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# Climate anomalies, land degradation and rural out-migration in Uganda

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## Abstract

Globally, rural livelihoods are increasingly challenged by the dual threats of land degradation and climate change. These issues are of particular concern in sub-Saharan Africa, where land degradation is believed to be severe and where climate change will bring higher temperatures and shifts in rainfall. To date, however, we know little about the relative effects of these various potential environmental stressors on migration. To examine these processes, we link longitudinal data from 850 Ugandan households with environmental data on soils, forests, and climate, and then analyze these data using approaches that account for potential spatial and temporal confounders. Our findings reveal that climate anomalies, rather than land degradation, are the primary contributor to environmental migration in Uganda, with heat stress of particular importance. Short hot spells increase temporary migration, an element of a diversified household livelihood strategy, while long-term heat stress induces permanent migration through an agricultural livelihoods pathway.

### Keywords

Migration; climate; soil degradation; deforestation; rural livelihoods; Africa

## Introduction

Smallholding agricultural households in many low and middle-income countries are increasingly challenged by the combined pressures of environmental degradation and global climate change (Morton 2007). Soil degradation hampers the capacity of smallholders to increase crop productivity (Nkonya et al. 2008) while deforestation limits opportunities to harvest forest products (Jagger 2012). High temperatures and shifts in rainfall regimes, in turn, increase the probability of crop failure (Fischer et al. 2005). In response to these suboptimal environmental conditions, researchers have found that smallholder households often diversify their livelihood strategies into a portfolio that includes local non-farm wage labor as well as migration (Hunter et al. 2015a).

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A number of studies have found that the environment exerts an important influence on human mobility, but the environmental migration picture revealed so far through this research is complex and multidimensional, exhibiting heterogeneity across environmental influences (Bohra-mishra et al. 2014; Nawrotzki et al. 2017; Lu et al. 2016); national and local contexts (Gray and Wise 2016; Nawrotzki and Bakhtsiyaravaa 2017); migration distances, purposes, and durations (Gray 2009, 2011; Massey et al. 2010); and migrant socioeconomic and demographic backgrounds (Hunter et al. 2014; Thiede and Gray 2017). The diversity of social and environmental data sources and methodological approaches employed throughout this scholarship is a strength, as it has allowed researchers to examine mobility at a multitude of spatial and temporal scales. However, it also intensifies the challenge of developing a synthetic understanding of environmental migration. In spite of the rapid growth of the environmental migration literature, we still know little about the relative importance of various potential environmental influences on migration and how migration outcomes may vary by the amount of time households spend under environmental stress (Jónsson 2010; Neumann & Hermans 2015).

Responding to these unresolved questions, this study examines the effects of multiple potential environmental influences on temporary and permanent migration in rural Uganda. To do so, we link longitudinal (2003, 2013) data from 850 households across Uganda with high-resolution data on climate variability (temperature, precipitation) and land quality (soil fertility, forest cover). We then use multivariate approaches to examine the environmental predictors of both temporary and permanent moves (defined as short and long-term departures from the household) while controlling for potential socio-demographic and regional confounders. We find that climate stress appears to be the major environmental influence on migration in rural Uganda. A decade of high rainfall is associated with a high probability of temporary migration whereas annual heat shocks are associated with an increase in temporary migration, suggesting that households engage in temporary migration as part of a diversified livelihood strategy. Extended periods of above-average temperatures increase permanent out-migration, however, indicating that smallholder households may eventually be pushed to send permanent migrants. Our study suggests that rising temperatures may be the most threatening aspect of environmental change to rural Ugandans and that these effects are likely transmitted through an agricultural livelihoods pathway.

