RURAL LIVELIHOODS AND ENVIRONMENTAL CHANGE IN UGANDA

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ABSTRACT

Maia Averyl Call: Rural Livelihoods and Environmental Change in Uganda
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Environmental changes, which include soil degradation, deforestation, and climate change, have long been posited as potential drivers of rural livelihood decisions in Sub-Saharan Africa. However, providing empirical evidence for these socio-environmental patterns has proven difficult due to a lack of spatially explicit longitudinal livelihoods data as well as appropriately fine-scale environmental data. To address this gap in the literature, this dissertation spatially links two waves of longitudinal household and plot survey data (collected in Uganda in 2003 and 2013) with a remotely sensed forest cover product and modeled climate data. These data provide a unique opportunity to quantitatively address three questions central to the topic of environmental change and rural livelihoods: 1) What is the relationship between perceived and measured soil fertility and soil degradation?; 2) How do environmental factors inform temporary and permanent migration decisions?; and 3) How do climate anomalies shape on-farm and non-farm smallholder livelihood strategies? Responding to the first question, the research suggests that both farmers' perceptions and laboratory measures can contribute to a holistic portrait of soil fertility. Addressing the second question, it appears that climate factors, and in particular heat, eventually drive permanent migrations. Similarly, findings from the third analysis indicate that while smallholders are able to successfully cope with short term climate stress, long periods of heat are likely to result in declining agricultural productivity and reduced opportunities for income through livelihood diversification, despite increased on-farm labor. Overall, this dissertation illustrates that Ugandan smallholders have good awareness of their current soil fertility and have successful strategies to cope with typical short periods climate stress. However, many of the current shifts resulting from soil degradation and rapid climate change may be beyond the scope of past experience, and smallholders may lack the analytic tools to perceive and cope with these changes. Likewise, extended periods of heat stress, which were previously atypical, cannot be managed through conventionally employed on-farm agricultural strategies and off-farm livelihood diversification approaches, and will eventually press some smallholders to migrate. These findings can inform rural development policy and have important implications for rural smallholders during an era of global environmental change.

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CHAPTER 1: INTRODUCTION

Introduction

Environmental changes have long been posited as drivers of rural livelihood decisions. In Sub-Saharan Africa, these environmental changes have been largely viewed in a negative light. For the past century, researchers have argued that soil fertility is degrading in the region, driven by rapid population growth (Stocking, 2003; Stoorvogel & Smalling, 2000; Wortmann & Kaizzi, 1998). Fears that population growth is also driving deforestation in the region have also emerged in recent decades (Geist & Lambin, 2002; Rudel, 2013). Sub-Saharan Africa is also considered by the Intergovernmental Panel on Climate Change to be a near term hot spot for the negative ramifications of climate change, with temperatures expected to rise and rainfall predicted to become more spatially and temporally unpredictable (IPCC, 2014). Taking into consideration that Sub-Saharan Africa is a region with high rates of poverty (Barrett, 2008), high population growth rates (Caldwell & Caldwell, 1990), a heavy reliance on natural resource based livelihoods (e.g. agriculture) (Ellis, 2000), and lack of market access due to market failures as well as poor infrastructure (Dorosh, Wang, You, & Schmidt, 2012; Linard, Gilbert, Snow, Noor, & Tatem, 2012), researchers have predicted that environmental changes may drive large-scale crop failure (Kotir, 2011), forced migration (Warner, 2010), and pressure to divest from agricultural livelihoods (Loison, 2015).

Against these sometimes sensationalist hypotheses, providing empirical evidence for these patterns has proved challenging. Until recent years, researchers have lacked the ability to join together fine-scale environmental data with longitudinal survey data to examine climate influences on livelihoods. In this dissertation, I draw together two waves of longitudinal household and plot survey data collected in Uganda in 2003 and 2013 with a remotely sensed forest cover product (Hansen et al., 2013) and gridded climate data (Hijmans, Cameron, Parra, Jones, & Jarvis, 2005; UEACRU et al., 2013) via a spatial linkage. These data allow me to quantitatively address three questions central to the broad subject of environmental change and rural livelihoods: 1) What is the relationship between perceived and measured soil fertility and soil degradation?; 2) How do environmental factors inform temporary and permanent migration decisions?; and 3) How do climate anomalies shape on-farm and off-farm smallholder livelihood strategies?

I address the first question in chapter two, where I explore the relationship between perceived and measured soil fertility and soil degradation. As a primary contributor to agricultural productivity, soil fertility is an essential part of rural livelihoods in Sub-Saharan Africa. Concerns about soil degradation in the region have been fueled in recent years by rapid population growth. While scholars have attempted to assess soil fertility in the region for decades, differences in methodologies, study sites, and theoretical approaches have resulted in heterogeneous and divergent findings. One of the major debates arising out of this work focuses on the value and veracity of farmers' perceptions and laboratory measures of soil fertility and soil degradation. Some scholars have argued that one more accurately reflects true soil fertility/degradation, while others have concluded that they are interchangeable. These discrepancies arise in large part from the lack of longitudinal, large-sample, spatially diverse data on this topic. Addressing this gap, this study examines the relationships between perceived and measured soil fertility and soil degradation in rural Uganda. Further, this research analyzes the extent to which crop productivity can be predicted by measured and perceived soil fertility. The analysis employs multilevel modeling techniques and draws upon a large-sample socio-environmental household survey collected in Uganda in 2003 and 2013. This approach reveals that soil fertility perceptions and measures are complementary but that farmers' perceptions of soil degradation appear to be based on landscape scale observations rather than chemical properties. Together, perceived and measured soil fertility are strong independent predictors of crop productivity, suggesting that laboratory measures may not be picking up all of the elements of soil fertility. Farmers' perceptions thus have the potential to provide valuable information on soil fertility, in combination with laboratory measures.

In chapter three, which builds on the findings in chapter two, I investigate the second question, examining the impact of environmental factors including soil fertility, tree cover, temperature and precipitation, on temporary and permanent migration. Sub-Saharan Africa, a region already facing concerns around deforestation and soil degradation, is expected to also be increasingly affected by climate change. Migration is one of the ways in which people in the region are expected to respond to these environmental stressors. However, previous studies suggest that the relationship between environment and migration is complex. In contrast to previous studies, which typically only examine temporary or permanent migration with a limited range of environmental predictors, we consider environmental drivers of both temporary and permanent migration patterns. We employ logistic regression and event history approaches, drawing upon longitudinal household level surveys and biophysical spatial data for rural Uganda. Our findings suggest that climate shocks have a larger impact on migration than soil fertility or tree cover. Further, temporary migrations appear to be a livelihood strategy supported by good environmental conditions and high agricultural income. Conversely, long periods of heat stress, which result in lowered agricultural income, appear to drive involuntary permanent migrations.

In the fourth and final substantive chapter, I investigate the relationship between climate anomalies and smallholder livelihood strategies. Sub-Saharan Africa is one of the regions of the world considered most critical in terms of the negative effects of global climate change. On-farm agricultural strategies and off-farm livelihood diversification into non-natural resource based livelihoods are the two major ways in which people are theoretically expected to respond to climate anomalies. However, few studies have examined the empirical implications of climate anomalies on these in situ adaptation strategies. Responding to this gap in the literature, we use regression approaches to analyze two waves of household survey data, spatially linked with climate data for rural Uganda. We find that household livelihoods are responsive to climate over short and long time scales. Droughts decrease agricultural productivity in the short term only, reducing individual livelihood diversification in the long term. Higher temperatures can be coped with in the short term, but in the long run above average temperatures lower agricultural productivity and reduce opportunities for diversification. These observations suggest that new livelihood strategies will be necessary if smallholders are to successfully adapt in situ to climate change.

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CHAPTER 2: RECONCILING THE DEBATE: PERCEIVING AND MEASURING SOIL FERTILITY IN UGANDA

Introduction

Soil fertility, the ability to provide crops with the essential nutrients to promote growth, is an integral element of rural livelihoods in rural Sub-Saharan Africa. For decades, scholars have attempted to accurately assess soil fertility in the region (Palm, Sanchez, Ahamed, & Awiti, 2007). These efforts were originally borne out of a social and historical context that fostered the concern that population growth and poverty were driving soil degradation, a process that includes erosion and nutrient depletion (Palm et al., 2007). In recent years, unprecedented population growth, stagnating crop yields, and concerns about global climate change have led to a resurgence of this narrative (Muchena, Onduru, Gachini, & de Jager, 2005; Sanchez, 2002; Tully, Sullivan, Weil, & Sanchez, 2015). Despite over a century of research on soil fertility and degradation in the region, variations in methodological approaches, study sites, and epistemologies have not resulted in consensus. Some scholars have argued that soil fertility in the region is intrinsically poor and soil has been degrading over the past century (Stoorvogel & Smalling, 2000; Wortmann & Kaizzi, 1998). Simultaneously, others have disputed these conclusions, citing as evidence methodological flaws and lack of agreement with farmers' perceptions (Scoones & Toulmin, 1998; Tiffen, Mortimore, & Gichuki, 1994). In the absence of longitudinal biophysical and socioeconomic data, this question has become more than just a debate about current soil fertility and soil degradation—it has become enmeshed in the discourse around the value (and veracity) of scientific and local knowledge.

Embedded within this interdisciplinary debate is a matter of practical concern. Farmers and agronomists may be coming to their, perhaps differing, conceptions of soil fertility and soil degradation based on very different perspectives and information. Much previous research has suggested that farmers' perceptions are based on factors such as crop yield and the number and kinds of weeds present in the field (E. Barrios et al., 2006; Gruver & Weil, 2007; Murage, Karanja, Smithson, & Woomer, 2000). Perceptions also have the potential to be shaped by external sociocultural elements, such as distance to the nearest marketplace or the relative wealth of neighbors (Briggs, 2013; Corbeels, Shiferaw, & Haile, 2000; Desbiez, Matthews, Tripathi, & Ellis-Jones, 2004; Ericksen & Ardón, 2003; Maconachie, 2012; Marenya, Barrett, & Gulick, 2008; Sillitoe, 1998). Agronomists, on the other hand, rely mostly upon biochemical measurements, such as carbon content, pH, and soil texture, to assess soil fertility and degradation. Policies implemented, or soil improvement measures suggested, based on measured soil fertility may have low uptake by farmers if farmers do not likewise perceive a problem with their soil fertility.

This research addresses these policy-relevant concerns while simultaneously providing further evidence for the theoretical debate. To do so, I first examine the relationship between perceptions and laboratory measures of soil fertility and perceptions and laboratory measures of soil degradation. Subsequently, I analyze the degree to which agricultural productivity can be predicted by measured soil fertility and perceived soil fertility. The analysis employs multilevel modeling techniques and draws upon a socially and environmentally heterogeneous large-sample plot-level soil and sociodemographic data collected in rural Uganda in 2003 and 2013. Broadly, the findings indicate that perceived soil fertility and measured soil fertility both contribute vital information to our understanding of soil fertility. Farmers' perceptions of soil degradation, conversely, appear to be based on erosion and landscape scale observations and are not associated with chemical laboratory measures. Together, both perceived and measured soil fertility are strong predictors of plot productivity. This finding suggests that biophysical measures may not be picking up all of the elements of soil fertility that contribute to crop production. Farmers' perceptions can contribute valuable information to the determination of soil fertility, in combination with laboratory measures.

Background

Over the past three decades, scholars across a range of disciplines have turned their attention to the relationship between scientific and local knowledge. Findings from these studies have demonstrated that a singular, broadly applicable and transferable approach may not always provide the best results if applied without the recognition of cultural variability and socio-environmental complexity. Ethnopedology, "a hybrid discipline nurtured by natural as well as social sciences [that] encompasses the soil and land knowledge systems of rural populations, from the most traditional to the most modern" (Barrera-Bassols & Zinck, 2003), emerged during this multidisciplinary turn.

Though early ethnopedology studies were primarily concerned with recording local knowledge and practices around soil, the field soon expanded into comparisons between local and laboratory knowledge of soil (Barrera-Bassols & Zinck, 2003). For some researchers, the goal of this pursuit is to validate local knowledge, with the underlying assumption that laboratory analysis is the 'true' way to evaluate soil fertility (Aynekulu, Carletto, Gourlay, & Shepherd, 2016; Corbeels et al., 2000; Ericksen & Ardón, 2003; Irungu, Warren, & Sutherland, 1996; Kiome & Stocking, 1995; Mairura et al., 2007; Okoba & Sterk, 2010). Others have also sought to understand the methods by which farmers evaluate soil fertility (e.g. weeds, crop color), as perceptions of soil fertility are one factor that drives agricultural management decisions (E. Barrios et al., 2006; Gruver & Weil, 2007; Murage et al., 2000). In recent years, however, scholars have argued that it is not enough to compare and categorize soil fertility measures in a vacuum (Briggs, 2013). Responding to these concerns, a number of researchers over the past several decades have examined how farmers' perceptions and laboratory measures of soil fertility relate to one another within their socio-environmental context (Berazneva, Mcbride, Sheahan, & David, 2016; Dawoe, Quashie-Sam, Isaac, & Oppong, 2012; Desbiez et al., 2004; L. C. Gray & Morant, 2003; Maconachie, 2012; Marenya et al., 2008; Odendo, Obare, & Salasya, 2010; Osbahr & Allan, 2003).

Studies that explore perceived and measured soil fertility have come to a wide range of differing conclusions. On one end of the spectrum, studies have found strong agreements between laboratory measures and farmers' perceptions in Ghana (Dawoe et al., 2012), Kenya (Mairura et al., 2007; Murage et al., 2000), and northern Ethiopia (Corbeels et al., 2000). Conversely, scholars in southern Ethiopia (Elias & Scoones, 1999), Burkina Faso (L. C. Gray & Morant, 2003), Nigeria (Maconachie, 2012), and Kenya (Marenya et al., 2008) detected no direct relationship between the two. Some scholars have observed that the socio-environmental context contributes greatly to farmers' perceptions (Briggs, 2013; Corbeels et al., 2000; Desbiez et al., 2004; Ericksen & Ardón, 2003; Maconachie, 2012; Marenya et al., 2008; Sillitoe, 1998). Yet other researchers argue that perceptions and laboratory measures should not be viewed as comparable but rather as complementary means by which to understand soil fertility (Agrawal, 1995; Showers, 2006). Finally, previous research suggests that farmers' methods of determining soil fertility may be better suited to considering soil fertility change, because of the time lag between soil fertility change and crop productivity (Marenya et al., 2008).

More specifically, Dawoe and colleagues (2012) find that in the Ashanti region of Ghana, farmers' indicators of soil fertility (or infertility) corresponds well with scientific assessment, and are unrelated to age, location, or gender of the head of household. Likewise, Desbiez and colleagues (2004) observe a strong relationship between scientific measures and perceptions of soil fertility in Nepal, but also argue that socio-environmental context, along with plot-specific characteristics, are an important element of how farmers assess fertility. Osbahr and Allan (2003), conversely, report no direct link between perceptions and scientific soil assessment in Niger. However, they argue that this is a result of the complex ethnopedological framework developed by farmers, which draws from social and cultural, as well as physical, environmental elements. Similarly, Maconachie (2012) concludes that the reason for the mismatch between farmers' perceptions and laboratory measures outside Kano, Nigeria is that socio-environmental context—exposure to urban culture and consumerism—can skew farmers' perceptions of their own soil productivity. Gray and Morant (2003) find that local and scientific measures of soil fertility change in southwestern Burkina Faso match poorly, perhaps because farmers' perceptions of soil fertility are based on the social and economic changes in the region, rather than biophysical shifts.

Alongside these descriptive and exploratory studies, Marenya and colleagues (2008) use small-sample (123 households) household-level longitudinal data (2002, 2005) in one agro-ecological zone in Kenya to econometrically examine the way in which perceptions relate to scientific measures and economic factors. The researchers find disagreement between Kenyan farmers' perceptions of soil fertility and laboratory measures, as well as no clear relationship between perceptions and gender and age of head of household, size of plot, or other contextual factors. In their analysis of farmers' perceptions of soil fertility degradation in western Kenya, Odendo and colleagues (2010) employ clustered, randomized sampling to gather perceptions data (N=331) representative of two different agro-ecological zones, one of which had higher agricultural potential than the other. No laboratory soil measures were gathered for comparison—rather, Odendo and colleagues conclude that farmers' perceptions were probably fairly accurate because their ways of measuring soil fertility (e.g. crop performance, crop color) were in accord with those used by agronomists in the field. These researchers then use econometric methods to explore how well various socio-ecological contextual factors are able to predict perceptions of degradation. Odendo and colleagues find that agro-ecological zone, food self-sufficiency, and awareness of soil fertility management practices all had a significant relationship with perceptions of soil degradation.

Through the variation in these findings, these studies highlight the complexity of the relationship between perceptions and laboratory measures of soil fertility. The diverse literature surrounding questions of local and laboratory knowledge illuminates both the cross-disciplinary interest and the difficulty of pursuing this line of inquiry. To further enrich our understanding of this topic requires a dataset that is longitudinal at the plot level (to investigate questions of soil fertility alongside questions of soil quality change), large-sample, and agro-ecologically diverse (to find commonalities across different cropping and environmental regimes). This study exploits just such a data source to first examine the relationship between perceived and measured soil fertility and soil degradation. Second, the research draws upon perceived and measured soil fertility to predict crop productivity per hectare, a commonly used measure of soil fertility. This research advances the discipline of ethnopedology by providing quantitative findings to stand alongside the current strong body of qualitative and locally specific research. Further, this study provides policy-relevant insights into the relationship between farmers' perceptions and laboratory measures of soil fertility.

