowledgment of forces of change within the irrigation projects. Of particular note in our research is the role agricultural extension officers may play in promoting crop diversification strategies and other sustainable agricultural techniques. Assuming institutional willingness to provide such services is present, engagement with extension officers may require new strategies aimed at enhancing interactions with distant and/or difficult-to-reach smallholders. The use of mobile technologies to communicate with farmers about alternative and sustainable production strategies is one such example.

In our research, more remote areas exhibited lower income levels and less connection to extension officers, while more accessible locations had better connection to extension officers and higher income levels. These elements appear important with respect to crop diversification as farmers in more accessible irrigation projects demonstrated higher levels of crop diversification. That said, farmers may be able to counter the disadvantages of their remoteness or isolation when growing conditions are favorable and when irrigation can take place during dry spells. The upland irrigation projects offer an example of this as, despite the poor road infrastructure in these irrigation projects, higher precipitation levels and reliable provision of water for irrigation purposes appear to allow for a more diverse array of crops to be grown.

These findings highlight biophysical, social, and institutional characteristics that may influence engagement in sustainable cultivation strategies within semi-arid agricultural systems. Further, several processes, such as improved exposure to extension officers, have been suggested that may influence adoption of sustainable farming practices.

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References

Altieri, M.A., 1995. Agroecology: The Science of Sustainable Agriculture. Westview Press, Boulder, CO, USA.

Altieri, M.A., 2004. Linking ecologists and traditional farmers in the search for sustainable agriculture. Front. Ecol. Environ. 2 (1), 35–42.

Ayuk, E.T., 2001. Social, economic and policy dimensions of soil organic matter management in sub-Sahara Africa: challenges and opportunities. Nutr. Cycl. Agroecosyst. 61 (1/2), 183–195.

Baumgartner, S., Quaas, M.F., 2010. Managing increasing environmental risks through agrobiodiversity and agrienvironmental policies. Agric. Econ. 41 (5), 483–496.

Boko, M., Niang, I., Nyong, A., Vogel, C., Githeko, A., Medany, M., Osman-Elasha, B., Tabo, R., Yanda, P., 2007. Africa. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Bradshaw, B., Dolan, H., Smit, B., 2004. Farm-level adaptation to climatic variability and change: crop diversification in the Canadian Prairies. Clim. Change 67 (1), 119–141.

Clay, D., Reardon, T., Kangasniemi, J., 1998. Sustainable intensification in the highland tropics: Rwandan farmers' investments in land conservation and soil fertility. Econ. Dev. Cult. Change 46 (2), 351–377.

Collier, P., Conway, G., Venables, T., 2008. Climate change and Africa. Oxf. Rev. Econ. Policy 24 (2), 337–353.

Cooper, P.J.M., Dimes, J., Rao, K.P.C., Shapiro, B., Shiferaw, B., Twomlow, S., 2008. Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: an essential first step in adapting to future climate change? Agric. Ecosyst. Environ. 126 (1/2), 24–35.

Cutforth, L.B., Francis, C.A., Lynne, G.D., Mortensen, D.A., Eskridge, K.M., 2001. Factors affecting farmers' crop diversity decisions: an integrated approach. Am. J. Altern. Agric. 16 (4), 168–176.

Degrande, A., Schreckenberg, K., Mbosso, C., Anegbeh, P., Okafor, V., Kanmegne, J., 2006. Farmers' fruit tree-growing strategies in the humid forest zone of Cameroon and Nigeria. Agroforest. Syst. 67 (2), 159–175.

D'Emden, F.H., Llewellyn, R.S., Burton, M.P., 2008. Factors influencing adoption of conservation tillage in Australian cropping regions. Aust. J. Agric. Resour. Econ. 52 (2), 169–182.

Diederen, P., van Meijl, H., Wolters, A., Bijak, K., 2003. Innovation adoption in agriculture: innovators, early adopters and laggards. Cahiers d'économie et sociologie rurales 67, 29–50.

Di Falco, S., Perrings, C., 2003. Crop genetic diversity, productivity and stability of agroecosystems: a theoretical and empirical investigation. Scott. J. Polit. Econ. 50 (2), 207–216.

D'Souza, G., Cyphers, D., Phipps, T., 1993. Factors affecting the adoption of sustainable agricultural practices. Agric. Resour. Econ. Rev. 22 (2), 159–165.