## Background

### Conceptual framework

Our central goal is to understand migration decision-making in a context where multiple, interrelated forms of environmental change are occurring, specifically climate variability and multiple forms of land degradation. These forms of environmental change are not independent, with deforestation contributing to climate change at regional to global scales and climate change potentially contributing to land degradation at a local scale, but here we focus on the human side of this human-environment system. To conceptualize these processes, we draw on Gray's (2009) environmental-risk, environmental-amenity and environmental-capital hypotheses, originally formulated to understand migration in an environmentally marginal area of the Ecuadorian Andes. We describe the hypotheses briefly here and motivate them below. The environmental risk hypothesis (H1) predicts that households exposed to environmental variability will send migrants as a coping mechanism to recent shocks as well as a form of insurance against future shocks. Closely related is the environmental amenity hypothesis (H2), which focuses on time-stable characteristics and predicts that households with access to environmental capital will retain migrants while adverse environmental characteristics will serve as a push factor for migration. In contrast to the first two hypotheses, the environmental capital hypothesis (H3) predicts that adverse environmental conditions (time-stable or time-varying) will reduce outmigration by undermining the resources needed for migration. Finally, we build on Gray's (2009) original test of these hypotheses by carefully decomposing migration into its constituent streams (here, temporary versus permanent), and testing whether environmental influences on migration vary across these streams. We refer to this as the stream heterogeneity hypothesis (H4).

The environmental risk hypothesis (H1) draws directly on the New Economics of Labor Migration framework, in which migration is viewed as an investment in future migrant remittances that are likely to be uncorrelated with origin-area environmental shocks (Stark and Bloom 1985), as well as on a large literature on exposure to environmental hazards, in which migration is a commonly-observed coping strategy (Hunter et al. 2015). Applied to this study, the hypothesis predicts that exposure to hot and dry climate anomalies will increase migrant departures. Similarly, the environmental amenity hypothesis (H2) draws on long-standing push-pull theories of migration (Lee 1966), as well as newer research showing how environmental amenities can retain and attract migrants in various contexts (Gutmann et al. 2005; Chi and Marcouiller 2011). Interpreted in our context, this hypothesis predicts that forest cover and soil quality will act to retain migrants, given that these attributes are key elements of rural livelihoods. The distinction made in Hypotheses 1 and 2 between time-varying versus time-stable characteristics also motivates us to examine both short and long-term climate anomalies, with the latter more closely approximating time-stable characteristics.

In contrast, the environmental capital hypothesis (H3) draws on a broad literature describing the many barriers to migration in low and middle income countries. Migrants incur costs in transportation, destination housing and the search for employment that can be large relative to the income of the sending household (Bryan and Morten 2019), and migrants often also need access to non-financial resources such as migrant networks (Massey and Espinosa 1997). The existence of these micro-level barriers is consistent with macro-level theories of migration transitions, in which societies evolve towards higher mobility as the human, social and financial resources that enable these moves accumulate (Skeldon 2012). Environmental shocks and disamenities thus might undermine the ability of households to send migrants and thereby create a mobility trap (Black et al. 2011b). In our study context, low forest cover, poor soil quality, and hot/dry conditions would be predicted to reduce migration under this hypothesis. When the costs of migration (economic and social) are high relative to household resources, we would expect this hypothesis to be supported in place of Hypothesis 1 and Hypothesis 2.

An additional core element of our conceptual framework is the recognition that migration encompasses a diversity of movements distinguished by duration and motivation as well as by characteristics of the migrant (Gray 2009; Gray & Bilsborrow 2013), motivating the stream heterogeneity hypothesis (H4). We distinguish these streams by duration (short versus long-term) and motivation (labor-related versus non-labor related), building on common classifications used in the literature and relevant to our study area. These distinctions between migration streams directly connect to the above hypotheses in that the social and financial costs of environmental change as well as the benefits of migration that distinguish Hypotheses 1 and 2 from Hypothesis 3 are a function of the duration, motivation, and composition of migration streams.