Methods

Study location

Uganda is a rural country, with 87% of the nearly 35 million Ugandans living outside of urban areas (Uganda Bureau of Statistics, 2014). For the most part, the soils of Uganda are highly weathered Oxisols and Ultisols with low nutrient reserves for farmers to draw upon (Palm et al., 2007; Ssali & Vlek, 2002). The population of the country is growing at a rapid rate of 3.03% annually, and much of this population growth is in rural areas. Rural population density, already high in some regions, is predicted to increase with population growth (United Nations Development Programme, 2014). Many rural households depend on income from smallholder agriculture as their primary livelihood strategy, but within Uganda there is much heterogeneity in agro-ecological conditions, cultural context, land tenure regimes, and access to markets (Yamano & Kijima, 2010).

Data

The analysis utilizes plot-level panel data collected in rural Uganda. The first wave of these data was collected in 2003 by the International Food Policy and Research Institute (IFPRI) in collaboration with the National Agricultural Research Laboratories (NARL) of Uganda. Households selected for this survey were chosen from within a sampling framework developed by the Uganda Bureau of Statistics (UBOS) for a larger survey (Nkonya et al., 2008). Using clustered random sampling, households were selected from eight different UBOS survey districts in an effort to represent Uganda's agro-ecological diversity (see Appendix F). In 2013, researchers from IFPRI, NARL, the University of North Carolina at Chapel Hill (UNC-CH), Cornell University, Purdue University, and Brown University collaborated to carry out the second wave of this survey. In both waves, enumerators collected survey and spatial data at the household, plot, and community levels, and took plot-level soil samples for laboratory soil analysis (see Appendix 1 for soil sampling and analysis procedures; see Appendix 2 for spatial data procedures).

In the 2013 follow-up, enumerators were able to return to 727 of the 849 households successfully interviewed in 2003. Of the 122 households not successfully re-interviewed, all but 11 were not re-interviewed due to budgetary restrictions, rather than refusal to answer (see Appendix 3 for differences in tracked and lost households). In addition to the original households, individuals who had split off to form new households in the intervening years were tracked and interviewed if they were still within the original parish. Including these split households, enumerators collected data from 831 households in 2013. Soil samples were successfully collected and analyzed from 1,965 plots in 2003 and 1,389 plots in 2013 (full sample). Of these plots, a subsample of 715 can be successfully spatially matched across the two years (restricted sample) (see Appendix 4 for matching procedure; see Appendix 5 for differences between full and restricted sample). The variables used in this analysis are drawn from the household and the plot level surveys. Specifically, the household roster provides information on the age, gender, and education of the head of household, while the module on household income provides household asset and livestock values and the primarily income source of the household. Information on the distance to the market and all weather road, the value of crop sales, and the agricultural training of the head of household also came from different modules of the extensive household survey. The plot level survey basic characteristics module is the source of information about topsoil depth. Variables are also drawn from the module on current crops cultivated and perceptions of plot level characteristics (including soil fertility and degradation).

Alongside these survey data, environmental data on precipitation and slope are drawn from two remotely sensed data sources. Average annual precipitation values for a given community were extracted from the WorldClim Global Climate Dataset at a 1 kilometer spatial resolution using a 1 kilometer buffer around the community centroid (Hijmans et al., 2005). This buffer size was chosen based on the spatial distribution of agricultural plots from the survey. Slope was calculated using the ASTER Global Digital Elevation Map (DEM), which has a spatial resolution of 30 meters (LP DAAC, 2016).

Table 1 contains full sample descriptive statistics for all variables used in this analysis, broken down by wave. On average, out of the options "infertile," "moderately fertile," and "highly fertile," most farmers perceive their soil to be moderately fertile in both 2003 and 2013. Simultaneously, farmers in 2013 believe that their soil quality has, on average, degraded from 2003 to 2013 (out of the options "degraded," "no change," and "improved"). Over all of the plots sampled at the two time points, as well as the restricted sample of spatially matched plots (see Appendix 5), soil pH appears to have decreased slightly between 2003 and 2013, suggesting that the soil has become more acidic and perhaps less hospitable for agriculture. Average organic matter in the soil appears to have decreased across the full sample but increased within the restricted sample. This discrepancy may result from the combined extensification-intensification effort of Ugandan farmers. Over the decade, farmers may have extended their agriculture into less productive lands, resulting in the apparent decrease in organic matter in the full sample. On already cultivated plots, however, farmers may have intensified their agriculture, adding more manure and other forms of organic amendments. Total phosphorus, on the other hand, appears to have decreased over this time period. Without amendments, most phosphorus is found in the underlying bedrock and farmers may be decreasing phosphorus content in soil through continuous cropping. Plot productivity, which is measured as monetary value produced per hectare due to the variability in crop types present on each plot, appears to have increased threefold between 2003 and 2013.

Analysis

The analysis draws upon both the full and the restricted plot-level samples for 2003 and 2013. The full sample is used to analyze the extent to which laboratory measures predict farmers' perceptions of soil fertility, as well as to explore the extent to which farmers' perceptions and laboratory measures predict plot productivity. For these analyses, the two waves of data are stacked to increase sample size, controlling for the year of survey data collection. The restricted sample is employed to examine the extent to which change in laboratory measures can predict farmers' perceptions of soil quality change between 2003 and 2013. For this model, the analysis is cross-sectional, with all variables originating from the 2013 survey other than the laboratory measures from 2003, which are included to control for survey baseline chemical properties.

For the two models in which farmers' perceptions are being predicted, ordinal logistic regression models are used, with standard errors corrected for clustering at the community level (Huber, 1981). To predict plot productivity per hectare, a three level random effects multilevel linear regression model is used, with random effects at the household and community levels to adjust for the non-independence of variables at these levels (Raudenbush & Bryk, 2002). District fixed effects are included to adjust for agro-ecological, socio-demographic, and other omitted variable differences between each of the districts. Year fixed effects are included in the stacked year analyses to adjust for structural and cultural differences between the two years of data collection. Because of these fixed effects, results can be interpreted s comparing plots in the same district in the same year. Values from the ordinal logistic regressions are shown as odds ratios. In all regressions, household asset values and household livelihoods value are transformed for normality, as they are highly right-skewed. Soil pH is included in the models as both a linear and squared term, as optimal pH for soil fertility is in the middle ranges of the scale.

Alongside perceived and measured soil fertility, a standard set of socio-demographic and environmental controls are employed in all models. Household level controls include the age, gender, and education level of the head of household, who is typically the person answering the survey questions. Differences in age, gender, and education have been shown to impact a farmer's ability to assess the fertility of his soil (or to increase plot productivity), perhaps due to differences in experience and access to agronomic information. Likewise, participation in agricultural training is adjusted for in the models (Marenya et al., 2008). Previous research has suggested that household size can influence perceptions of soil fertility, regardless of actual soil fertility or productivity, because a larger household would require greater productivity to maintain the same standard of living as a smaller household (Carswell, 2002). Agricultural households, where crop yield provides the primary household income, may also be more comfortable assessing soil fertility than households for which agriculture is a supplement to off-farm employment. Theory suggests that asset values could influence farmers' perceptions (and productivity) by increasing access to soil amendments or decreasing the reliance of a household on agricultural production for sustainability. Similarly, livestock could provide households with an alternative source of income and stability, as well as large quantities of manure to enrich the soil (Scoones, 2000). To control for potential market effects, measures of distance to the nearest local market and distance to the closest all-weather road (still usable during the rainy season, when flooding and muddy conditions are common) are included. Market access has previously been seen to impact farmers' perceptions by providing them with the opportunity to compare their soil fertility or living condition with those of a wider range of individuals (Maconachie, 2012). Further, access to markets and all-weather roads could improve the ability of households to obtain soil amendments or attend training courses at local farmers' organizations.

At the plot-level, measures of both distance from household to plot (calculated using GPS locations for household and plots) and plot size are incorporated into the model. In an earlier study, distance from household to plot was demonstrated to impact a farmers' ability to apply organic amendments and the frequency with which a farmer visits a plot (Zingore, Murwira, Delve, & Giller, 2007). Plot size has also been shown to directly impact productivity and could through this mechanism influence perceptions of fertility (Barrett, 1996). Topsoil depth, as estimated by the farmer, could impact perceptions by having a very real impact on a soil's ability to hold moisture and support crops. Perceived erosion, both rill and sheet, could alter perceptions of fertility (and crop productivity) by negatively influencing the landscape, though fertility may not be specifically affected. Cropping type may also impact perceptions and productivity, as some crops may be more productive than others and more or less likely to deplete soil fertility. A community-level average measure of annual precipitation was also included in the models, as rainfall may impact productivity or perceived fertility, as well as the chemical composition of the soil by promoting decomposition, erosion, leaching, and other processes. To adjust for a small number of missing data cases in these variables, community (or district, if necessary) mean values were interpolated, and an indicator for missingness for a given variable was included in the model.

Results and Discussion

Perceived and measured soil fertility and soil degradation

As one might expect from the complex and contradictory evidence found in the literature, it appears from the findings that the relationship between perceived and measured soil fertility and soil degradation is complicated. Examining the joint tests for soil fertility (Table 2), findings suggest that laboratory measures of soil fertility predict perceived soil fertility in both 2003 and 2013. However, in 2003 higher soil organic matter is associated with greater odds of perceived high soil fertility, while in 2013 only higher phosphorus is associated with higher soil fertility. Considering both years together through the stacked model, it appears that, as in 2003 alone, higher organic matter is significantly associated with higher odds of perceived higher soil fertility.

In addition to the positive and significant relationship between perceived and measured soil fertility, the findings suggest that that several household and plot characteristics are significant predictors of perceived soil fertility. Though the joint test indicates that the overall relationship is not significant, in the stacked model, households that have received agricultural training have about one and a half times greater odds of perceiving their soil as more fertile. As many factors that may contribute to soil fertility, such as weed growth, management strategies, and labor time invested, are not observable through the laboratory measures, the significant and positive relationship between agricultural training and perceived soil fertility may be representative of actual management strategies being employed to shape soil fertility. Through the joint test, it is clear that, in addition to the laboratory measures, several other plot characteristics are associated with perceived soil fertility. Specifically, farmers perceive plots with deeper topsoil and less rill erosion as more fertile. These observations suggest that farmers' perceptions of soil fertility are encapsulating more about actual soil fertility than the chemical laboratory measures alone, which do not account for additional biophysical properties like topsoil depth and erosion.

In contrast, the cross-sectional analyses find no relationship at all between perceived and measured soil degradation (Table 3). Although the models include a number of covariates that have been shown in the literature to be related to perceived soil degradation in our model, few of them appear to be significant. Farmers appear to be generating their perceptions of soil degradation through plot level characteristics, in particular topsoil depth and rill erosion. Plots with shallow topsoil and greater rill erosion are perceived as significantly degraded. From these findings, it is possible to conclude that the chemical properties tested by laboratory measures are difficult for farmers to observe changing over time, unlike easily observable processes like erosion. Farmers' perceptions of soil degradation are therefore reflective of important landscape scale elements of soil degradation not accounted for by laboratory measures but not indicative of changes that may be occurring in the chemical properties of the soil.

Plot productivity, predicted by perceptions and laboratory measures

Both perceptions and laboratory measures are found to be positively associated with higher crop productivity per hectare (Table 4). In particular, more optimal pH is associated with higher productivity. As both perceived and measured soil fertility are significant in the same model, it is clear that perceptions and laboratory measures are complementary rather than substitutes for one another, each providing something different to the measurement of soil fertility.

In addition to perceived and measured soil fertility, plot and household characteristics are observed to be significantly associated with plot productivity per hectare. A household having a male head of household with access to agricultural training and higher livestock and asset values is associated with higher crop productivity per hectare. Most of these characteristics are reflective of an overall increased socio-economic status, which improves access to labor, improved seeds, and other factors that increase plot productivity. Increased distance to a local market is associated with decreased crop productivity per hectare, perhaps because increased distance makes it costlier to transport crops to market. Lack of access to markets may also de-incentivize farmers to produce a surplus for the purpose of sale.

Plots further away from a household appear to be more productive per hectare, as are those with greater topsoil depth. Greater topsoil depth is better for agriculture. Plots further from the household may be more recently cleared or fallowed, increasing their crop productivity when cultivated. Counterintuitively, sheet erosion is associated with to improved productivity. High productivity from intensive farming may, however, be the reason for the sheet erosion, as these questions were asked at the same points in time. Larger plots appear to be less productive per hectare than smaller plots, and increased slope is associated with decreased plot productivity. The inverse plot size-plot productivity relationship has been observed in a number of past studies, though the exact mechanisms for this relationship remain unclear (Bevis & Barrett, 2016). Crop productivity per hectare on all of the plots has increased between 2003 and 2013, likely due to more intensive management.

Conclusions

Advancing our holistic understanding of soil, this analysis addresses the relationship between perceived and measured soil fertility and soil degradation. Building on this, the study then examines the relationship between perceived soil fertility, measured soil fertility, and crop productivity per hectare. On the whole, farmers' assessments are found to correspond to lab measures for fertility but not degradation. While it is possible that farmers' perceptions of degradation might be inaccurate, it is equally possible that perceptions of degradation may just be capturing some additional element of soil degradation not expressed through laboratory measures of fertility change, such as erosion or weed growth. The results of the productivity analysis suggest that perceptions of fertility may be picking up something that laboratory assessments are not. Throughout the analysis, it is clear that context matters—socio-environmental characteristics contribute to farmers' perceptions of soil fertility.

From a practical standpoint, these findings have several implications. It is very apparent from the results that there is a difference between the way that soil degradation is understood by laboratory measures and farmers' perceptions. Perceived and measured soil fertility, on the other hand, can be seen as complementary. Many previous studies comparing perceptions and measures have conflated soil fertility and soil degradation, and our observations demonstrate that this is highly problematic. Additionally, this analysis highlights the value of considering perceptions alongside laboratory measures when trying to accurately assess multidimensional soil fertility for policy or research purposes (Agrawal, 1995).

Addressing the theoretical debate, a number of previous studies have found relationships between perceived and measured soil fertility, while yet others have argued that they are not associated and not interchangeable. This research illustrates that both of these perspectives have the potential to be correct, especially when considering both soil fertility and soil degradation. The purpose and origin of perceptions and laboratory measures is different, and there is little benefit to be gained from placing these two perspectives at odds with one another or trying to validate one against the other.

The methodological significance of this analysis is threefold. First, the findings demonstrate the utility of large-sample, clustered, randomly sampled plot-level longitudinal data for the investigation of questions surrounding soil degradation. Without longitudinal plot-level data, it is not possible to assess the processes of degradation. Second, these results reinforce the findings of previous researchers who have argued for the necessity of laboratory soil analysis, rather than simply relying on perceptions of soil fertility and degradation. While perceptions do appear to be related to laboratory measures of soil fertility, this is not the case in regard to degradation. It is clear from the analysis that perceptions are much more contextualized than laboratory measures, and are best used as complementary to, rather than as a substitute for, laboratory measures. Finally, the significance of context observed in this analysis argues for the importance of analyzing soil fertility within its socio-ecological context (Dawoe et al., 2012).

For policy, these findings produce a strong argument for the value of integrated soil fertility management (ISFM). ISFM approaches soil fertility management broadly, promoting the importance of attempting to understand all of the processes (biological, physical, chemical, social, economic, and political) that may play a role in shaping soil fertility (Vanlauwe et al., 2015). The ISFM approach is one component of a broader push to recognize the value of local knowledge (perceptions) alongside Western, ‘scientific’ knowledge (laboratory measures). Local knowledge, like scientific knowledge, is forever changing and incorporating new information. Rather than imagining ‘local knowledge’ as static, policymakers should consider that Western, scientific approaches have great potential to be incorporated into local knowledge. Together, perceptions and laboratory measures can provide farmers, researchers, and NGOs alike with an improved portrait of multidimensional soil fertility.