Ewel, J.J., 1999. Natural systems as models for the design of sustainable systems of land use. Agroforest. Syst. 45 (1–3), 1–21.

Falkenmark, M., Röckstrom, J., 2008. Building resilience to drought in desertification-prone savannas in sub-Saharan Africa: the water perspective. Nat. Resour. Forum 32 (2), 93–102.

Feder, G., 1982. Adoption of interrelated agricultural innovations: complementarity and the impacts of risk, scale, and credit. Am. J. Agric. Econ. 64 (1), 94–101.

Feder, G., Just, R.E., Zilberman, D., 1985. Adoption of agricultural innovations in developing countries: a survey. Econ. Dev. Cult. Change 33 (2), 255–298.

Feder, G., Umali, D.L., 1993. The adoption of agricultural innovations: a review. Technol. Forecast. Soc. Change 43 (3/4), 215–239.

Fraser, E.D.G., Mabee, W., Figge, F., 2005. A framework for assessing the vulnerability of food systems to future shocks. Futures 37 (6), 465–479.

Fustec, J., Lesuffleur, F., Mahieu, S., Cliquet, J.B., 2010. Nitrogen rhizodeposition of legumes: a review. Agron. Sustain. Dev. 30 (1), 57–66.

Genius, M., Pantzios, C.J., Tzouvelekas, V., 2006. Information acquisition and adoption of organic farming practices. J. Agric. Resour. Econ. 31 (1), 93–113.

Gentry, A.H., 1988. Changes in plant community diversity and floristic composition on environmental and geographical gradients. Ann. Mo. Bot. Gard. 75 (1), 1–34.

Ghadim, A.K.A., Pannell, D.J., 1999. A conceptual framework of adoption of an agricultural innovation. Agric. Econ. 21 (2), 145–154.

Gould, B.W., Saupe, W.E., Klemme, R.M., 1989. Conservation tillage: the role of farm and operator characteristics and the perception of soil erosion. Land Econ. 65 (2), 167–182.

Heal, G., 2000. Nature and the Marketplace: Capturing the Value of Ecosystem Services. Island Press, Washington, DC, USA.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. Climatol. 25 (15), 1965–1978.

Holling, C.S., 1973. Resilience and stability of ecological systems. Annu. Rev. Ecol. Syst. 4 (1), 1–23.

Holt-Giménez, E., 2002. Measuring farmers' agroecological resistance after Hurricane Mitch in Nicaragua: a case study in participatory, sustainable land management impact monitoring. Agric. Ecosyst. Environ. 93 (1–3), 87–105.

Huho, J.M., Ngaira, J.K.W., Ogindo, H.O., Masayi, N., 2012. The changing rainfall pattern and the associated impacts on subsistence agriculture in Laikipia East District, Kenya. J. Geogr. Reg. Plan. 5 (7), 198–206.

Isakson, S.R., 2007. Uprooting Diversity? Peasant Farmers' Market Engagements and the On-Farm Conservation of Crop Genetic Resources in the Guatemalan Highlands. Political Economy Research Institute, Amherst, MA, USA.

Jarvis, D., Hodgkin, T., 2000. Farmer decision making and genetic diversity: linking multidisciplinary research to implementation on-farm. In: Brush, S.B. (Ed.), Genes in the Field: On-Farm Conservation of Crop Diversity. International Plant Genetic Resources Institute/International Development Research Centre/Lewis Publishers, Rome, Italy/Ottawa, Canada/Boca Raton, FL, USA.

Khumalo, S., Chirwa, P.W., Moyo, B.H., Syampungani, S., 2012. The status of agrobiodiversity management and conservation in major agroecosystems. Agric. Ecosyst. Environ. 157, 17–23.

Knight, J., Weir, S., Woldehanna, T., 2003. The role of education in facilitating risk-taking and innovation in agriculture. J. Dev. Stud. 39 (6), 1–22.

Knowler, D., Bradshaw, B., 2007. Farmers' adoption of conservation agriculture: a review and synthesis of recent research. Food Policy 32 (1), 25–48.

Kunzi, E., Droz, Y., Maina, F., Wiesmann, U., 1998. Patterns of peasant livelihood strategies: local actors and sustainable resource use. East. South. Afr. Geogr. J. 8, 55–65.