## Previous research

Since the publication of Gray (2009), a large literature has developed that uses demographic and econometric methods to test for environmental influences on various types of migration (Borderon et al. 2019; Cattaneo et al.2019; Kaczan & Orgill-Meyer 2020). The majority of this literature has focused on the consequences of climate and natural disasters for long-distance and permanent migration, and it has largely supported the environmental risk hypothesis (H1) (Bohra-Mishra et al. 2014; Mueller et al. 2014; Jennings and Gray 2015; Mastrorillo et al. 2016; Nawrotzki and DeWaard 2016; Bohra-Mishra et al. 2017; Call et al. 2017; Riosmena et al. 2018). Nonetheless, a significant fraction of studies also document trapping processes that are consistent with the environmental capital hypothesis (H3) (Cattaneo and Peri 2016; Nawrotzki and Bakhtsiyarava 2017; Thiede and Gray 2017). Fewer studies have compared these effects across diverse migration streams, and even fewer have examined the consequences of land quality for out-migration, despite an early emphasis on these issues by Henry et al. (2003, 2004). This absence of studies that examine both terrestrial and atmospheric dimensions of environmental change, as well as that address the diversity of population movements, motivates the present study. Below, we discuss in detail the most relevant previous studies that have addressed one or more of these issues.

The potential role of land degradation in migration was addressed early in the development of this literature by Henry et al. (2003), but has since received relatively little attention. Henry et al. (2003) developed a gravity model of province-to-province flows in Burkina Faso using census data, with demographic, climate, agricultural, and soil variables included as predictors, and suggested that soil degradation in the origin increased out-migration. Gray and Bilsborrow (Gray 2010; Gray and Bilsborrow 2013) extended this research to the household level using retrospective migration histories from Ecuador and self-reported soil quality indicators. This research revealed that international migration increased with a land quality index (Gray and Bilsborrow 2013) and decreased with self-reported soil degradation (Gray 2010). Using a similar approach, Massey et al. (2010) found that out-migration from the Chitwan study area in Nepal increased with perceived environmental degradation, with some differences across migration streams. Other recent studies have made use of more sophisticated field measurements of soil quality. Using household panel data from Uganda and Kenya attached to baseline laboratory measurements of soil properties, Gray (2011) found that high soil quality decreased rural out-migration in Kenya but increased it in Uganda. Chen and Mueller (2018) used population registry data from coastal Bangladesh linked to data on soil salinity to show that internal migration increased with salinity, while international migration declined.

Very few previous studies have investigated the consequences of vegetation cover and quality on out-migration. Rindfuss et al. (2007) showed that baseline forest cover reduced outmigration using panel data from Nang Rong, Thailand. Hunter et al. (2014) subsequently showed that temporary migration, but not permanent migration, increased with vegetation greenness in South Africa. Taken together, this small literature on land degradation and migration provides mixed evidence, with some studies supporting the environmental amenity hypothesis (H2), others supporting the environmental capital hypothesis (H3), and some supporting both for different migration streams (and thus also supporting the stream heterogeneity hypothesis, H4). Clearly, more research is needed to address the ongoing global concern that land degradation is displacing populations in low and middle-income countries (van der Geest et al. 2010; Black et al. 2011b; Neumann et al. 2015).

A larger literature has investigated how the effects of climate and weather exposures vary across migration streams. Henry et al. (2004) again led the way, showing that rainfall variability in Burkina Faso increased women's rural-bound migration while decreasing other outwards streams including by women to international destinations and by men to urban destinations. Subsequent studies have also found differing climatic effects across migration streams in Ecuador (Gray 2009; Gray and Bilsborrow 2013), Mexico (Nawrotzki et al. 2016), the historical Netherlands (Jennings and Gray 2015), Ethiopia (Gray and Mueller 2012a), Bangladesh (Gray and Mueller 2012b; Carrico and Donato 2019), Pakistan (Mueller et al. 2014), and Indonesia (Thiede and Gray 2017), among other study sites. In many cases, longer-distance and more costly migration streams are more responsive to climate (Gray and Mueller 2012a; Gray and Bilsborrow 2013; Jennings and Gray 2015; Nawrotzki et al. 2016; Thiede and Gray 2017; Carrico and Donato 2019), but in some cases it is the reverse (Gray 2009; Gray and Mueller 2012b) or there is no clear pattern (Henry et al. 2004; Mueller et al. 2014). Across these studies, adverse climates generally tend to increase migration (Gray and Mueller 2012a; Gray and Mueller 2012b; Mueller et al. 2014; Carrico and Donato 2019), but have also been observed to decrease it (Jennings and Gray 2015; Thiede and Gray 2017) or have mixed effects (Henry et al. 2004; Gray 2009; Gray and Bilsborrow 2013; Nawrotzki et al. 2016). Taken together this literature thus indicates strong support for neither the environmental risk hypothesis (H1) nor the environmental capital hypothesis (H3), but does support the stream heterogeneity hypothesis (H4). A key limitation, however, is that, with the exception of Hunter et al. (2014), none of these studies have investigated temporary migration, which is by far the most common form of mobility in low and middle-income countries (Banerjee and Duflo 2007). Below, we test the four hypotheses for both climate and land degradation as well as for both temporary and permanent migration streams.