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Tables

Table 2.1 Descriptive statistics (full sample)

	2003				2013			
	Mean	St. Dev	Minimum	Maximum	Mean	St. Dev	Minimum	Maximum
Perception of Soil Fertility (1=poor, 2=average, 3=good)	2.01	0.50	1	3	2.02	0.43	1	3
Perception of Soil Quality Change (1=degraded, 2=no change, 3=improved)					1.46	0.69	1	3
pH	6.09	0.60	4	7.80	6.05	0.60	4	7.90
Organic Matter (%)	6.04	3.50	0.69	32.52	5.64	3.12	0.48	29.05
Total Phosphorus (ppt)	0.99	0.97	0	15.45	0.72	0.86	0.01	16.65
Sand (%)	61.63	15	13.32	93.12	55.98	15.73	7.12	91.12
Topsoil Depth (cm)	2.58	1.16	0.40	7.50	2.22	1.09	0	6.20
Age of Head of HH	42.07	13.19	16	86	50.58	13.46	15	105
Male Head of HH	0.82	0.38	0	1	0.74	0.44	0	1
Formally Educated Head of HH	0.82	0.38	0	1	0.83	0.37	0	1
Accessed Agricultural Training	0.31	0.46	0	1	0.32	0.46	0	1
Household Size	6.17	2.86	1	19	6.78	3.25	1	21
Agriculture primary income source	0.63	0.48	0	1	0.76	0.43	0	1
Asset Value (USD[1])	3,799	6,405	49	74,687	10,172	29,947	30	343,023
Livestock Value (USD[1])	503	1,473	0	21,853	976	4,082	0	100,063
Distance to All-Weather Road (km)	2.24	2.84	0	25	4.81	8.83	0	59.55
Distance to Local Market (km)	3.33	3.16	0.05	27	4.26	4.18	0	40.23
Distance from HH to Plot (km)	0.25	0.33	0.001	2.39	0.29	0.40	0.002	4.78
Crop Value per Ha (USD[1]/ha)	524	2,041	0	37,800	1,745	20,713	0	601,854
Plot Size (ha)	0.48	1.15	0.003	24.22	0.29	0.38	0.0006	6.83
Precipitation (mm)	120	18	81	185	121	16	81	148
Slope (%)	8.80	6.75	0.33	40.60	7.33	5.69	0	35.96
Rill Erosion	0.34	0.47	0	1	0.38	0.49	0	1
Sheet Erosion	0.40	0.49	0	1	0.46	0.50	0	1

Legumes grown	0.41	0.49	0	1	0.43	0.49	0	1
Cereals grown	0.40	0.49	0	1	0.53	0.5	0	1
Tubers grown	0.35	0.48	0	1	0.32	0.47	0	1
Banana grown	0.24	0.43	0	1	0.19	0.39	0	1
Exports grown	0.15	0.36	0	1	0.14	0.35	0	1
Observations		1,987				1,389		

[1] All USD values are adjusted for inflation between 2003 and 2013 and calculated based on 2013 average exchange rates

Table 2.2 Ordinal logistic regression predicting perception of soil fertility (1=poor, 2=average, 3=good)

	Stacked	2003	2013
Laboratory Measures			
pH	2.172	1.047	3.855
sq(pH)	0.959	1.045	0.885
Organic Matter (%)	1.045+	1.093***	0.987
ln(Total Phosphorus)	1.061	0.875	1.530***
Sand (%)	1.006	1.005	1.005
Household Characteristics			
Age of Head of HH	1.003	0.995	1.013+
Male Head of HH (0/1)	0.992	0.996	0.922
Formally Educated Head of HH (0/1)	1.001	0.707+	1.823+
Accessed Agricultural Training (0/1)	1.337*	1.132	1.683*
Household Size	0.99	1.021	0.941
Agriculture primary income source of HH (0/1)	1.121	1.045	1.073
ln(Asset Value)(USD)	1.034	1.03	0.99
ln(Livestock Value) (USD)	1.038	1.035	1.075+
ln(Distance to Local Market)(km)	1.083	1.173*	0.883
ln(Distance to All-Weather Road)(km)	1.002	0.882	1.072
Plot Characteristics			
ln(Distance from HH to Plot)(km)	1.088*	1.118**	1.073

ln(Plot Size)(ha)	1.047	1.019	1.062
Precipitation(mm)	1.003	1.005	0.989
Slope(%)	0.985	0.995	0.977
Topsoil Depth(cm)	1.345***	1.386***	1.451***
Rill Erosion (0/1)	0.683**	0.660**	0.713
Sheet Erosion(0/1)	1.045	0.939	1.243
Year Fixed Effect (2013)	1.126		
Constant	39.047	13.886	5.777
Joint Test of Laboratory Measures	18.94**	46.76***	19.18**
Joint Test of Household Characteristics	12.980	10.43	11.99
Joint Test of Plot Characteristics	61.43***	58.68***	36.47***
Observations	3344	1987	1387

*** p<0.001, ** p<0.01, * p<0.05, + p<0.1

Robust standard errors clustered at community level

Coefficients reported as odds ratios

Cropping types (legumes, cereals, tubers, banana, cash crops) included but not shown

District fixed effects included

Table 2.3 Ordinal logistic regression predicting perception of soil change (1=degraded, 2=no change, 3=improved)

Laboratory Measures	
pH	3.455
sq(pH)	0.902
Organic Matter (%)	0.976
ln(Total Phosphorus)	0.954
Sand (%)	1.002
Household Characteristics	
Agriculture primary income source of HH (0/1)	0.811
ln(Asset Value)(USD)	1.005
ln(Livestock Value) (USD)	1.037

ln(Distance to Local Market)(km)	1.513+
ln(Distance to All-Weather Road)(km)	0.783
Plot Characteristics	
ln(Distance from HH to Plot)(km)	1.023
ln(Plot Size)(ha)	0.836
Precipitation(mm)	0.99
Slope(%)	1.055*
Topsoil Depth(cm)	1.291+
Rill Erosion (0/1)	0.553*
Sheet Erosion(0/1)	1.074
Constant	352689.891
Joint Test of Laboratory Measures	2.000
Joint Test of Household Characteristics	11.380
Joint Test of Plot Characteristics	31.15**
Observations	715

*** p<0.001, ** p<0.01, * p<0.05, + p<0.1

Robust standard errors clustered at community level

Coefficients reported as odds ratios

2003 baseline soil sample measures included but not shown

Cropping types (legumes, cereals, tubers, banana, cash crops), percentage overlap between 2003 and 2013, age, gender, education, and training of head of household included but not shown

District fixed effects included

Table 2.4 Multilevel random effects regression predicting plot productivity/ha (USD)

	Stacked	2003	2013
Laboratory Measures			
pH	1.873**	1.858+	-0.712
sq(pH)	-0.131*	-0.111	0.060
Organic Matter (%)	-0.005	-0.009	0.000
ln(Total Phosphorus)	0.032	0.063	0.084+
Sand (%)	-0.001	-0.002	-0.001

Perception	0.246***	0.247**	0.238**
Household Characteristics			
Age of Head of HH	-0.002	-0.003	-0.000
Male Head of HH (0/1)	0.242**	0.259*	0.182*
Formally Educated Head of HH (0/1)	-0.130	-0.036	-0.079
Accessed Agricultural Training (0/1)	0.122+	0.073	0.148*
Household Size	-0.002	-0.012	-0.002
Agriculture primary income source of HH (0/1)	0.058	0.124	-0.039
ln(Asset Value)(USD)	0.084**	0.101*	0.090**
ln(Livestock Value) (USD)	0.025+	0.032	0.024+
ln(Distance to Local Market)(km)	-0.065+	-0.020	-0.094+
ln(Distance to All-Weather Road)(km)	0.085*	0.059	0.070
Plot Characteristics			
ln(Distance from HH to Plot)(km)	0.078***	0.066*	0.029
	-		-
ln(Plot Size)(ha)	0.721***	-0.700***	0.630***
Precipitation(mm)	0.001	0.004	-0.002
Slope(%)	-0.014*	-0.020*	0.001
Topsoil Depth(cm)	0.128***	0.103**	0.058
Rill Erosion (0/1)	-0.016	0.054	-0.167*
Sheet Erosion(0/1)	0.211**	0.347**	0.038
Year Fixed Effect (2013)	1.585***		
Constant	-6.777**	-8.247**	5.748*
Joint Test of Laboratory Measures	36.54***	41.14***	5.44
Joint Test of Household Characteristics	46.46***	20.20*	39.94***
Joint Test of Plot Characteristics	2256.2**	1965.44***	463.5***
Observations	3,344	1,965	1,379
Number of groups	122	121	104

*** $p<0.001$, ** $p<0.01$, * $p<0.05$, + $p<0.1$

Cropping types (legumes, cereals, tubers, banana, cash crops) included but not shown

District fixed effects included

CHAPTER 3: WHAT DRIVES ENVIRONMENTAL MIGRANTS? LONGITUDINAL EVIDENCE FROM UGANDA

Introduction

In recent years, environmental change has been linked with a range of harmful potential social outcomes including agricultural failure, health problems, and increased poverty (Bilsborrow, 2009; IPCC, 2014). Through these and other mechanisms, climate change and environmental degradation have subsequently been posited as primary drivers of largescale involuntary human migration and mobility (Myers, 2002). The general premise of this scenario is that, as a result of climate and environmental issues, millions of people worldwide will be forced to permanently move long distances for survival (Warner, Hamza, Oliver-Smith, Renaud, & Julca, 2010).

Despite the ubiquity of this framing, the literature offers a wide range of spatially and socio-demographically heterogeneous findings on the relationship between the environment and migration (Gray & Mueller, 2012; Halliday, 2006; Henry, Schoumaker, & Beauchemin, 2004; Munshi, 2003). Some researchers predict that environmental shocks will lead to a massive increase in the number of 'environmental refugees' from low income countries in the next century (Gemenne, 2011; Myers, 2002). Conversely, others have found evidence that climate change may leave many households 'stuck,' without the necessary resources to relocate or send migrants as part of a rural livelihood strategy (Ellis, 2000; Foresight, 2011). Further, in contrast to the 'environmental refugee' hypothesis, several studies have suggested that environmental disasters are more likely to induce local, temporary moves than long-distance permanent migrations (Gray, 2009, 2011; Massey, Axinn, & Ghimire, 2010).

Our analysis builds upon a growing body of literature that has explored environmental effects on migration by linking large-sample socio-demographic data with gridded environmental datasets. Through this approach, studies have been able to examine the broader relationships between different environmental factors and types of human mobility. Past researchers have explored the effects of natural disasters (Gray and Mueller, 2012a; Gray et al., 2014; Halliday, 2006), climate variability (Bohra-mishra et al., 2014; Gray and Mueller, 2012b; Henry et al., 2004; Hunter et al., 2013; Jennings and Gray, 2014; Mueller et al., 2014; Nawrotzki and Bakhtsiyarava, 2016), and land degradation (Gray, 2011; Gray & Bilsborrow, 2014; Hunter et al., 2014) on permanent and long and short term temporary migration. At present, however, very few of these studies have simultaneously explored a number of different environmental and climatic drivers (Gray & Bilsborrow, 2013) along with a range of different migration outcomes (Gray, 2011). Thus, due to the range of contexts, scales, types of migration, and time periods captured by these analyses, it is difficult to discern whether the range of outcomes found in previous studies are based on actual variation in processes or differences in data and methods (Gray & Bilsborrow, 2013).

To address these unresolved questions, we combine Ugandan longitudinal (2003, 2013) survey data from 850 households with temperature, precipitation, soil fertility, and forest cover data. We analyze these data using logistic regression approaches to examine temporary migration processes in 2003 and 2013 and negative binomial regression models to examine permanent migration for each year between 2003 and 2013. We find that climate shocks appear to be the major driver of migration in rural Uganda. Years of high rainfall are associated with high temporary migration while short term heat shocks are associated with low male temporary migration, suggesting that temporary migration is enabled by higher agricultural productivity and lower demand for on-farm labor. Extended periods of heat are associated with an increase in male permanent migration, however, indicating that households may eventually be pushed through necessity to send permanent migrants. Our study suggests that rising temperatures may be the most threatening aspect of global climate change and that climate change migration is likely to be a gendered process.

Background

Researchers have long theorized that most migration events fall somewhere on a spectrum ranging from completely voluntary moves to forced displacements (Hugo, 1996). The most straightforward 'forced' migrations are those induced by a natural disaster while the most clear 'voluntary' migrations are those involving a wealthy household choosing where and when to relocate. Most migration events fall somewhere between 'forced' and 'voluntary'. Households may be 'pushed' to send migrants by economic or environmental stress, or individuals may be 'pulled' to migrate for educational or employment opportunities (Black, Adger, et al., 2011). These 'push' and 'pull' factors are mediated and moderated by a host of socio-economic, demographic, and environmental characteristics including the age, education, and gender of a potential migrant, household resource availability, and community accessibility of migration destinations.

The factors that drive migrations are intrinsically linked to the variety of lengths and intentions associated with migration events. Temporary migrations, where the migration event lasts less than 12 months and where the migrants intend to return to the household (Hunter et al., 2014), are a common element of rural livelihood strategies in the developing world (K. Warner et al., 2010). Through rural-rural or rural-urban seasonal labor migration, household members can provide households with remittance income and lessen household food stress (Black, Bennett, Thomas, & Beddington, 2011; Ellis, 2000). In contrast, permanent migrations are those wherein an individual or household leaves an area without intent to return (Hunter et al., 2014). Permanent migrations may be due to family formation or result from necessity when an area ceases to provide sufficient livelihood opportunities (Ellis, 2000).

In the rural developing world, migration is often associated with environmental stress through these livelihood pathways. Opportunities for in situ off-farm livelihoods are often limited in these contexts and many households are heavily dependent on natural resource-based livelihoods (e.g. agriculture, harvesting forest products). These livelihood contexts lead to high exposure, high sensitivity, and low adaptive capacity, resulting in households highly vulnerable to shifts in the environmental landscape (Hugo, 1996; Hunter, 2005; McLeman & Smit, 2006).

Environmental changes can take many forms but soil degradation, deforestation, and climate variability are considered particularly concerning across the developing world, particularly in Sub-Saharan Africa. For over a century, population-driven soil degradation has generally been considered to be a serious issue in the region (Nkonya, Pender, Kaizzi, & Edward, 2005; Stocking, 2003; Stoorvogel & Smalling, 2000; Wortmann & Kaizzi, 1998), though there have been several well-known case studies demonstrating that population expansion may not always have the expected deleterious effects on soil fertility (Carswell, 2002; Mortimore & Harris, 2005; Tiffen et al., 1994). Declining soil fertility has been shown to reduce agricultural productivity, already low in Sub-Saharan Africa, increasing household vulnerability and food insecurity (Sanchez, 2002). Some researchers have observed that soil degradation may lead to permanent migration by stressing these rural livelihood systems (Afifi, 2011; Henry, Boyle, &

Lambin, 2003; Van der Geest, 2011) while others have found that households with poor soil fertility may lack the resources necessary to support migration (Gray, 2011).

As with soil degradation, deforestation concerns stem largely from the context of rapid population growth, which in turn has led to increased demand for forest products. Between 2000 and 2012, Sub-Saharan Africa experienced high rates of forest loss (Hansen et al., 2013). Apart from the clear environmental issues related to loss of carbon sequestration and biodiversity from deforestation, forest product collection and harvesting of forest for timber, sometimes illegally, is a staple of many rural livelihoods in Sub-Saharan Africa (Jagger, Shively, & Arinaitwe, 2012). Loss of forest can weaken this aspect of rural livelihood strategies, potentially contributing to a heavier reliance on agriculture, livestock production, nonfarm diversification strategies, and migration. In Ghana, for example, deforestation has been cited as a driving factor of rural-urban migration (Carr, 2005).

These environmental concerns are only exacerbated by the current and projected impacts of climate change on Sub-Saharan Africa. According to the Intergovernmental Panel on Climate Change's latest assessment, Sub-Saharan Africa is likely to experience increased temperatures and increased spatial and temporal variability of precipitation (IPCC, 2014). This constellation of climate effects alone has the potential to wreak havoc on crop seasonality, agricultural productivity, and natural resource based livelihoods more broadly. When combined with soil degradation and deforestation, it is clear that in rural households in Sub-Saharan Africa will be increasingly faced with the need to adapt through in situ (e.g. livelihood diversification) or ex situ (e.g. migration) processes. Migration has been shown to generally increase with periods of drought but these effects are inconsistent across migration types (Findlay & Geddes, 2011; Gray & Mueller, 2012; Henry et al., 2004; Munshi, 2003). Likewise, high temperatures have been broadly shown to increase migration, but these effects vary across contexts (Gray & Mueller, 2012; Gray & Wise, 2016).

In reviewing the literature, it is clear that environmental shifts in Sub-Saharan Africa are potential drivers of migration, though these effects vary substantial across countries. It is less clear whether these conflicting findings are based on substantive differences in context or methodological variations. Few of these studies consider more than one environmental factor and many data sources are unable to disaggregate temporary and permanent migrations, though they clearly are largely driven by different processes. Further, few of these studies consider different motivations (e.g. labor, marriage) for migration, or the individual (e.g. gender) characteristics that may shape these processes. Responding to these gap in the literature, our study examines the effect of precipitation, temperature, soil fertility, and forest cover on temporary and permanent migration in Uganda, stratifying by migration characteristics and controlling for a range of socio-demographic household and individual factors.

Data Collection

The Ugandan context

To address these gaps in the literature, we link longitudinal survey data with fine-scale gridded environmental data for rural Uganda. Though Uganda is highly diverse in regard to agro-ecological regimes, cultural contexts, land tenure types, and access to markets, among other characteristics, the country is also united by some key elements. Population density across Uganda, as in many parts of East Africa, is much higher than in other parts of the continent (United Nations Development Programme, 2014). Further, Uganda, like most of East Africa, exhibits sub-optimal crop productivity, low rates of economic growth, and high poverty rates (Pender, Place, & Ehui, 2006). Even though the overall percentage of the GDP that comes from agriculture declined from 52% to 15% between 1992 and 2010, nearly 80% of the population is currently employed in agriculture (Uganda Bureau of Statistics, 2014).

Since the pre-colonial period, migration has been a staple of Ugandan livelihood strategies. Many of these migration flows are seasonal and cyclical, with individuals temporarily migrating for education or employment opportunities in cotton and coffee plantations or mines (Black, Crush, Peberdy, & Ammassari, 2006). As part of a household livelihood strategy, these cyclical migration flows can provide remittances to rural households while also lessening individual food insecurity by decreasing household size (Ellis, 2000). Ugandans also engage in rural to urban migration. In 2011, the total population growth rate of Uganda was 3.4% while the urban population growth rate was 5.4%, suggesting that the difference arises from rural-urban migration rather than exorbitantly higher rates of natural increase (Mukwaya, Bamutaze, Mugarura, & Benson, 2011). Finally, though forced displacement due to attacks from the Lord's Resistance Army (LRA) continues to plague northwestern Uganda (Internal Displacement Monitoring Centre, 2017), none of the communities chosen for our study have experienced forced displacement due to conflict between 2003 and 2013.

Socio-environmental data

The survey data collection took place in 2003 and 2013. The 2003 wave was collected by the International Food Policy and Research Institute (IFPRI) in collaboration with the National Agricultural Research Laboratories (NARL) of Uganda. These researchers selected their sample population from a sampling framework developed by the Uganda Bureau of Statistics (UBOS) for a larger survey, the Uganda National Panel Survey (Nkonya et al., 2008). Using a two-stage clustered random sampling approach, 850 households were selected from eight different UBOS survey districts in an effort to represent Uganda's agro-ecological diversity (see Appendix F). In 2013, a team of researchers from IFPRI, NARL, the University of North Carolina at Chapel Hill (UNC-CH), Cornell University, Purdue University, and Brown University carried out the second wave of this survey.

In both waves, Ugandan enumerators conducted surveys and gathered spatial data at the household, plot, and community levels, and collected plot-level soil samples for laboratory soil analysis (see Appendix 1 for soil sampling and analysis procedures; see Appendix 2 for spatial data procedures). Survey enumerators were able to return to 727 of the 849 households successfully interviewed in 2003 during the 2013 follow-up (see Appendix 3 for differences between tracked and lost households). Further, original household members who had formed their own households in between surveys were tracked down and interviewed about their new households if they were still living within their original parish. In total, survey enumerators were able to collect household and plot survey and soils data from 831 households in 2013. In addition, soil samples were successfully collected and laboratory analyzed from 1,965 plots in 2003 and 1,389 plots in 2013.