Lam, W.F., 1996. Improving the performance of small-scale irrigation systems: the effects of technological investments and governance structure on irrigation performance in Nepal. World Dev. 24 (8), 1301–1315.

Lin, B.B., 2007. Agroforestry management as an adaptive strategy against potential microclimate extremes in coffee agriculture. Agric. For. Meteorol. 144 (1/2), 85–94.

Lin, B.B., 2011. Resilience in agriculture through crop diversification: adaptive management for environmental change. Bioscience 61 (3), 183–193.

Liniger, H., Gichuki, F.N., Kironchi, G., Njeru, L., 1998. Pressure on the land: the search for sustainable use in a highly diverse environment. East. South. Afr. Geogr. J. 8, 29–44.

Lithourgidis, A.S., Dordas, C.A., Damalas, C.A., Vlachostergios, D.N., 2011. Annual intercropping: an alternative pathway for sustainable agriculture. Aust. J. Crop Sci. 5 (4), 396–410.

Loreau, M., 1998. Biodiversity and ecosystem functioning: a mechanistic model. Proc. Natl. Acad. Sci. U. S. A. 95 (10), 5632–5636.

Loreau, M., Naeem, S., Inchausti, P., Bengtsson, J., Grime, J.P., Hector, A., Hooper, D.U., Huston, M.A., Raffaelli, D., Schmid, B., Tilman, D., Wardle, D.A., 2001. Biodiversity and ecosystem functioning: current knowledge and future challenges. Science 294 (5543), 804–808.

LRWUA, 2004. Likii River Water Users Association – River Abstraction Survey. Rural Focus, Nanyuki, Kenya.

LWRUA, 2009. Likii Water Resources Users Association – Final Constitution. Likii Water Resources Users Association, Nanyuki, Kenya.

Méndez, V.E., Gliessman, S.R., Gilbert, G.S., 2007. Tree biodiversity in farmer cooperatives of a shade coffee landscape in western El Salvador. Agric. Ecosyst. Environ. 119 (1/2), 145–159.

Mitchell, C.E., Tilman, D., Groth, J.V., 2002. Effects of grassland plant species diversity, abundance, and composition on foliar fungal disease. Ecology 83 (6), 1713–1726.

Moguel, P., Toledo, V.M., 1999. Biodiversity conservation in traditional coffee systems of Mexico. Conserv. Biol. 13 (1), 11–21.

Morris, R.A., Garrity, D.P., 1993. Resource capture and utilization in intercropping: water. Field Crops Res. 34 (3/4), 303–317.

Napier, T.L., Camboni, S.M., 1993. Use of conventional and conservation practices among farmers in the Scioto River Basin of Ohio. J. Soil Water Conserv. 48 (3), 231–237.

Neill, S.P., Lee, D.R., 2001. Sustainable agriculture: the case of cover crops in northern Honduras. Econ. Dev. Cult. Change 49 (4), 793–820.

Ngigi, S.N., Savenije, H.H.G., Gichuki, F.N., 2007. Land use changes and hydrological impacts related to up-scaling of rainwater harvesting and management in upper Ewaso Ng'iro river basin, Kenya. Land Use Policy 24 (1), 129–140.

Nkonya, E., Schroeder, T., Norman, D., 1997. Factors affecting adoption of improved maize seed and fertilizer in northern Tanzania. J. Agric. Econ. 48 (1), 1–12.

Pannell, D.J., Marshall, G.R., Barr, N., Curtis, A., Vanclay, F., Wilkinson, R., 2006. Understanding and promoting adoption of conservation practices by rural landholders. Aust. J. Exp. Agric. 46 (11), 1407–1424.

Parra López, C., Calatrava Requena, J., 2005. Factors related to the adoption of organic farming in Spanish olive orchards. Span. J. Agric. Res. 3 (1), 5–16.

Pautsch, G.R., Kurkalova, L.A., Babcock, B.A., Kling, C.L., 2000. The Efficiency of Sequestering Carbon in Agricultural Soils. Working Paper 00-WP 246. Center for Agricultural and Rural Development, Ames, IA, USA.

Peeters, L.Y.K., Soto-Pinto, L., Perales, H., Montoya, G., Ishiki, M., 2003. Coffee production, timber, and firewood in traditional and *Inga*-shaded plantations in southern Mexico. Agric. Ecosyst. Environ. 95 (2/3), 481–493.