Finally, our study builds directly on a previous analysis of the same data sources that examined the consequences of climate anomalies and soil quality for livelihood diversification and agricultural productivity (Call et al. 2019). This analysis revealed that droughts reduced agricultural productivity, and in the long-term also reduced livelihood diversification outside of agriculture. High temperatures could be coped with in the short-term with altered agricultural strategies, but in the long-term led to lower agricultural productivity and reduced opportunities for diversification. Soil fertility was associated with agricultural intensification and thus supported rural livelihoods. These findings motivate our selection of environmental variables, described below, as well as their interpretation.

## The research context

We address these issues using national-scale household-level data from Uganda, a country at the crux of concerns about rural livelihoods, migration, and environmental change. Uganda is highly diverse in regard to agro-ecology, culture, land tenure systems, and market integration, but the country is also united by some key characteristics. 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 much of East Africa, exhibits sub-optimal crop productivity, low rates of economic growth, and high rates of poverty (Pender et al. 2006; Tittonell and Giller 2013; Sheahan and Barrett 2017). Ugandans also continue to depend heavily on natural resource-based livelihoods, with 80% of the population engaged to some extent in rain-fed agriculture, and many people reliant on the harvesting of forests for charcoal, fuelwood, and timber (Uganda Bureau of Statistics 2014).

As a result, Ugandan livelihoods are intrinsically linked with environmental conditions, in particular soil fertility, forest cover, rainfall, and temperature. Considering soil fertility, the soils of Uganda are for the most part highly weathered Oxisols and Ultisols with low nutrient reserves (Palm et al. 2007; Ssali and Vlek 2002). Nutrient balance studies suggest that soil fertility is severely degrading, though African farmers rarely perceive the problem to be extreme (Stoorvogel and Smalling 1990; Mortimore and Harris 2005). Regarding forest cover, deforestation and forest degradation due to agricultural expansion and wood harvesting is prevalent across the country, with an observed 8.5% loss of forest cover between 2002 and 2012 (Hansen et al. 2013). Forests are harvested for charcoal and fuelwood, supplying over 93% of all energy used in Uganda, and this demand was expected to double from 2010 to 2025 (Khundi et al. 2011).

Uganda’s climate is primarily zoned as warm arid or sub-humid tropical, with average temperatures ranging from 15 to 30 degrees Celsius and total annual rainfall ranging from 750 millimeters in the eastern and western regions to 1500 millimeters in the central region of the country (Call et al. 2019). Uganda has one rainy and one dry season in the northern region while the southern region near Lake Victoria has a bimodal rainfall region, with rainy seasons from March to May and September to December (Ronner and Giller 2013). Consistent with the broader region, global climate change is expected to result in increased temperatures and shifts in the spatial and temporal patterning of rainfall regimes across Uganda (Salerno et al. 2019). Increased temperatures will be directly damaging to crops but may also increase the prevalence of harmful weeds and pests. Dry spells and irregular rainy seasons will likely become more common and when the rains do come, they may be heavier than average, resulting in flooding and mudslides (IPCC 2014).