We combine these survey data with high-resolution climate and forest cover data. Our measures of temperature and precipitation data are extracted for each community from the University of East Anglia Climatic Research Unit's (CRU) time-series 3.24. CRU is a monthly global dataset with a resolution of 0.5 degrees (approximately 50 km at the equator) generated through interpolation of data from a network of over 4,000 weather stations worldwide (UEACRU et al., 2013). CRU data are broadly considered to be a reliable source of climate measures in Africa (Zhang, Kornich, & Holmgren, 2013). Further, the precipitation information produced by CRU is viewed as more spatially and temporally realistic than other climate products in regard to variation in patterns in the mid-latitude regions (Los, 2015). Our measure of forest cover is generated using the Global Forest Change 2000-2013 dataset, which has a resolution of 1 arc-second per pixel (approximately 30 meters at the equator) (Hansen et al., 2013). Specifically, we draw upon the 2000 and 2010 Landsat reanalysis images, which provide spatially explicit information about percentage of tree cover at the pixel level.

Analysis

In order to estimate the impact of the environmental predictors on migration, we begin by using the survey data to construct an individual measure of temporary migration and a household-year measure of permanent migration. Concurrently, we use the survey and soils data to generate our measure of soil fertility and to build a number of controls at the individual and household levels to account for additional potential influences on migration decisions. Following this, we use spatial methods to extract monthly community-level measures of temperature and precipitation as well as measures of forest cover for 2000 and 2010 from high-resolution gridded reanalysis products. Next, we employ a combination of logistic regression, multinomial logistic regression, and discrete time event history analysis to estimate the impact of the climate and environmental predictors on temporary and permanent migration. Finally, we examine the impact of climate and environmental factors on household crop productivity in order to better interpret the findings from our migration analysis.

Migration measures

To examine environmental influences on migration, measures of temporary and permanent migration were constructed using the household roster and a retrospective migration module respectively. The household roster section of the survey included a question about the number of months that a household member was present in the household during the last 12 months. For those household members who were absent, the survey included a question on motivation for absence. Household members who were present in the household for less than 12 months are considered to be temporary migrants in this survey. The temporary migration category is broken down into short and long term temporary migrants by the number of months that a household member is absent from the household. Those who were absent less than 6 months are defined as a short term temporary migrant while those who are absent between 6 and 11 months are defined as long term temporary migrants. Temporary and permanent migrations include both economic (labor) and non-economic migrations. Migration motivations were decomposed into economic and non-economic reasons for migration, with economic reasons being all of those that were related to moving for employment or income generation. Male and female temporary migrations were also examined separately, to assess potential gendered differences in migration patterns (see Table 1 for descriptive statistics).

Permanent migrations were measured using a retrospective migration module that was part of the 2013 wave of the survey. This module asked the household respondent to list the individuals who had migrated in the years between 2003 and 2013 as well as the years they had migrated, the migration motivation, whether they moved to a rural or urban destination, and whether their move was local (within district), internal, or international. These data were used to construct a measure of the number of permanent migrants sent from a household each year. This measure was decomposed into measures of number of economic/non-economic migrants, rural/urban migrants, male/female migrants, and within-district/beyond district migrants sent by a household in a given year) (see Table 2 for descriptive statistics).

These survey data were also used to generate a standard set of controls that have previously been found to have an effect on mobility (White & Lindstrom, 2005). Individual level controls include age, gender, marital status, and whether the migrant was a child of the head of household while household level controls include age, gender, and educational level of head of household, household size, household distance to the nearest market, land tenure status of the household, household asset value, and household livestock value (see Tables 1 and 2 for descriptive statistics).

Environmental measures

As previously mentioned, temperature and precipitation values were derived from high-resolution monthly CRU data. For all parts of our analysis, we use z-scores (with 1980-2013 as the period of comparison) to measure temperature and precipitation anomalies. For temporary migration, we generate z scores using 12 and 120 month moving averages starting with the month of survey while for permanent migration we generate z scores using yearly 12 and 120 month moving averages starting with 2003 and continuing on through 2013. We chose to construct 12 month (1 year) and 120 month (10 year) climate anomalies to test for differences between short term coping and long term adaptation to climate shocks, as previous research has shown that these differences can exist (Bohra-mishra et al., 2014; Gray & Wise, 2016).

Our measure of forest cover is the average percentage tree cover of the pixels within a 1 kilometer buffer of the community centroid, a buffer size chosen based on previous research exploring the relationship between forest cover and socio-environmental factors in Uganda (Call et al., 2017). To measure soil fertility, we draw upon biophysical measures of soil fertility as well as farmers' perceptions of soil fertility. We generate our measure of soil fertility using principal components analysis to construct and index of five measured soil properties, pH, carbon, nitrogen, phosphorus, and clay content. Several of these soil fertility measures were strongly right-skewed and those were log transformed prior to analysis to prevent the outliers from overly influencing the outcomes. These soil fertility measures were also weighted by the relative area of their plot in reference to the total area of land owned by a household prior to analysis. The results of the analysis demonstrate that greater than 50% of the variance is explained by the first principal component, meaning that it is a suitable measure of soil fertility. The value of the first principal component, referred to in the analysis as measured soil fertility, was then rescaled to range from 0 to 10. In addition to measured soil fertility, we operationalize soil fertility with area-weighted perceived soil fertility, referred to in the analysis simply as perceived soil fertility. We have chosen to include this subjective measure of soil fertility because previous research has suggested that perceptions can often predict migration patterns more strongly than objective measures (Massey et al., 2010). Further, an analysis of these data examining the relationship between perceived and measured soil fertility found them to be complementary predictors of crop productivity (Call 2017, under review) (see Table 2 for descriptive statistics).

Regression approaches

Logistic regression models were estimated to assess the effects of environmental factors on person-year stacked cross-sectional data for temporary migration while controlling for additional factors. Once the temporary migrations were decomposed into long and short term temporary migrations, economic and noneconomic temporary migrations, and female and male temporary migrants, they were analyzed using multinomial logistic regression models. Using a negative binomial approach, we then estimated the relationship between environmental factors and the yearly number of permanent migrations from a household collected through a retrospective migration module. As with temporary migration, these permanent migrations were decomposed migration motivation, migration destination, migrant gender, and migration distance. In the event history analysis, we include both linear and squared terms for the year to adjust for potential errors in retrospection (VanWey, 2005). Standard ordinary least squared regression was used to investigate the association between environmental and climate factors and crop productivity using stacked cross-sectional data from 2003 and 2013. In all models, district fixed effects are included to adjust for agro-ecological, socio-demographic, and other omitted variable differences between each of the districts. Year fixed effects are included in the stacked temporary migration analyses to account for structural and cultural differences between the two years of data collection. Fixed effects for crop type (e.g. legumes, cash crops, tubers, cereals, banana) were included in the crop productivity analysis to adjust for crop-specific differences in yield and market value. Al models are clustered at the community-levels to adjust for the non-independence of residuals. Values from the logistic regressions are shown as odds ratios while values from the event history analysis are shown as incidence rate ratios, which can be interpreted like odds ratios. In all regressions, household asset values, household livestock values, and household distance to nearest market are log transformed for normality, as they are highly right-skewed.

Results and Discussion

Results from the analysis can be found in Tables 3, 4, and 5. Table 3 presents odds ratios of environmental effects on temporary migration while Table 4 presents incidence rate ratios for environmental effects on permanent migration. Table 5 contains the results of our crop productivity analysis. We will begin by examining the overall significance of the environmental effects jointly and individually before elaborating on each migration subpopulation. We will conclude with a discussion of the results of the household and individual level control variables.

We find that environmental effects are highly significant for both temporary and permanent migration. However, the strength and directionality of specific environmental and climate predictors differs greatly between temporary and permanent migration, as well as between different subcategories of migrations. Environmental effects are highly jointly significant for temporary migration both in the short term as well as when long term climate effects are considered. For permanent migration, environmental factors are only significant in the long-term climate specification. For temporary migration, soil fertility, forest cover, temperature shocks, and precipitation shocks are all significant predictors, while only soil fertility and temperature shocks are significant predictors of permanent migration.

We broadly observe that climate shocks, rather than soil fertility or tree cover, appear to have the most significant influence on migration flows in rural Uganda. These findings are particularly significant because soil degradation in particular, and to some extent forest loss, are both generally viewed as drivers of migration in Sub-Saharan Africa. In fact, we observe essentially no effects of forest cover on permanent or temporary migration in our population and we find that soil fertility appears to be inhabiting the role of natural capital, or at least perceived natural capital, supporting both temporary and permanent migrations. Perceived soil fertility may be significantly associated with migration while measured soil fertility is not due to (1) the way in which soil fertility is measured and (2) the previously substantiated hypothesis that migration decisions may be based on perceptions of conditions rather than empirical conditions themselves (Massey et al., 2010). Our findings highlight the large differences between the causes, and purposes, of temporary and permanent migration decisions. Considering these two types of mobility simultaneously may prevent researchers from clearly assessing environmental influences on migration. Further, the results of our analysis indicate that climate and environmental effects on migration are complex, providing heterogeneous influences on migration flows rather than a unidirectional ‘push’ as posited by the ‘environmental refugee’ literature.

In the primary temporary migration specification, short term precipitation and perceived soil fertility had large and significant effects and short term temperature had a small and marginally significant effect (Table 3). The odds of temporary migrations increase 70 % with every additional standard deviation (SD) that precipitation is above the 30-year climate mean, increase 63% for every unit increase in perceived soil fertility, and decrease 10% with 1 SD temperature deviation above the mean. When temporary migrations are decomposed into short and long term migration lengths, the odds of short term temporary migration decrease 15% with 1 SD temperature deviation above the mean while the odds of long term temporary migration increased 121% for 1 SD of above-average precipitation and increase 85% with 1 unit increase in perceived soil fertility. Similarly, the odds of economically motivated temporary migration decrease 36% with 1 SD precipitation anomaly above the mean, 16% with 1 SD temperature deviation above the mean, and increase 51% with 1 unit increase in perceived soil fertility. Conversely, the odds of non-economically motivated migration increase 140% with 1 SD of precipitation above the mean and 54% with 1 unit increase in perceived soil fertility. In addition, in the alternative long term climate specification, the odds of non-economically motivated increase 71% for every 1 SD of a 10-year moving average of precipitation above the climate mean. Temporary migrations in female and male subpopulations appear to be similarly related to climate and environmental factors, with the odds of female migration increasing 95% with 1 SD precipitation deviation above the mean (56% with 1 SD of a 10-year moving average of precipitation deviation) while the odds of male migration increase 49% with the same 1 SD precipitation deviation above the mean. Perceived soil fertility is likewise similarly associated with increased odds of female (64% per 1 unit increase) and male (62% per 1 unit increase) temporary migration. Male migration is also related to temperature, with the odds decreasing by

14% with 1 SD temperature deviation above the mean. Considering decadal climate patterns, female migration odds increase 56% with 1 SD 10-year precipitation deviation above the mean.

As our study population consists of relatively poor rural Ugandan households, this pattern suggests that years of high rainfall may provide households with the necessary resources to send migrants, though not for directly economic reasons, and a lower demand for agricultural labor. We test this hypothesis by considering the overall influence of climate shocks and environmental factors on crop productivity (Table 5). While we observe that increased rainfall has a positive effect on both crop productivity (kg/ha) and crop value (USD/ha), we also find that the negative effect heat shocks on crop productivity is not mirrored by crop value, where short term heat shocks likely increase the market gate value of a given crop for those with an adequate harvest. Nonetheless, these findings broadly support the hypothesis that years of high rainfall provide impoverished households with the resources they require to send temporary migrants while years of above average heat may increase income per hectare but likely reduce harvest and may require male household members to spend an increased amount of time on farm labor to cope, reducing opportunities for migration.

The primary permanent migration specification suggests that there are no short-term effects of environment on the odds of permanent migration in Uganda. However, the alternative long term climate specification reveals that these effects manifest after long periods of heat rather than instantaneously, as with the climate influences on temporary migration. The odds of a permanent migration increase by 65% with 1 SD of long term temperature deviation above the temperature mean. Decomposing permanent migration into economically and non-economically motivated moves, we find that the odds of economic migration increase 140% with 1 SD temperature deviation above the mean at the decadal scale, and 36% with 1 unit increase in perceived soil fertility, while non-economic moves show no climate associations. Similarly, urban migrations appear to be much more strongly related to climate effects than rural migrations, with the odds of an urban migration increasing 75% with 1 SD of long term temperature deviation above the mean. As with economic migration, the odds of urban migration increase 46% with every 1 unit increase in perceived soil fertility. Rural migration is marginally affected by temperature, with the odds decreasing slightly (10%) with 1 SD of short term temperature deviation above the mean and increasing 60% with 1 SD of long term temperature deviation above the mean. Considering gender differences, the odds of female permanent migrations decrease 9% with 1 SD temperature anomaly above the mean but are not associated with long term climate trends, while the odds of male permanent migrations increase by 130% with 1 SD of long term temperature deviation above the mean but are not associated with short term heat shocks. Migration distance shows no relationship with environmental factors or short term climate deviations but the odds of both within district and beyond district migrations increase with 1 SD of long term temperature deviation above the mean by 86% and 48% respectively.

Based on the strong relationship between long term periods of heat and increased permanent migration, we hypothesize that long-term heat shocks may eventually push households to send male labor migrants out of necessity due to household crop income Though we do not see a significant effect of decadal heat shocks on crop yield, we do observe that crop value per hectare significantly decreases after extended periods of heat, supporting our hypothesis (Table 5). We believe that the reduction in crop value per hectare after a decade of above average temperatures is associated with a household shift from planting more economically valuable, but temperature sensitive, crops to planting staple crops (Salazar-

Espinoza, Jones, & Tarp, 2015). These staple crops can provide the household with a consumption-smoothing effect.

Finally, the effects of our household and individual level control variables are generally highly significant, fitting with our expectations based on previous literature and migration theory. Unmarried male children of the head of household are the most likely individuals to migrate. Older, larger, female-headed households with greater assets are generally the households with the greatest odds of sending temporary or permanent migrants. These factors are broadly true across migration subcategories. The general lack of variation in the effects of our household and individual controls across different types of migration is also worth mentioning. Wealthier, larger households were clearly best positioned to send migrants regardless of any variation in individual or environmental circumstances. This finding is in contrast with the broader narrative of environmental migration, which argues that poorer and more vulnerable households are most likely to be displaced by environmental shifts. However, it does support the idea of 'poverty traps,' wherein poor households are unable to engage in necessary migration due to lack of resources (Barrett, 2008). It is particularly notable that female headed households were significantly more likely to send economic permanent and temporary migrants and significantly less likely to send non-economic migrants, possibly due to reduced ownership rights for women (Place, 2009). Older households are also more likely to send migrants, likely due to the household lifecycle stage, a hypothesis supported by the observation that children of the head of household have increased odds of participating in economic migrations.

Conclusions

In this article, we thoroughly examine the effect of a range of environmental factors on migration in rural Uganda. In contrast to previous research, we explore both temporary and permanent migrations, examine the influence of both short and long periods of climate stress, and consider different motivations and characteristics shaping these migration processes. Our research has significant implications for environmental migration theory, research approaches, and migration policy implementation.

From a theoretical perspective, these findings reveal that climate variability, rather than other environmental factors, is driving migration, at least in the Ugandan context. In particular, heat has the largest influence on migration processes. In the short term, heat appears to be reducing opportunities for temporary migration, a common household livelihood strategy. Long periods of heat stress, however, may be pushing households to send migrants in order to provide remittance income in the face of reduced crop income. We also find that these migration responses are gendered. Heat pressures have the largest influence on male labor migrations, with female migrations largely unaffected by negative climate pressure.

In regard to our methodology, we build on previous research to develop a multifaceted approach to examining environmental migration in rural developing contexts. Novel elements of our approach include (1) exploring temporary migration through cross-sectional household roster data in conjunction with retrospective annual data for permanent migration; (2) considering both environmental and climate factors; (3) examining short and long term climate anomalies; (4) using a GIS to extract environmental measures using community spatial data; and (5) employing both perceived and measured indicators of soil fertility. Through this approach, we are able to examine the diversity and complexity of environmental influences on migration patterns, improving our ability to assess whether the heterogeneity of findings in the broader environmental migration literature is based on substantive or methodological differences. To advance environmental migration theory further yet, it would be beneficial to employ this methodological approach in a multi-country framework, with the goal of assessing whether these observed patterns hold across national contexts.

This research has broader, policy-oriented implications, especially in the context the ‘environmental refugee’ narrative. As noted previously, climate change is predicted to lead to increased heat and changes in the volume, as well as the spatio-temporal patterning, of rainfall in Sub-Saharan Africa (IPCC, 2014). This study suggests that, at least in the Ugandan context, climate change may indeed eventually result in some degree of permanent displacement if long periods of above-average heat become the new climatic norm. However, we also find that these displacements appear to be associated with decreased agricultural income. Based on this research, we believe that improved access to in situ adaptation strategies, such as heat resistant crop types and rural employment, is likely to have the best chance of decreasing climate-driven permanent migration.