Perfecto, I., Vandermeer, J.H., Bautista, G.L., Nuñez, G.I., Greenberg, R., Bichier, P., Langridge, S., 2004. Greater predation in shaded coffee farms: the role of resident neotropical birds. Ecology 85 (10), 2677–2681.

Philpott, S.M., Lin, B.B., Jha, S., Brines, S.J., 2008. A multi-scale assessment of hurricane impacts on agricultural landscapes based on land use and topographic features. Agric. Ecosyst. Environ. 128 (1/2), 12–20.

Polsky, C., Neff, R., Yarnal, B., 2007. Building comparable global change vulnerability assessments: the vulnerability scoping diagram. Glob. Environ. Change 17 (3-4), 472–485.

Rahm, M.R., Huffman, W.E., 1984. The adoption of reduced tillage: the role of human capital and other variables. Am. J. Agric. Econ. 66 (4), 405–413.

Rockström, J., Barron, J., 2007. Water productivity in rainfed systems: overview of challenges and analysis of opportunities in water scarcity prone savannahs. Irrig. Sci. 25 (3), 299–311.

Rogers, E.M., 1995. Diffusion of Innovations. The Free Press, New York.

Ryan, R.L., Erickson, D.L., De Young, R., 2003. Farmers' motivations for adopting conservation practices along riparian zones in a Mid-Western agricultural watershed. J. Environ. Plan. Manage. 46 (1), 19–37.

Saha, A., Love, H.A., Schwart, R., 1994. Adoption of emerging technologies under output uncertainty. Am. J. Agric. Econ. 76 (4), 836–846.

Saltiel, J., Bauder, J.W., Palakovich, S., 1994. Adoption of sustainable agricultural practices: diffusion, farm structure, and profitability. Rural Sociol. 59 (2), 333–349.

Samberg, L.H., Shennan, C., Zavaleta, E.S., 2010. Human and environmental factors affect patterns of crop diversity in an Ethiopian highland agroecosystem. Prof. Geogr. 62 (3), 395–408.

Schmitt, G., 1991. Why is the agriculture of advanced Western economies still organized by family farms? Will this continue to be so in the future? Eur. Rev. Agric. Econ. 18 (3/4), 443–458.

Shiferaw, B.A., Okello, J., Reddy, R.V., 2009. Adoption and adaptation of natural resource management innovations in smallholder agriculture: reflections on key lessons and best practices. Environ. Dev. Sustain. 11 (3), 601–609.

Somda, J., Nianogo, A.J., Nassa, S., Sanou, S., 2002. Soil fertility management and socio-economic factors in crop-livestock systems in Burkina Faso: a case study of composting technology. Ecol. Econ. 43 (2/3), 175–183.

Tengo, M., Belfrage, K., 2004. Local management practices for dealing with change and uncertainty: a cross-scale comparison of cases in Sweden and Tanzania. Ecol. Soc. 9 (3), 4.

Vandermeer, J., van Noordwijk, M., Anderson, J., Ong, C., Perfecto, I., 1998. Global change and multi-species agroecosystems: concepts and issues. Agric. Ecosyst. Environ. 67 (1), 1–22.

Wiesmann, U., Gichuki, F.N., Kiteme, B.P., Liniger, H., 2000. Mitigating conflicts over scarce water resources in the highland-lowland system of Mount Kenya. Mt. Res. Dev. 20 (1), 10–15.

Yachi, S., Loreau, M., 1999. Biodiversity and ecosystem productivity in a fluctuating environment: the insurance hypothesis. Proc. Natl. Acad. Sci. U. S. A. 96 (4), 1463–1468.

Zimmerer, K.S., 2010a. Woodlands and agrobiodiversity in irrigation landscapes amidst global change: Bolivia, 1990–2002. Prof. Geogr. 62 (3), 335–356.

Zimmerer, K.S., 2010b. Biological diversity in agriculture and global change. Annu. Rev. Environ. Resour. 35, 137–166.

Zimmerer, K.S., 2011. The landscape technology of spate irrigation amid development changes: assembling the links to resources, livelihoods, and agrobiodiversity-food in the Bolivian Andes. Glob. Environ. Change 21 (3), 917–934.

Zimmerer, K.S., 2014. Conserving agrobiodiversity amid global change, migration, and nontraditional livelihood networks: the dynamic uses of cultural landscape knowledge. Ecology and Society 19 (2), 1.