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Tables

Table 3.1 Descriptive Characteristics of Temporary Migration (individual-year)

	Mean	Std Deviation	Min	Max	Definition
Outcomes					
Temporary Migration (0/1)	0.173	0.378	0	1	0=Individual present in household 12 months, 1=Individual present in household less than 12 months
Predictors					
Perceived Soil Fertility	1.063	0.623	0.125	3	Perceived soil fertility (1=poor, 2=average, 3=good) weighted by plot area
Measured Soil Fertility	1.410	1.274	0.039	9.109	Plot level soil fertility index derived from PCA of measured soil characteristics weighted by plot area
Tree Cover (%)	21.624	6.537	6.567	43.550	Tree cover percentage for 1 km community buffer
Z-Score of Precipitation (12 month lag)	0.698	1.190	-0.972	3.487	Z-score of 12 mo precipitation average relative to 1981-2013
Z-Score of Temperature (12 month lag)	1.005	0.988	-0.334	2.229	Z-score of 12 mo temperature average relative to 1981-2013
Z-Score of Precipitation (10 year lag)	0.566	0.863	-1.421	2.032	Z-score of 120 mo precipitation average relative to 1981-2013
Z-Score of Temperature (10 year lag)	0.615	0.423	0.070	1.104	Z-score of 120 mo temperature average relative to 1981-2013
Average monthly precipitation, 1981-2013 (mm)	105.186	12.596	75.588	135.545	Average monthly precipitation, 1981-2013 (mm)
Average monthly temperature, 1981-2013 (C)	22.355	2.225	16.571	25.928	Average monthly temperature, 1981-2013 (C)
Unmarried (0/1)	0.728	0.445	0	1	Marital status of individual
Child of Head of Household (0/1)	0.554	0.497	0	1	Individual is the child of head of household
Female (0/1)	0.514	0.500	0	1	Gender of individual
Age	45.709	13.575	14	105	Age of individual
Female Head of Household (0/1)	0.176	0.381	0	1	Female head of household
Education Level of Head of Household (0/1)	0.859	0.348	0	1	No formal education=0, Some formal education=1
Household Size	7.683	3.244	1	26	Number of household members
Primarily Agricultural Household	0.676	0.468	0	1	Agriculture is the primary source of income
Distance to Market (km)	3.729	3.702	0	40.234	Distance to the nearest market
Secure Land Tenure	0.328	0.469	0	1	Land tenure is either owned through freehold or leased
Household Asset Value (USD)	6,264	10,634	49	87,634	Total value of household assets
Household Livestock Value (USD)	798	2,101	0	21,853	Total value of household livestock

Year	2008	5	2003	2013	Year when cross-sectional data were collected
N=8,214					

Table 3.2 Descriptive Characteristics of Permanent Migration (household-year)

	Mean	Std Dev	Min	Max	Definition
Outcomes					
Permanent Migrants	0.084	0.379	0	10	Number of permanent migrants per household per year
Econmic Migrants	0.041	0.233	0	6	Number of economic migrants per hosuehold per year
Non-Economic Migrants	0.043	0.283	0	10	Number of non-economic migrants per household per year
Urban Migrants	0.043	0.275	0	9	Number of urban migrants per household per year
Rural Migrants	0.041	0.243	0	8	Number of rural migrants per household per year
Female Migrants	0.048	0.257	0	6	Number of female migrants per household per year
Male Migrants	0.036	0.219	0	5	Number of male migrants per household per year
Within District Migrants	0.030	0.233	0	9	Number of within-district migrants per household per year
Beyond District Migrants	0.053	0.292	0	10	Number of beyond district migrants per household per year
Predictors					
Perceived Soil Fertility	1.046	0.639	0.125	3	Perceived soil fertility (1=poor, 2=average, 3=good) weighted by plot area
Measured Soil Fertility	1.093	0.962	0.039	8.994	Plot level soil fertility index derived from PCA of measured soil characteristics weighted by plot area
Tree Cover (%)	21.619	6.543	7.673	43.550	Tree cover percentage for 1 km community buffer
Z-Score of Precipitation (12 month lag)	0.4070285	1.12579	-2.167003	3.187824	Z-score of 12 mo precipitation average relative to 1981-2013
Z-Score of Temperature (12 month lag)	0.3102964	0.1519616	-0.0123705	0.6929282	Z-score of 12 mo temperature average relative to 1981-2013
Z-Score of Precipitation (10 year lag)	0.1584112	0.2579378	-0.6550084	1.054249	Z-score of 120 mo precipitation average relative to 1981-2013
Z-Score of Temperature (10 year lag)	0.2901761	0.0716657	0.1259098	0.4522321	Z-score of 120 mo temperature average relative to 1981-2013
Average monthly precipitation, 1981-2013 (mm)	22.131	2.374	16.571	25.928	Average monthly precipitation, 1981-2013 (mm)
Average monthly temperature, 1981-2013 (C)	104.020	13.131	75.588	135.545	Average monthly temperature, 1981-2013 (C)
Age of Head of Household (2003)	41.842	13.977	16	86	Age of the head of household in 2003

Female Headed Household (2003)	0.182	0.386	0	1	Female headed household in 2003
Household Size (2003)	6.045	2.867	1	19	Number of people in the household in 2003
Distance to Market (km) (2003)	3.053	2.903	0.05	23.75	Distance to the nearest market in 2003
Secure Land Tenure (2003)	0.375	0.484	0	1	Land tenure is either owned through freehold or leased in 2003
Education Level of Head of Household (2003)	0.824	0.381	0	1	No formal education=0, Some formal education=1
Household Asset Value (USD) (2003)	3,447	5,736	49	74,687	Total value of household assets
Household Livestock Value (USD) (2003)	460	1,370	0	21,853	Total value of household livestock
Year	2008	3.162	2003	2013	Years from 2003 to 2013
N=7,865					

Table 3.3 Multinomial logistic regression of temporary migration (person-year)

	All Migrations	Migration Length		Migration Motivation		Migrant Gender	
		Short Term	Long Term	Economic	Non-Economic	Female	Male
Environmental Factors							
Z-Score of Precipitation (12 months)	1.711***	0.797	2.212***	0.640*	2.398***	1.949***	1.486*
Z-Score of Temperature (12 months) x 10	0.895+	0.850**	0.923	0.838**	0.908	0.928	0.864*
Perceived Soil Fertility	1.628**	1.008	1.852**	1.509*	1.542*	1.638*	1.620**
Measured Soil Fertility	1.005	1.045	1.002	1.059	1.038	1.023	0.987
Tree Cover (%)	1.013	0.993	1.02	1.013	1.01	1.002	1.023+
Average monthly precipitation, 1981-2013 (mm)	0.981+	1.015	0.967**	0.989	0.98	0.99	0.972**
Average monthly temperature, 1981-2013 (C)	0.91	1.376**	0.774*	1.037	0.889	0.977	0.839*
Individual Characteristics							
Unmarried	1.092	0.677	1.300+	1.555+	0.997	1.253	0.946
Child of Head of Household	1.164	1.399	1.094	2.397***	0.917	1.045	1.328+
Female	0.878*	0.688**	0.956	0.801+	0.908		
Age	1.041	1.069	1.036	1.052	1.057	1.055	1.026
Age*Age	1.000	0.999+	1.000	0.999+	0.999	0.999+	1.000
Household Characteristics							
Female Head of Household	1.378	1.341	1.382	1.761*	1.152	1.505+	1.217
Education Level of Head of Household	1.055	0.632	1.302	0.909	1.089	1.07	1.039
Household Size	1.027	0.949+	1.057+	0.944*	1.059+	1.022	1.032

Secure Land Tenure	0.771	0.901	0.723	1.254	0.623*	0.691+	0.853
ln(Household Asset Value)(USD)	1.146+	1.316***	1.099	1.663***	0.977	1.148+	1.147+
ln(Household Livestock Value)(USD)	1.019	1.033	1.018	1.107+	0.989	1.014	1.026
ln(Distance from Market)	0.988	1.052	0.988	0.939	0.933	1.063	0.922
Year	0.953	0.829+	1.02	0.930	0.935	1.022	0.901
Observations	8,224	8,224		8,224		8,224	
Joint test of environmental factors	26.38***	64.70***		60.11***		47.91***	
Joint test of individual characteristics	13.45**	30.84***		61.21***		15.16*	
Joint test of household characteristics	11.01+	33.74***		100.21***		22.78*	
Long Term Climate Specification							
Z-Score of Precipitation (120 months)	1.287	0.962	1.443	0.861	1.713*	1.564*	1.092
Z-Score of Temperature (120 months) x 10	1.018	1.367	0.989	1.987	0.711	0.724	1.365
Joint test of environmental factors	19.50**	48.49***		36.88***		15.81*	

Robust standard errors, clustered at the community level
*** p<0.001, ** p<0.01, * p<0.05, + p<0.1
District fixed effects included but not shown
Constants included but not shown

Table 3.4 Negative binomial regression of permanent migration (number of individuals per household per year)

	All Permanent Migrations	Migration Motivation		Migration Destination		Migrant Gender		Migration Distance	
Environmental Factors		Economic	Non-Economic	Urban	Rural	Female	Male	Within District	Beyond District
Z-Score of Precipitation (12 months)	0.995	1.003	0.981	1.033	0.969	1.052	0.919	1.043	0.968
Z-Score of Temperature (12 months) x 10	0.950	1.002	0.904	1.001	0.902+	0.910+	1.005	0.921	0.977
Perceived Soil Fertility (2003)	1.144	1.365*	0.961	1.463**	0.891	1.119	1.234	1.005	1.216
Measured Soil Fertility (2003)	0.986	0.932	1.052	0.963	1.040	1.036	0.902	0.967	1.006
Tree Cover (2000) (%)	1.014	1.008	1.020	1.022	1.007	1.016	1.012	1.014	1.013
Average monthly precipitation, 1981-2013 (mm)	1.012	1.006	1.019*	1.011	1.013	1.019*	0.999	1.012	1.010

Average monthly temperature, 1981-2013 (C)	1.087	1.252*	1.019	1.319*	0.990	1.087	1.080	1.051	1.108
Household Characteristics									
Age of Head of Household (2003)	1.100***	1.105*	1.114**	1.114*	1.108**	1.111**	1.088*	1.102*	1.115**
Age of Head of Household*Age of Head of Household	0.999***	0.999*	0.999**	0.999*	0.999***	0.999**	0.999*	0.999*	0.999*
Female Head of Household (2003)	0.955	1.366+	0.607*	1.078	0.792	0.759	1.313	0.669+	1.145
Education Level of Head of Household (2003)	0.853	0.874	0.853	0.860	0.860	0.920	0.857	0.849	0.843
Household Size (2003)	1.032	1.069**	0.979	1.049+	0.990	1.054*	1.003	1.017	1.035
ln(Distance to market)(2003)(km)	0.991	0.863	1.096	0.829	1.137	1.094	0.863	1.311+	0.862
Secure Land Tenure	0.790	0.738	0.874	0.689*	0.937	0.731	0.878	0.904	0.738+
ln(Household Asset Value)(USD)	1.129*	1.183+	1.079	1.210*	1.038	1.132*	1.119	1.117	1.136+
ln(Household Livestock Value)(USD)	1.004	1.011	1.005	1.033	0.972	0.981	1.049	0.986	1.014
Year	1.221*	1.203+	1.254+	1.149	1.340***	1.308**	1.140	1.356**	1.180
Year*Year	0.988	0.992	0.983	0.993	0.980**	0.980*	0.996	0.978*	0.991
Observations	7,876	7,876	7,876	7,876	7,876	7,876	7,876	7,876	7,876
Joint test of environmental factors	8.75	14.92*	10.58+	23.20**	9.42	13.31+	8.39	5.11	5.66
Joint test of household characteristics	30.85***	25.25**	24.09**	24.45**	20.12**	41.91***	14.44+	23.56**	15.07+
Long Term Climate Specification									
Z-Score of Precipitation (120 months)	1.041	0.558	2.094	1.112	0.911	1.354	0.764	0.634	1.179
Z-Score of Temperature (120 months) x 10	1.653**	2.409***	1.165	1.749*	1.592+	1.286	2.298***	1.864*	1.477+
Joint test of environmental factors	14.00+	30.72***	10.27	28.12***	7.39	10.67	21.01**	8.86	7.93

Robust standard errors, clustered at the community level
*** p<0.001, ** p<0.01, * p<0.05, + p<0.1
District fixed effects included but not shown
Constants included but not shown

Table 3.5 Ordinary Least Squares regression of household crop value and productivity

	Crop productivity (kg/ha)	Crop value (USD/ha)
Environmental Factors		
Z-Score of Precipitation (12 months)	0.520***	0.223***
Z-Score of Temperature (12 months) x 10	-0.504***	0.160**
Perceived Soil Fertility (2003)	0.135	0.192*
Measured Soil Fertility (2003)	0.149**	0.081*
Tree Cover (%)	-0.018+	-0.01
Average monthly precipitation, 1981-2013 (mm)	-0.022**	-0.016**
Average monthly temperature, 1981-2013 (C)	-0.142+	-0.138*
Household Characteristics		
Female Head of Household	-0.225*	-0.174*
Education Level of Head of Household	0.019	0.148+
Household Size	0.028+	0.011
ln(Distance to market)(km)	0.058	-0.064
Secure Land Tenure	-0.108	0.183*
ln(Household Asset Value)(USD)	0.192***	0.087**
Total plot area	-0.268***	-0.310***
Year	-0.149**	0.098***
Observations	1,311	1,311
R-squared	0.535	0.448
Joint test of environmental factors	11.74***	6.14***
Joint test of household characteristics	5.98***	6.90***
Long Term Climate Specification		
Z-Score of Precipitation (120 months)	0.058	0.168
Z-Score of Temperature (120 months) x 10	-0.31	-0.619*
Joint test of climate and environmental factors	5.45***	3.93***

Robust standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05, + p<0.1
District and crop type fixed effects included but not shown
Constants included but not shown

CHAPTER 4: CLIMATE ANOMALIES AND SMALLHOLDER LIVELIHOODS IN UGANDA

Introduction

Scientists worldwide are in consensus that climate change will have a significant global impact on ecosystem services, agricultural productivity, and livelihoods (IPCC 2014). These effects are likely to be the most extreme in the rural developing world, where smallholders often rely heavily upon natural-resource-based livelihoods (Iiyama et al. 2008). As temperatures and irregularity of rainfall increases (IPCC 2014), smallholders may find their livelihoods undermined due to reduced agricultural income, shifting access to employment opportunities, and a decline in food produced for household consumption (Knox et al. 2012; Mueller, Gray, and Kosec 2014). To adapt successfully in situ to livelihood destabilization, smallholders often have to employ a constellation of complementary responses, with on-farm and off-farm strategies supporting one another (Clay and Schaffer 1984; Eakin 2005).

Examining on-farm strategies, a number of studies have observed that smallholders have changed their agricultural practices as a result of climate anomalies (Thomas et al. 2007; Bharwani et al. 2005; Roncoli, Ingram, and Kirshen 2001; Reenberg, Nielsen, and Rasmussen 1998; Reenberg 1994). Likewise, researchers have observed that climate anomalies have influenced smallholder diversification into off-farm livelihoods both as a risk management strategy (Paavola 2008) and to cope with the adverse effects of climate anomalies (Fischer et al. 2005). These studies provide some evidence that rural smallholders are utilizing on-farm and off-farm livelihood diversification strategies to manage livelihood stress from climate variability.

However, the findings are generally limited by cross-sectional case study approaches and small sample sizes. Further, few studies consider differences in livelihood responses to short term and long term climate anomalies, or examine both on-farm and off-farm livelihood strategies.

Responding to these gaps in the literature, we analyze longitudinal household survey data from 850 households and nearly 2,000 agricultural plots in rural Uganda which are linked with high resolution gridded climate data. Using these data, we examine livelihood responses to short term and long term climate anomalies, considering on-farm agricultural strategies as well as off-farm livelihood diversification. We find that smallholder livelihoods are responsive to climate over short and long time scales. Droughts decrease agricultural productivity in the short term and reduce individual livelihood diversification over time. Higher temperatures can be successfully coped with in the short term, but in the long run, above average temperatures reduce agricultural productivity and limit opportunities for diversification. Considering that Sub-Saharan Africa is predicted to experience increasingly high temperatures, these observations suggest that new approaches to livelihoods will be necessary if smallholders are to successfully adapt to climate change.

Background

Theorizing in situ adaptation strategies

To develop our theoretical framework, we draw together two related but rarely intersecting literatures—research examining on-farm agricultural strategies and studies exploring off-farm livelihood diversification. Each of these literatures provides important insights into an aspect of smallholder livelihoods, which are typically composed of both on-farm and off-farm elements (Barrett, Reardon, and Webb 2001). Scholars have generally observed that livelihood diversification into off-farm activities increases livelihood security and improves farm efficiency

(Mehta 2009). Both on-farm and off-farm livelihood diversification can decrease the vulnerability of rural households by distributing risk (Ellis 2000) and can provide households with a form of self-insurance (Barrett, Reardon, and Webb 2001).

On-farm agricultural strategies employed by smallholders may include changes in agricultural management approaches, agricultural intensification, and agricultural extensification. To reduce risk, smallholders may choose to plant additional types of crops (Di Falco, Veronesi, and Yesuf 2011). Some smallholders may also choose to plant more drought-resistant crops or to focus their agricultural production on staple crops, rather than cash crops, in order to provide a consumption smoothing effect and prevent household food shortages (Moniruzzaman 2015). In addition to crop choice, smallholders may also vary the timing of crop planting. Smallholders may choose to plant a portion of their crops during the conventional planting period while reserving the remainder of their seeds to plant later, in case the first sowing fails (Di Falco, Veronesi, and Yesuf 2011). Along with these management approaches, smallholders may choose to intensify their agricultural production through the input of crop amendments (e.g. inorganic fertilizer, manure, crop residue) or the investment of additional hours of labor (Scoones 2000). If land is available, smallholders may also choose to extensify their cultivated land, increasing the odds that some percentage of their crop area may survive during poor agricultural conditions (Paavola 2008).

Often in parallel with these agricultural management choices, smallholders are faced with off-farm livelihood diversification choices and opportunities. In rural parts of Africa, off-farm income generally accounts for 40-45% of average household income (Reardon 1997). Off-farm livelihood diversification can include owning a small business (e.g. roadside stand, butchery, tailor shop), performing unskilled (e.g. farm labor) or semi-skilled labor (e.g. carpentry, bricklaying, technician), providing transportation (e.g. driving a boda boda), or seeking wage labor (e.g. working at a store, teaching, medicine) (Smith et al. 2001). Off-farm livelihood diversification can occur at the household level, with some members of the household focusing on agriculture while others pursue off-farm labor, or at the individual level, with an individual supplementing on-farm agricultural activities with off-farm activities (Ellis 2000). Some scholars have theorized that household livelihood diversification is a sign of a robust household that can afford to strategically distribute household human capital while individual livelihood diversification suggests that a household is scrambling to make ends meet and thus preventing household members from specializing (Little et al. 2001; Ellis 2000; Reardon et al. 2000). These strategies are not mutually exclusive, however. Household income diversification may be facilitated by individual activity diversification (Bryceson 2002).

Synthesizing previous research

Though many forms of stress can impact smallholder livelihood strategies, the ramifications of climate anomalies are of particular concern in Sub-Saharan Africa. Climate change is predicted to reshape the agricultural landscape of the region, threatening the success of current regional staple crops and broadly reducing agricultural productivity (Lobell et al. 2008; Teixeira et al. 2013). Recent research suggests that heat in particular is predicted to be especially economically and socially damaging (Carleton and Hsiang 2016). In response to climate stress, smallholders are generally expected to employ some combination of shifting on-farm agricultural strategies and increased off-farm livelihood diversification (Paavola 2008; Fischer et al. 2005).

Recent literature examining climate variability and agricultural strategies has a strong focus on crop choice and rainfall. During periods of high rainfall, research suggests that farmers tend to plant a greater proportion of drought-sensitive crops (Cho, McCarl, and Wu 2014;

Moniruzzaman 2015). Further, researchers have found that periods of drought are associated with a shift away from permanent and cash crops toward staple crops, which are less valuable but can provide households with food during periods of climate stress (Salazar-Espinoza, Jones, and Tarp 2015). In the one study that explored temperature effects, researchers found that farmers have been observed to shift their crop proportions toward those that are more drought and heat tolerant (Cho, McCarl, and Wu 2014).

In addition to crop switching, climate stress is associated with crop diversification. Recent research has found that during droughts, farmers are more likely to increase crop variety in order to increase production (Di Falco, Bezabih, and Yesuf 2010; Lei et al. 2016). Though crop diversity may increase, the crops being chosen during periods of poor rainfall are generally those that are more drought-resistant and therefore less risky (Di Falco and Bezabih 2012). Along with responding to droughts, farmers have been observed to react to rainfall uncertainty by diversifying their crop portfolio, especially during seasons of low rainfall (Bezabih and Sarr 2012). Researchers have also observed qualitatively that farmers intensify agriculture through increased labor and extensify cultivated land in response to drought (Paavola 2008).

Exploring the limited research on the relationship between climate variability and diversification into off-farm livelihoods, we once again find that most of the focus is on rainfall as a climate mechanism. Researchers find that households may be more likely to engage in non-agricultural labor during periods of drought (Silwal 2013; Porter 2012; Rose 2001; Paavola 2008). Agricultural households have also been observed to be more likely to be involved in non-agricultural activity in areas with higher rainfall variability (Menon 2009; Bandyopadhyay and Skoufias 2015; Ito and Kurosaki 2009; Kochar 1999; Rose 2001).

Our research contributes to the existing literature in a number of ways. First, it examines both on-farm livelihood strategies and off-farm livelihood diversification in response to climate anomalies in the same context, an approach which has previously been employed primarily in the qualitative descriptive literature (Paavola 2008). Second, much of the focus of past research has been on the influence of rainfall on livelihoods. Few studies have explored the dynamics between temperature and livelihood diversification, though recent research suggests that heat stress may be one of the most detrimental dimensions of global climate change (Carleton and Hsiang 2016). Further, this research examines the impacts of both short term and long term periods of climate stress on livelihood diversification. Though research indicates that short and long term climate stress may have different effects on adaptation approaches, there has been limited research on this topic in the context of livelihood diversification (Senaka Arachchi 1998). Our research also goes beyond examining crop choice, the predominant agricultural outcome in the literature, and quantitatively analyzes the impact of climate stress on agricultural inputs and labor intensification. Finally, this study examines the associations between climate stress and household income diversification as well as individual activity diversification, providing us with the opportunity to quantitatively assess whether divergent processes for household and individual livelihood diversification do exist in the context of climate change (Scoones and Toulmin 1998; Ellis 2000).

Methods

The Ugandan context

To contribute to these gaps in the literature, we spatially link household survey data from rural Uganda with fine-scale gridded temperature and precipitation data. Despite the large amount of social, cultural, and environmental variability across the country, Uganda is united by some shared characteristics. Uganda's population density, as in many parts of Sub-Saharan Africa, is much higher than in other parts of the continent (United Nations Development Programme 2014). Uganda, once again like most of Sub-Saharan Africa, exhibits sub-optimal crop productivity, low rates of economic growth, and high rates of poverty (Pender, Place, and Ehui 2006). Further, though the overall percentage of the Gross Domestic Product (GDP) that comes from agriculture declined from 52% to 15% between 1992 and 2010, nearly 80% of the population is currently employed in agriculture (Uganda Bureau of Statistics 2014).

Survey and environmental data

The two waves of household survey data employed in this analysis were collected in 2003 and 2013. To collect the 2003 wave, researchers from International Food Policy and Research Institute (IFPRI) collaborated with the National Agricultural Research Laboratories (NARL) of Uganda. Prior to 2003 survey data collection, the IFPRI researchers used a two-stage clustered random sampling approach to select 850 households from communities surveyed by the Uganda Bureau of Statistics (UBOS) for the Uganda National Panel Survey (Nkonya et al. 2008) (see Appendix F). The second wave of data were collected in 2013 by a team of researchers from IFPRI, NARL, the University of North Carolina at Chapel Hill (UNC-CH), Cornell University, and Purdue University.

Ugandan enumerators collected survey and spatial data at the household, plot, and community levels, and gathered plot-level soil samples for laboratory soil analysis in both waves of the survey (see Appendix 1 for soil sampling and analysis during both waves; see Appendix 2 for spatial data procedures). In the second wave of the survey, enumerators returned to 727 of the 849 households successfully interviewed in 2003 (see Appendix 3 for differences between tracked and lost households). In addition, in cases where original household members had split off to form their own households between the first and second waves, new households were tracked and interviewed if the households were located within the same parish as the original household. Including these tracked households, enumerators collected survey data from 831 households in 2013.

We draw high-resolution gridded temperature and precipitation data from the University of East Anglia Climatic Research Unit's (CRU) time-series 3.24. CRU, produced by the interpolation of data from a global network of over 4,000 weather stations. CRU is a monthly global dataset with a resolution of 0.5 degrees (approximately 50 km at the equator) (UEACRU et al. 2013). These data are viewed as a highly reliable source of climate measures in Africa (Zhang, Kornich, and Holmgren 2013). The CRU data were also chosen because the precipitation values provided by CRU are considered a more spatially and temporally accurate representation of mid-latitude precipitation variation than other climate products (Los 2015).

Analysis

In order to examine how smallholders cope with short and long term climate anomalies, we first construct measures of on-farm agricultural strategies and off-farm livelihood diversification using the survey data. From these data, we also construct measures of household capital as well as additional control variables. We then use GIS to extract community-level measures of temperature and precipitation from the CRU data. After combining the survey and climate data, we analyze this dataset using multivariate approaches appropriate for our hierarchical data structure. Finally, to provide clarity about the relationships we observe in our analysis, we examine the relationship between climate anomalies and plot-level crop productivity and value.

On-farm agricultural strategies

Our plot-level measures of agricultural strategies include the number of crops planted over the course of the year, whether the household ever applied organic fertilizer in the past year, and the number of hours of labor a household invested in a plot in the past year. These measures are all constructed using the plot-level agricultural component of the household survey. To build our measure of the number of the crops planted over the course of the year, we generate an indicator for each unique crop planted in a plot in each of the two seasons and sum together these indicators. On average, a plot was planted with three different crops over the course of the year, suggesting that on average in one season a plot was mono-cropped while smallholders practiced some kind of mixed cropping in the other season. There is, however, a large range in the number of crops planted in a plot over the course of the year, with the smallest number being one crop (e.g. for perennials like banana) and the largest being 18 discrete crops.

To operationalize whether or not a household applied an organic fertilizer (e.g. crop residue or manure) we generate an indicator variable where 0 represents no organic fertilizer application and 1 represents some organic fertilizer application. In our sample, 16% of plots were organically fertilized during the year. We chose to use an indicator variable for organic fertilizer application rather than a value for the amount of fertilizer applied to each plot because that information was not collected as part of the plot-level agricultural survey.

We sum together the number of hours of labor from family members, neighbors, and hired laborers during both agricultural seasons to calculate the total number of hours of labor applied to a plot in a given year. Though the amount of labor applied to a plot ranges greatly, the average number of hours of labor applied to a plot over the course of the year is 543 hours, or roughly two and a half full person-months of labor assuming a 50-hour work week.

Off-farm livelihood diversification

To construct our measures of off-farm livelihood diversification, we use information from the household roster as well as a module on household sources of income. From the household roster, we extract information on the primary and secondary activities performed by each adult (age 18 and above) member of the household. Using this information, we construct our measure of individual livelihood diversification. Individuals whose primary and secondary activities were on-farm, including working in agriculture as well as livestock tending, are assigned a value of 0 to represent that they are not involved in a diversified livelihood strategy. The remainder of individuals usually reported one on-farm livelihood strategy as well as one off-farm strategy, such as hospitality or transportation. These individuals are assigned a value of 1 to indicate that they are involved in a diversified livelihood approach. Nearly 75% of all individuals participated in a diversified livelihood approach.

The module on household sources of income provided us with information about the primary and secondary sources of household income. As with the individual livelihood diversification measure, households are assigned a livelihood diversification value of 0 if their primary and secondary income sources are on-farm, either agriculture or livestock-based. We chose not to disaggregate on-farm livelihood diversification into purely agriculture households and households that have both agriculture and livestock because the vast majority of households in our survey data operate using a mixed cropping-livestock system if they do not diversify into off-farm activities. Those households where one or both of their income sources are from an off-farm activity are assigned a livelihood diversification value of 1 to represent that they are involved in off-farm livelihood diversification. Similar to individual livelihood diversification, almost 70% of all households in our sample employed a diversified livelihood income strategy.

Climate measures

Our measures of temperature and precipitation are extracted from high-resolution monthly CRU data. Throughout our analysis, temperature and precipitation anomalies are operationalized using z-scores (with 1980-2013 used as the reference period). Our z-scores are constructed using regressive moving averages at 12 months (1 year) and 120 months (10 year), starting in 2002 and 2012 respectively (survey data were collected about livelihood diversification and agricultural intensification in the year prior to the survey). We employ z-scores based on a 12-month moving average to examine how smallholders cope with short term climate anomalies while we explore smallholder adaptation to long term climate stress through z-scores based on a 120-month moving average (Bohra-mishra et al., 2014; Gray & Wise, 2016). Descriptively, we observe that precipitation appears to have varied significantly both in the long and short term from the 30-year climate average, with some communities experiencing periods of above average rainfall while others have experienced droughts. Conversely, all temperature anomalies have involved above average temperatures, reflective of the global increase in temperature resulting from climate change (IPCC 2014)(see Table 1 for descriptive statistics).

Control variables

The survey data are also used to generate a set of controls based on the sustainable livelihoods framework (Scoones 2000; Ellis 2000). To adjust for differences in household assets, we consider relevant aspects of four of the five different types of capital described in the framework (e.g. human, physical, financial, social[1], and natural capital). Our measures of human capital include whether the head of household has any formal education, whether the head of household has participated in technical training, and the household size. We measure financial

[1] We do not include any measures of social capital as our survey did not collect sufficient information to measure social capital at the household leve1.

and physical capital simultaneously through the estimated value of household assets, which includes farm equipment as well as the value of home and durable goods.

Natural capital is measured through area of agricultural land, distance from a plot to household (as more proximate plots require less labor to maintain), and area-weighted measures of perceived and measured soil fertility. We have chosen to include the subjective perceptions measure of soil fertility alongside the objective measured soil fertility because previous research has argued that perceptions play an important role in shaping livelihood decisions (Massey, Axinn, and Ghimire 2010). In addition, in an analysis examining the relationship between perceived and measured soil fertility, they were found to be complementary predictors of crop productivity (Call 2017, under review) (see Table 1 for descriptive statistics). Our measured soil fertility index is generated through principal components analysis. We construct an index of five measured soil properties: pH, carbon, nitrogen, phosphorus, and clay content after log transforming those soil properties that were strongly right skewed to prevent outliers from influencing the outcome of the analysis. Greater than 50% of the variance is explained by the first principal component, indicating that it is a suitable measure of soil fertility in our data. The value of the first principal component was then rescaled to range from 0 to 10. For the household level analysis, we also weight the plot-level soil fertility measures by the relative plot size to the total amount of land owned by a household.

Alongside these different types of household capital, we include variables indicating the age of the head of household (or individual), gender of the head of household (or individual), and distance to the nearest market. These attributes can all contribute to variation in vulnerability and adaptive capacity (Adger 2006). Age and gender both shape access to livelihoods and resources from a power relations standpoint (Nelson et al. 2016). Market distance modulates access to resources and opportunities spatially and temporally (Kotir 2011). Smallholders located further away from towns may have reduced opportunities to obtain off-farm employment.

Regression approaches

Logistic regression models are estimated to examine the impact of short and long term climate anomalies on off-farm livelihood diversification at the individual and household levels, controlling for differences in capital and adaptive capacity. This analysis takes advantage of the two waves of longitudinal data by stacking the waves and performing the analysis at the household-year. To explore agricultural intensification approaches, we employ three different model types determined by the outcome of interest. To estimate the number of crops planted, a count variable, we use a Poisson regression. We examine whether or not households applied organic fertilizer to a plot through a logistic regression approach. To assess the log-transformed total hours of labor invested in a plot, we drew upon an ordinary least squares modeling approach. All of these plot-level analyses are performed on a two-wave stack of the cross-sectional plot-year data. Finally, ordinary least squared regression is used to investigate the relationship between climate anomalies, on-farm agricultural management, and crop productivity using plot-level stacked cross-sections of the longitudinal data from 2003 and 2013.

For all models, we include district fixed effects to account for agro-ecological, socio-demographic, and other unmeasured differences between the districts. Year fixed effects are included in all models to adjust for differences between the two years of data collection. For the crop productivity and agricultural intensification analyses, fixed effects for crop type (e.g. legumes, cash crops, tubers, cereals, banana) are included to adjust for crop-specific differences in yield and market value. Standard errors are clustered at the community level in all analyses. Logistic regression coefficients are shown in all tables as odds ratios while Poisson regression coefficients are displayed as incidence rate ratios and ordinary least squares regression coefficients are displayed as raw values. In all regressions, household asset values and household distance to nearest market are log transformed to reduce skewness.

Results and Discussion

The results of our analysis can be found in Tables 2, 3, and 4. Table 2 presents the effects of climate anomalies on three major types of on-farm agricultural strategies while Table 3 shows the effects of climate on household and individual off-farm livelihood diversification. Table 4 examines the relationship between climate anomalies and crop production, with and without agricultural management strategies. In this section, we will first explore the overall significance of short and long term climate anomalies on smallholder livelihoods. We will then explore how these findings are informed by our controls for household capital and adaptive capacity.

Broadly, we find that households appear to be adapting to short-term heat stress by employing crop diversification and increased organic inputs (Table 2). Through these management strategies, households are able to increase crop income per hectare (Table 4). Hot years are associated with higher crop income per hectare, likely due to uneven crop production success and increased demand, leading to higher market prices. During hot years, we also observe lower odds that one of the top two income sources of a household comes from an off-farm livelihood strategy, but higher odds that individuals will participate in off-farm activities (Table 3). Households maybe be prioritizing agricultural during this time to take advantage of high market prices but individuals may also be pushed to participate in several different livelihood activities to provide additional livelihood security to the household.

Extended periods of heat stress are associated with increased labor on the farm, which may prevent individuals from having the time to pursue off-farm livelihood activities (Table 2).

Exploring this, we do observe that a decade of heat stress is associated with lower odds of individual activity diversification, though heat stress appears to have no long-term impact on household-level diversification (Table 3). These long periods of heat stress are also associated with reduced crop income, possibly due to households planting less valuable but more heat-resistant staple crops (Salazar-Espinoza, Jones, and Tarp 2015) (Table 4). Without sufficient crop income, households may not be able to afford the opportunity cost for individuals to diversify into off-farm livelihood strategies (Barrett, Bezuneh, and Aboud 2001). Long periods of heat stress are also associated with decreased odds of planting more unique crops and from applying organic fertilizers (Table 2). During these periods of heat stress, households may be concentrating on a limited number of staple crops, for consumption smoothing (Salazar-Espinoza, Jones, and Tarp 2015), and may have had to divest of assets like livestock (Kusunose and Lybbert 2014), which provide an important source of organic manure.

Turning to precipitation, we observe that high rainfall years are associated with reduced farm labor and, in turn, increased odds of individual livelihood activity diversification (Tables 2, 3). These high rainfall years are also associated with increased crop productivity and increased crop income (Table 4). During high rainfall years, households can get the same crop production without investing in labor, providing household members with the time and resources to diversify into off-farm livelihood activities. These findings suggest that in periods of drought, households have to invest more labor in agriculture to maintain production, as has been observed descriptively in previous research (Paavola 2008).

After a decade of high rainfall, however, on-farm strategies remain largely unchanged (Table 2). Households do appear to be planting lower numbers of unique crops (Table 2), which may be because households have the confidence that they can grow a riskier crop portfolio without concern for precipitation variability (Salazar-Espinoza, Jones, and Tarp 2015). Though household off-farm livelihood diversification is largely unaffected, individuals appear to be more likely to pursue off-farm livelihood activities during extended periods of above average rainfall (Table 3). It is likely that when households have more resources, individuals are able to more easily access off-farm livelihood activities.

Household capital and adaptive capacity play an important role in shaping livelihood responses. In regard to household capital, we observe that wealthier households have lower odds of household livelihood diversification, which is supported by research arguing that middle income households in Sub-Saharan Africa have the highest livelihood diversification (Loison 2015). Focusing on adaptive capacity, increased distance to market is also associated with lower odds of individual and household livelihood diversification, likely because of the increased difficulty in accessing off-farm labor opportunities (Kijima 2010). We also find that women have lower odds of individual activity diversification, perhaps due to restrictive gender norms and household labor expectations (Tibesigwa, Visser, and Twine 2015). Few household characteristics significantly impact agricultural strategies, though we do observe that more educated heads of household have increased odds of applying organic fertilizer. Increased education may provide smallholders with an improved understanding of the importance of replenishing soil nutrients (Osbahr 2001).

Conclusions

Through this article, we present empirical evidence for the impacts of climate anomalies on two major elements of smallholder livelihoods: on-farm agricultural strategies and off-farm livelihood diversification. In addition to examining both on-farm and off-farm livelihood strategies, our research advances the in situ climate adaptation literature by (1) exploring the influence of temperature, as well as precipitation, on smallholder livelihoods; (2) examining the effect of short and long term climate anomalies; (3) addressing not just crop choice but also agricultural management; and (4) considering both household and individual off-farm livelihood diversification. In broad strokes, we find that droughts decrease agricultural productivity in the short term and lengthy droughts reduce individual livelihood diversification. Smallholders can cope with hot spells in the short term, but long periods of above average temperatures depress agricultural productivity, reducing individual diversification opportunities. Our research has significant implications for the in situ climate adaptation literature, socio-environmental research methodologies, and climate change adaptation policy.

In regard to the literature, our research finds that the largest livelihood impacts come from heat stress, which is predicted to only become worse in Sub-Saharan Africa as a result of global climate change (Teixeira et al. 2013). We also provide empirical evidence for several patterns that have been proposed in the literature, including different livelihood responses based on the length of climate anomalies (Senaka Arachchi 1998) and divergent processes for household and individual livelihood diversification (Scoones and Toulmin 1998; Ellis 2000). The findings from our research also highlight the value of considering both on-farm and off-farm smallholder livelihood strategies within the same context. By examining both elements of in situ adaptation, along with crop productivity, we are able to gain an improved understanding of the complex processes through which households adapt to climate stress.

Based on our observations, we argue that the methodological approach we employ has the potential to be used to more effectively examine climate-driven livelihood diversification across a range of contexts. We found significant differences between responses to short term climate anomalies and extended periods of climate stress, suggesting that it is important to examine the long term, as well as instantaneous, effects of heat and drought. Future studies should also consider examining the impacts of heat stress rather than concentrating solely on drought as the limiting factor for agricultural production, as we found that heat had a particularly strong influence on smallholder livelihoods.

The findings from our research have important policy implications. We find that farmers are fairly adept at coping with short term heat stress and drought using on-farm agricultural intensification strategies and, to some extent, individual livelihood diversification. However, in the long run agricultural production declines, even with these strategies in place, and households appear to lose the resources necessary to diversify their livelihoods. Heat stress is increasing in Sub-Saharan Africa and smallholders do not appear to currently be equipped to adapt to long term heat stress and increased spatial and temporal rainfall variability. Policy initiatives are needed to successfully introduce drought and heat resistant crops, in order to reduce the need for labor during periods of extended climate stress. Further, it is likely to be necessary that smallholders have greater access to off-farm livelihood strategies, in order that they have a source of income to turn to during poor agricultural seasons.

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Tables

Table 4.1 Descriptive statistics for on-farm and off-farm livelihood diversification

	N	Mean	St. Dev.	Min	Max	Description
Household Characteristics (household-year)						
Household livelihood diversification	1314	0.69	0.46	0	1	0=Primary and secondary sources of household income are on-farm, 1=Either primary or secondary source of household income is off-farm
Female headed household	1314	0.22	0.41	0	1	1=Female headed household, 0=Male headed household
Age of head of household	1314	45.82	14.70	15	105	Age of head of household
Formally educated head of household	1314	0.83	0.38	0	1	1=Head of household has formal education, 0=Head is not formally educated
Household size	1314	6.27	3.05	1	26	Number of people in the household
Distance to market	1314	3.70	3.74	0	40.23	Distance to the nearest market (km)
Secure land tenure	1314	0.33	0.47	0	1	1=Freehold or leasehold land tenure (more secure), 0=Customary land tenure (less secure)
Household Asset Value	1314	5,395	10,199	49	87,634	Total value of household assets (USD)
Individual Characteristics (person-year)						
Individual livelihood diversification	2703	0.72	0.45	0	1	0=Primary and secondary activities are on-farm, 1=Either primary or secondary activity is off-farm
Female	2703	0.54	0.50	0	1	1=Female, 0=Male
Age	2703	39.66	15.00	18	105	Age of individual
Plot Characteristics (plot-year)						
Distance from plot to home	2703	0.27	0.35	5.95E-04	4.70	Distance from the plot to the homestead (km)
Area of plot(ha)	2703	0.34	0.56	5.50E-04	15.40	Area of a plot
Perceived soil fertility	2703	2.00	0.39	1.00	3	Perceived soil fertility as assessed by respondent on a scale where 1=poor, 2=average, 3=good
Measured soil fertility index	2703	5.23	1.74	0	10	Plot level soil fertility index derived from PCA of measured soil characteristics
Climate Factors (community-year)						

Average monthly precipitation, 1981-2013	122	103.84	13.12	75.59	135.55	Average monthly precipitation, 1981-2013 (mm)
Average monthly temperature, 1981-2013	122	22.09	2.40	16.57	25.93	Average monthly temperature, 1981-2013 (C)
Z-Score of Precipitation (1 year lag)	122	0.86	0.68	-1.35	2.08	Z-score of 12 mo precipitation average relative to 1981-2013
Z-Score of Temperature (1 year lag)	122	0.37	0.09	0.03	0.60	Z-score of 12 mo temperature average relative to 1981-2013
Z-Score of Precipitation (10 year lag)	122	0.18	0.28	-0.75	0.65	Z-score of 120 mo precipitation average relative to 1981-2013
Z-Score of Temperature (10 year lag)	122	0.18	0.05	0.07	0.32	Z-score of 120 mo temperature average relative to 1981-2013
Management Strategies (plot-year)						
Applied organic fertilizer	2703	0.16	0.36	0	1	1=Applied any organic fertilizer, 0=Did not apply any organic fertilizer
Total hours of labor	2703	543	1,853	0	56,448	Total hours of labor applied to a given plot in a year by family and non-family/hired labor
Number of crops planted	2703	3.08	2.25	1	18	Total number of distinct crops planted over the course of the year
Plot Productivity Outcomes (plot-year)						
Kilograms of crops produced per hectare	2703	9,305	68,829	0	2909091	Total kilograms of crops produced per hectare
Monetary value of crops produced per hectare	2703	1,027	2,628	0	28853	Total monetary value of crops produced per hectare

Table 4.2 Results from the analysis of on-farm livelihood diversification

	Number of crops planted (Incidence Rate Ratios)	Applied organic fertilizer (Odds Ratios)	ln(Total Hours of Labor) (Raw Coefficients)
Short Term Climate Variability			
Z-Score of Precipitation (1 year lag)	0.977	1.273	-0.238***
Z-Score of Temperature (1 year lag) x 100	1.017***	1.042**	-0.002
Household Characteristics			
Age of head of household	1.001+	1.001	0.003
Female headed household	0.997	1.121	-0.083

Head of household has formal education	1.014	1.376+	-0.008
Head of household has participated in technical training	0.992	0.879	-0.003
Household size	0.998	1.085**	0.027**
ln(Household Asset Value)(USD)	1.000	1.048	-0.068*
ln(Distance to market)(km)	1.001	0.926	0.060+
Plot Characteristics			
ln(Distance from plot to home)	0.970***	0.587***	0.056***
ln(Area of plot)(ha)	1.055***	1.223*	0.355***
Perceived soil fertility	0.979	1.056	-0.010
Measured soil fertility index	1.016*	0.969	0.034+
Average monthly precipitation, 1981-2013 (mm)	1.002	0.997	-0.001
Average monthly temperature, 1981-2013 (C)	0.995	0.867	0.000
Year (2013)	1.671***	12.907***	-0.472+
Observations	2,681	2,659	2,629
R-squared			0.356
Long Term Climate Variability			
Z-Score of Precipitation (10 year lag)	0.890**	1.460	-0.171
Z-Score of Temperature (10 year lag) x 100	0.974**	0.856**	0.090***

Standard errors are robust and clustered at the community level

*** p<0.001, ** p<0.01, * p<0.05, + p<0.1

District fixed effects, crop type fixed effects, and constants included but not shown

Base category for year is 2003

Table 4.3 Results from the analysis of off-farm livelihood diversification

	Household Level	Individual Level
Short Term Climate Variability		
Z-Score of Precipitation (1 year lag)	0.896	1.299+
Z-Score of Temperature (1 year lag) x 100	0.973*	1.043**

Individual Characteristics		
Female		0.855*
Age		0.995
Household Characteristics		
Female headed household	0.948	1.264
Age of head of household	0.991+	0.993
Formally educated head of household	1.409+	1.083
Household size	0.955*	1.070**
ln(Distance to market)(km)	0.782*	0.651***
Secure land tenure	1.117	1.226
ln(Household Asset Value)(USD)	0.846**	1.111
Environmental Characteristics		
Area-weighted Perceived Soil Fertility	0.972	0.925
Area-weighted Measured Soil Fertility Index	0.972	0.981
Average monthly precipitation, 1981-2013 (mm)	1.006	1.022*
Average monthly temperature, 1981-2013 (C)	0.941	1.004
Year (2013)	0.934	0.993
Observations	1,317	2,805
Long Term Climate Variability		
Z-Score of Precipitation (10 year lag)	1.533	1.920*
Z-Score of Temperature (10 year lag) x 100	0.975	0.799***

Standard errors are robust and clustered at the community level

*** p<0.001, ** p<0.01, * p<0.05, + p<0.1

District fixed effects, crop type fixed effects, and constants included but not shown

Base category for year is 2003

Table 4.4 Results from the analysis of plot productivity

	ln(Kilograms of crops produced/ha)		ln(Monetary value of crops produced/ha)(USD)	
	Without management choices	With management choices	Without management choices	With management choices
Short Term Climate Variability				
Z-Score of Precipitation (1 year lag)	0.142*	0.220**	0.035	0.132*
Z-Score of Temperature (1 year lag) x 100	0.003	-0.003	0.019***	0.016**
Household Characteristics				
Age of head of household	0.001	-0.001	-0.002	-0.003
Female headed household	-0.143+	-0.073	-0.150*	-0.073
Head of household has formal education	0.007	-0.005	-0.053	-0.048
Head of household has participated in technical training	-0.019	0.004	0.079	0.110+
Household size	0.011	0.002	0.005	-0.008
ln(Household Asset Value)(USD)	0.136***	0.168***	0.096***	0.135***
ln(Distance to market)(km)	0.025	0.006	-0.007	-0.043
Plot Characteristics				
ln(Distance from plot to home)(km)	0.045	0.049	0.063*	0.042
ln(Area of plot)(ha)	-0.653***	-0.785***	-0.639***	-0.806***
Perceived soil fertility	0.278***	0.306***	0.333***	0.347***
Measured soil fertility index	-0.035	-0.056+	-0.015	-0.03
Average monthly precipitation, 1981-2013 (mm)	-0.018**	-0.017**	-0.014*	-0.013*
Average monthly temperature, 1981-2013 (C)	-0.173**	-0.164**	-0.123*	-0.106*
Management Choices				
Applied organic fertilizer		0.156		0.254**
ln(Total hours of labor)		0.321***		0.491***
Number of crops planted		0.183***		0.009

Year (2013)	0.539*	0.44	2.035***	2.028***
Observations	2,442	2,377	2,442	2,377
R-squared	0.366	0.407	0.408	0.484
Long Term Climate Variability				
Z-Score of Precipitation (10 year lag)	0.091	0.131	0.132	0.169
Z-Score of Temperature (10 year lag) x 100	0.01	-0.008	-0.031	-0.067**

Standard errors are robust and clustered at the community level

*** $p<0.001$, ** $p<0.01$, * $p<0.05$, + $p<0.1$

District fixed effects, crop type fixed effects, fallow fixed effects, and constants included but not shown

Base category for year is 2003

CHAPTER 5: CONCLUSIONS

Conclusions

This dissertation set out to examine the interactions between environmental change and smallholder livelihoods in rural Uganda. Each of the three substantive chapters explored a different key dimension of this relationship. The second chapter was focused on soil fertility, a major component of agricultural productivity regardless of other environmental factors. This chapter interrogated the relationship between perceived and measured soil fertility, finding that both farmers' perceptions and laboratory measures can offer useful contributions to a holistic understanding of soil fertility. These results will hopefully provide some resolution to the lengthy debate in the literature between those who argue for 'indigenous knowledge' and the value of perceptions and those who counter-argue that laboratory measures of chemical components and texture are a much more accurate way to assess soil fertility (Gray & Morant, 2003; Karltun, Lemenih, & Tolera, 2013; Maconachie, 2012). This perspective informs both the third and fourth chapters, wherein soil fertility is operationalized through both perceptions and laboratory measures.

Building on the findings from the second chapter, the third and fourth chapters focus on smallholder adaptation to environmental change, both through ex situ (e.g. migration) and in situ (e.g. livelihood diversification) responses. The third chapter specifically examines the effect of environmental factors on migration flows in Uganda. Though there is a large body of research addressing environmental migration (Gray & Mueller, 2012; Halliday, 2006; Henry, Schoumaker, & Beauchemin, 2004; Munshi, 2003, there is as of yet a lack of consensus as to which environmental factors have the strongest influence in driving (or hampering) migration. This research contributes to the literature by shedding some light on how both endogenous factors (e.g. soil fertility, forest cover) and exogenous factors (e.g. climate anomalies) are shaping temporary and permanent migration. From the findings, it is clear that exogenous climate factors, and in particular heat anomalies, are the most important environmental shapers of temporary and permanent migration, largely through an agricultural pathway. This research also reveals that this migration process is gendered, with short term heat anomalies hampering male temporary migration and long periods of heat stress pressing men into permanent migration.

The fourth chapter delves into in situ adaptation to climate anomalies, addressing both on-farm and off-farm livelihood responses. As in the case of the third chapter, heat stress is exposed as the most important driver of both shifts in on-farm agricultural strategies as well as off-farm livelihood diversification. To be more specific, smallholders are able to cope with short term heat stress by coupling off-farm livelihood diversification with strategic on-farm agricultural choices that stabilize agricultural production. In the long run, however, extended periods of heat stress cannot be managed through agricultural adaptation and with reduced agricultural productivity, opportunities for income generation through off-farm livelihood diversification are likewise diminished.

Several important broad observations emerge from synthesizing the components of this dissertation. First, environmental factors, both endogenous and exogenous, play a critical role in shaping both ex situ and in situ livelihood strategies. Though they were examined in separate chapters, it is clear that the lack of effectiveness of in situ adaptation strategies after long periods of heat stress seen in the fourth chapter is likely a mechanism for the heat-induced permanent migration we observe in the third chapter. This finding emphasizes the value of examining the full constellation of adaptation strategies in concert with one another. From a policy standpoint, this research suggests that improving in situ livelihood adaptation opportunities is likely to in turn reduce environmentally induced migration.

Second, this research finds that heat stress is the most important environmental factor driving both migration and in situ livelihood strategies. Though other researchers have recently argued that heat stress is likely to be the most socially and environmentally damaging aspect of climate change (Carleton & Hsiang, 2016), few previous empirical studies have examined this, especially in regard to in situ livelihood strategies. This research suggests that more work needs to be done exploring the ramifications of heat stress in particular on smallholder livelihoods.

Third, it is apparent from the third and fourth dissertation chapters that the length of climate stress is an important element informing livelihood choices. Few current studies adequately explore this avenue, especially in regard to in situ livelihood strategies. Fourth and finally, we observe throughout the three substantive chapters that smallholders have conventional, and effective, ways to assess environmental conditions and handle short term environmental stress. However, in this current era of global environmental change, it is important to consider that these conventional approaches may no longer be sufficient to sustainably maintain smallholders' rural livelihoods.

In addition to these substantive observations, this dissertation has provided me with an opportunity to learn about the pitfalls of data collection and management, and to develop some ideas on how to improve data collection for a future wave of this project. One of my biggest takeaways from using these data is that retrospective questionnaires are hard to fill out, especially when they involve questions about income or crop production a year or more ago. To elicit a more accurate response, it could be useful to ask about a typical week of income during a rainy season and a typical week of income during a dry season, or in some other way attempt to make the question a little bit simpler to answer. Another challenge of these data was spatially matching together the plots in 2003 with the plots in 2013, in order to compare soil fertility. To simplify this process, survey enumerators could use a GPS unit to pinpoint the actual location of the plot on the ground during data collection, ensuring that they are collecting soil samples from the same location.

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APPENDIX A: SOIL SAMPLING AND ANALYSIS

Sampling protocol:

In both waves of the survey, soil sampling followed the same protocol. In each plot, twelve to fifteen sub-samples were collected from each plot, with sampling distributed across the plot in an attempt to represent the overall plot condition. Enumerators did not collect samples from within two meters of the edge of the plot, to avoid contamination with nonagricultural soil or soil from another plot. Further, enumerators were instructed to avoid termite mounds or other areas that are within the plot but do not appear to be typical of the soil within the plot. Enumerators collected each sub-sample using a soil probe, inserted in the soil up to the 20-centimeter mark. In cases where the soil was too dry and hard, or gravely/stony, enumerators used a hoe or shovel to dig down to 20 centimeters. The enumerators were then instructed to take a slice of soil from the shovel down, in approximation of the soil core achieved with the soil probe. Once these sub-samples were collected, they were mixed together in a bucket and a representative 500-gram sample was isolated for laboratory drying, grinding, and chemical and textural analysis.

Analysis protocol:

Before laboratory analysis, soil samples were first air dried, ground, and then passed through a 2 millimeter sieve. For all tests, reference samples were run every 20 samples for calibration. No samples were run in duplicate. In both 2003 and 2013, soil pH was determined in a 2.5:1 water to soil suspension, with the pH measured in the soil suspension after a 30-minute equilibration time (Okalebo et al., 2002). In both 2003 and 2013, soil texture was determined by the hydrometer method (Bouyoucos, 1936) after destruction of organic matter with hydrogen peroxide and dispersion with sodium hexametaphosphate (Okalebo et al., 2002). In 2003, soil organic carbon was determined by wet oxidation with sulfuric acid and potassium dichromate (Walkley and

Black, 1934). In 2013, however, organic carbon was calculated using the colorimetric method, as described by Okalebo and colleagues (2002). While these two methods are not identical, previous research has found a 95% correlation between organic carbon values determined by these two methods on identical soil samples (Sato et al., 2014). Values determined colorimetrically may be marginally higher and have a wider standard deviation than those determined using the Walkley-Black method. In both years, organic carbon was converted to organic matter by multiplication of a factor of 1.73. In both 2003 and 2013, total N and total P were determined colorimetrically by Kjeldahl digestion with concentrated sulphuric acid (Okalebo et al., 2002). For the soil samples collected in 2003, exchangeable K, Ca, and Mg were extracted by a single extraction with ammonium lactate buffered at pH 3.8 (Foster, 1971). In contrast, for the soil samples collected in 2013, exchangeable K was extracted by a single extraction with Mehlich-3 extracting solution buffered at pH 2.5 (Mehlich, 1984).

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APPENDIX B: GPS DATA

In both 2003 and 2013, enumerators captured global positioning satellite (GPS) points at the vertices for each plot for which a single plot survey was conducted. Enumerators also collected GPS points at the locations of the primary dwelling for each household. After collection, ArcGIS was used to clean and manage these spatial data. First the plot vertices were converted to plot polygons using the point-to-line tool and a Python script was written to convert lines into polygons. These polygons were then used to calculate the area within each plot. Spatially-weighted centroids were also generated for each plot using these plot polygons. Centroids were used in conjunction with the household location points to generate the distance from a given plot to its household.

APPENDIX C: ATTRITION

Attrition from the original household sample was 14% between 2003 and 2013. Attrition was not evenly distributed across districts. In Kapchorwa, for instance, all households from the original survey were contacted in 2013. In Mbarara, alternatively, enumerators did not manage to visit 52 of the original sample, and of those visited, one household was unable or unwilling to participate in the follow-up. Most attrition is an artifact of the enumerators not visiting a given household rather than the household being absent or refusing to participate in the survey (Table C1).

Although it is unlikely that these differences are the reason households are absent from the follow-up, since most of the missing households were never contacted, there are some significant differences between households that were tracked and households. Most of this may have to do with the nonrandom missingness of these responses, since most of the households not contacted were located in Mbarara district. Attrited households have significantly higher fertility perception, organic matter percentage, total nitrogen, total phosphorus, available potassium, total clay, total silt, crop value, and distance to local market than tracked households. They also have significantly lower pH, total sand, age of head of household, household size, and plot size (Table C2).

Table C1: Attrition from original household sample

District	Tracked	Attrited			Total	Attrition
		Total	Did Not Visit	No Response		
Masaka	125	13	12	1	138	9.4%
Iganga	105	7	4	3	112	6.3%
Kapchorwa	55	0	0	0	55	0%
Soroti	63	7	5	2	70	10%
Arua	105	6	5	1	111	5.4%
Lira	97	16	15	1	113	14.2%
Kabale	92	20	18	2	112	17.9%

Mbarara	85	53	52	1	138	38.4%
Total	727	122	111	11	849	14.4%

Table C2: Differences between tracked and attrited households

	Tracked		Attrited		
	Mean	SD	Mean	SD	T-Test
Fertility Perception	2.00	0.50	2.07	0.49	*
pH	6.11	0.56	5.99	0.76	**
Organic Matter (%)	5.72	3.30	7.78	3.98	***
Total Nitrogen (ppt)	2.00	1.65	2.64	1.62	**
Total Phosphorus (ppt)	0.95	0.88	1.19	1.34	**
Available Potassium (ppm)	0.29	0.29	0.35	0.34	**
Sand (%)	62.77	14.87	55.61	14.28	***
Clay (%)	24.93	10.29	26.95	7.95	***
Silt (%)	12.32	7.99	17.47	10.45	***
Age of Head of HH	42.52	13.14	39.69	13.24	***
Male Head of HH	0.82	0.38	0.80	0.40	
Formally Educated Head of HH	0.82	0.38	0.82	0.39	
Accessed Agricultural Training	0.30	0.46	0.32	0.47	
Household Size	6.28	2.83	5.52	2.74	***
Agriculture primary income source	0.63	0.48	0.63	0.48	
Asset Value (USD[1])	3749.86	6492.51	4059.12	5919.51	
Livestock Value (USD[1])	499.98	1468.38	516.72	1502.11	
Distance to Local Market (km)	5.06	0.12	6.91	0.32	***
Crop Value per Ha (USD[1]/ha)	549.72	2007.08	1045.65	2167.51	***
Plot Size (ha)	0.50	1.14	0.38	1.18	+
Observations	727		122		

*** p<0.001, ** p<0.01, * p<0.05, + p<0.1

[1] All USD values are adjusted for inflation and calculated based on 2013 average exchange rates

APPENDIX D: SPATIAL MATCHING

In order to compare soil laboratory measures and single plot survey data from 2003 with these data from 2013, it is important to ascertain that the plots are the same in both years. Plots are defined by land usage. A plot may contain a single cropping system or may include mixed cropping. Only agricultural (cropped or temporarily fallowed) plots were surveyed and sampled for soil laboratory testing during the single plot survey. Since land usage may have shifted drastically over the decade between 2003 and 2013, it was not sufficient to ask farmers about current and past cropping in order to match plots. Therefore, plots were matched using the polygons created from the GPS vertices collected by the enumerators.

The matching process involved both visual observation of overlap and similarities in plot shape and size as well as use of the intersection tool in ArcGIS to create a percentage overlap value for both 2003 and 2013. Using both 2003 and 2013 overlap values as controls is important, for example, in the circumstance where a plot from 2003 is fully surrounded by a plot from 2013. The plot from 2003 would have a 100% match with the plot from expanded plot in 2013, but from the perspective of the plot from 2013, the plot from 2003 would only capture a small percentage of the total area. Controlling for these differences in overlap adjusts for these shifts.

As the general shape and size of a plot may have shifted over time, all plots from 2003 that overlap with one or more plots from 2013 (and, likewise, plots from 2013 that overlap with one or more plots from 2003) are matched one to many with all of the plots with which they overlap. Those plots which do not have a spatial match in the alternative year are not included in the longitudinal (restricted) analyses conducted using these data, although they are used when the full sample is employed with a year fixed effect.

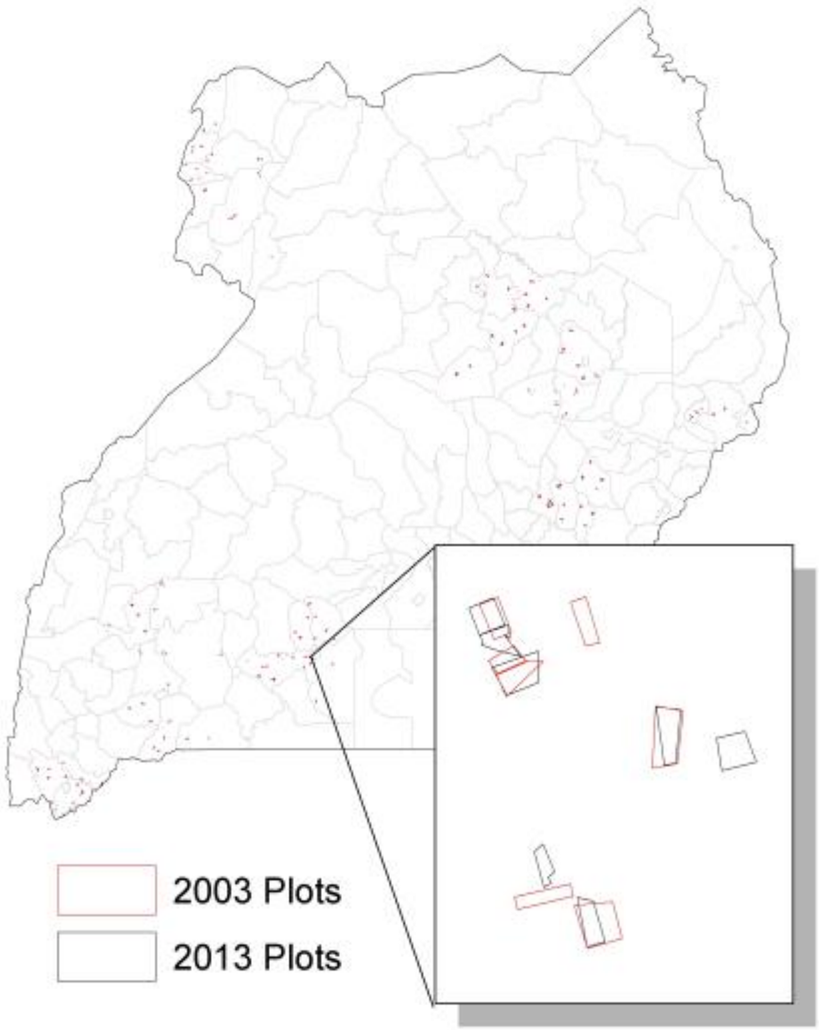

Figure D1: Example of plot matching of plot polygons

APPENDIX E: FULL AND RESTRICTED SAMPLE

Table E1: Summary statistics for full and restricted sample

	2003					2013				
	Full		Restricted		T-Test	Full		Restricted		T-Test
	Mean	SD	Mean	SD		Mean	SD	Mean	SD	
Fertility Perception	2.01	0.5	1.96	0.47	*	2.02	0.43	1.98	0.42	+
Perception of Soil Quality Change						1.46	0.69	1.39	0.65	*
pH	6.09	0.6	6.17	0.49	***	6.05	0.6	6.09	0.6	
Organic Matter (%)	6.04	3.5	5.5	2.65	***	5.64	3.12	6.04	3.11	**
Total Nitrogen (ppt)	2.1	1.66	1.95	1.42	**	2.48	1.05	2.6	1.03	**
Total Phosphorus (ppt)	0.99	0.97	0.92	0.97	*	0.72	0.86	0.74	0.77	
Available Potassium (ppm)	0.3	0.3	0.29	0.25		0.26	0.33	0.29	0.34	*
Sand (%)	61.63	15	62.7	13.47	+	55.98	15.73	54.57	15.93	+
Clay (%)	25.25	9.99	25.22	9.45		29.96	10.61	30.61	10.11	
Silt (%)	13.13	8.63	12.08	7.57	**	14.07	9.92	14.82	10.54	
Topsoil Depth (cm)	2.58	1.16	2.57	1.18		2.22	1.09	2.23	1.15	
Age of Head of HH	42.07	13.19	42.91	12.87		50.58	13.46	50.66	12.73	
Male Head of HH	0.82	0.38	0.83	0.37		0.74	0.44	0.76	0.43	
Formally Educated Head of HH	0.82	0.38	0.83	0.38		0.83	0.37	0.85	0.36	
Accessed Agricultural Training	0.31	0.46	0.29	0.45		0.32	0.46	0.31	0.46	
Household Size	6.17	2.86	6.57	2.85	***	6.78	3.25	6.84	3.23	
Agriculture primary income source	0.63	0.48	0.61	0.49		0.76	0.43	0.77	0.42	
Asset Value (USD[1])[2]	1,760	6,405	1,940	6,413		4,033	29,947	4,258	25,414	
Livestock Value (USD[1])[2]	115	1,473	132	717	*	248	4,082	220	4,231	
Distance to All-Weather Road (km)	2.24	2.84	1.92	2.62	**	4.81	8.83	3.92	7.43	*
Distance to Local Market (km)	3.33	3.16	2.86	2.67	***	4.26	4.18	4.32	4	
Distance from HH to Plot (km)	0.25	0.33	0.21	0.28	**	0.29	0.4	0.23	0.28	***
Crop Value per Ha (USD[1]/ha)[2]	179	2,041	210	1,887	***	600	20,713	574	23,739	+
Plot Size (ha)	0.48	1.15	0.59	0.95	*	0.29	0.38	0.33	0.44	+
Precipitation (mm)	120	18	119	17		121	16	118	17	**
Slope (%)	8.8	6.75	7.75	5.74	***	7.33	5.69	7.74	5.74	
Rill Erosion	0.34	0.47	0.36	0.48		0.38	0.49	0.39	0.49	
Sheet Erosion	0.4	0.49	0.42	0.49		0.46	0.5	0.46	0.5	
Legumes grown	0.41	0.49	0.47	0.5	*	0.43	0.49	0.43	0.5	

Cereals grown	0.4	0.49	0.47	0.5	***	0.53	0.5	0.5	0.5	
Tubers grown	0.35	0.48	0.42	0.49	**	0.32	0.47	0.31	0.46	
Banana grown	0.24	0.43	0.3	0.46	**	0.19	0.39	0.25	0.44	**
Exports grown	0.15	0.36	0.23	0.42	***	0.14	0.35	0.19	0.39	*
Observations	1,987		715			1,389		715		

*** p<0.001, ** p<0.01, * p<0.05, + p<0.1

[1] All USD values are adjusted for inflation and calculated based on 2013 average exchange rates

[2] Reporting median rather than mean, as distributions are highly right-skewed

APPENDIX F: STUDY COMMUNITY LOCATIONS

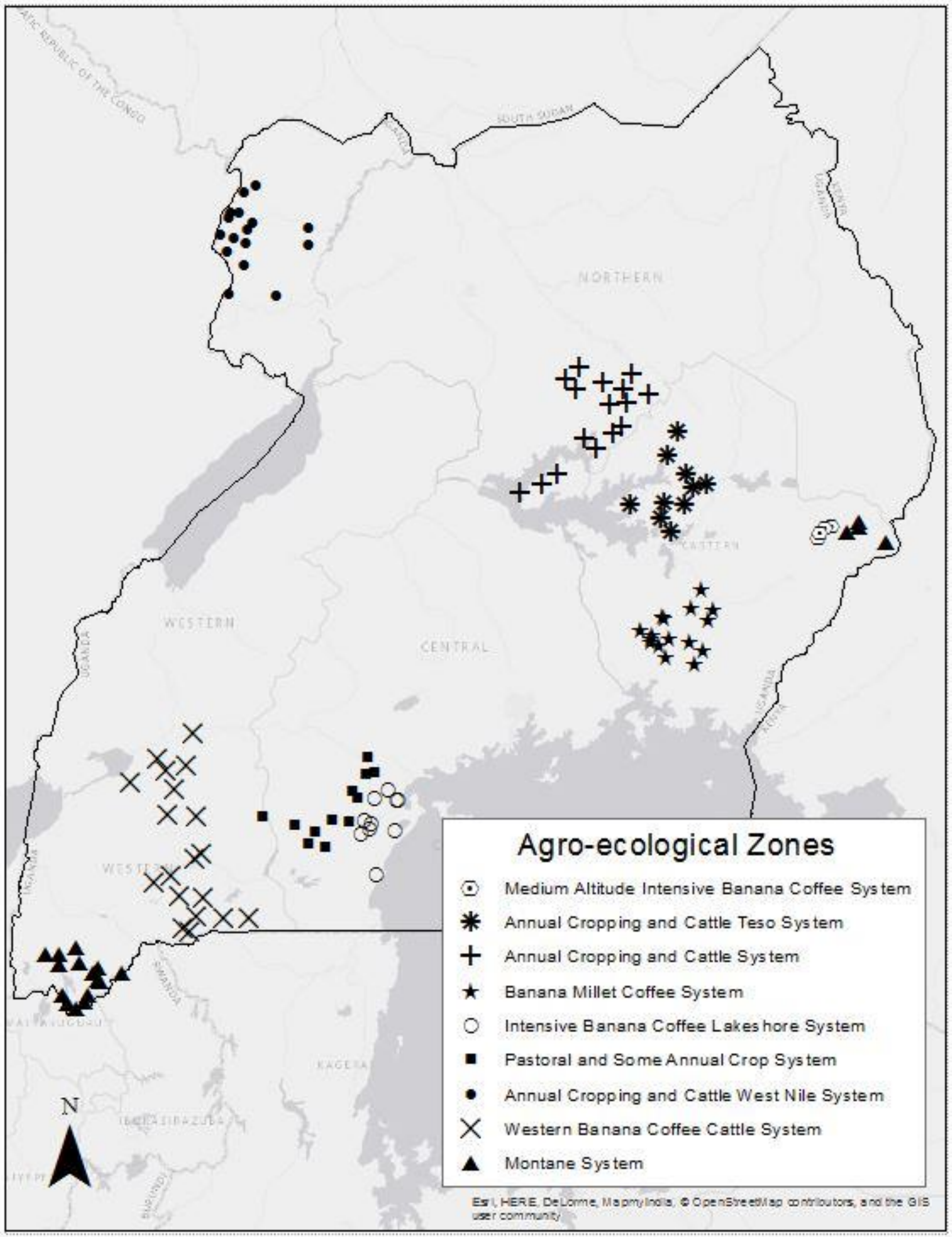

Figure F1 Map showing study community locations within nine distinct agro-ecological (cropping regime) zones