Migration has long been a pervasive feature of Ugandan livelihoods, including temporary, permanent, rural-rural and rural-urban flows. Temporary flows are often motivated by education or seasonal employment in commercial agriculture or urban areas (Black et al.

2006). As part of a multi-dimensional household livelihood strategy, these cyclical migration flows can provide income to rural households while also lessening household food insecurity by decreasing household size (Ellis 2000). Ugandans also engage in permanent migration, much of which is rural to urban. In 2011, the total population growth rate of Uganda was 3.4% while the urban population growth rate was 5.4%, a gap driven primarily by rural-urban migration (Mukwaya et al. 2011). Uganda also has an extensive history of regionally-specific processes of forced household displacement and relocation (Hartter et al. 2015), but these are outside the scope of our inquiry into national-scale patterns of individual departures from households.

## Data and methods

To test the hypotheses above, we follow several steps as described below. First, we use original household and individual-level data to construct measures of migration, soil fertility, and socio-demographic controls. Following this, we use spatial methods to extract monthly community-level measures of temperature and precipitation as well as measures of forest cover from existing gridded datasets. Finally, we utilize logistic regression, multinomial logistic regression, and negative binomial regression to estimate the impact of the climate and environmental predictors on temporary and permanent migration while controlling for potential spatial and temporal confounders.

### Household data collection

The key innovation that enables this research was the creation of a 10-year longitudinal dataset (2003-2013) on Ugandan households and their agricultural soils by the authors and collaborators (Bevis et al. 2017; Call et al. 2019). As described below, this effort faced significant challenges in tracking households and standardizing the soil analysis protocols over time. Despite these challenges, this effort successfully resulted in the creation of the one of the longest-duration household panels in Sub-Saharan Africa (Beegle et al. 2011; Dercon et al. 2012; Kilic et al. 2015), and one of the very few household panels globally that includes attached data on soil parameters (Yamano and Kijima 2010; Carletto et al. 2017).

Household-level 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 from a frame developed by the Uganda Bureau of Statistics (UBOS) for a larger survey, the Uganda National Household Survey, which used a two-stage, clustered random sampling approach (Nkonya et al. 2008). In an effort to represent Uganda's agro-ecological diversity, eight districts (Arua, Iganga, Kabale, Kapchorwa, Lira, Masaka, Mbarara, and Soroti) were selected by judgement from the 56 UBOS sample districts, and then a random sample of 123 rural communities with 851 sample households was sampled among those that participated in UBOS.

In 2013, a team of researchers from IFPRI, NARL, the University of North Carolina, Cornell University, and Purdue University carried out the second wave targeting the same households, who were identified using the name of the household head, the name of the interviewee, and the household's geolocation from 2003. In the 2013 follow-up, interviews were conducted between May and August by regionally-specific teams of enumerators in local languages, targeting the household head or another adult member when the household head was absent. Seven hundred and twenty-seven of the 849 households interviewed in 2003 were successfully re-interviewed. Further, original household members who had formed their own households between rounds were also tracked and interviewed if they were still living within their original parish. This approach allowed us to track agricultural parcels from 2003 to connected households, and also refreshed the sample with younger households. In total, enumerators were able to collect data from 831 households in 2013. Baseline households lost to follow-up were on average younger, smaller, and more isolated than tracked households (Supplementary Material), likely reflecting both household departures as well as remote communities that were ultimately excluded from the follow-up due to budgetary constraints. In both waves, Ugandan enumerators conducted structured interviews, collected geographic coordinates at household, plot, and community locations, and also collected plot-level soil samples for laboratory analysis. The interview data are described below, and the collection and laboratory analysis of the soils data are described in the Supplementary Materials.

## Climate and forest data sources

We link these household data to high-resolution climate and forest cover data using geographic coordinates collected at the community level. Our measures of mean monthly temperature and precipitation rate are extracted 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 kilometers at the Equator) generated through interpolation of data from a network of over 4,000 weather stations worldwide (UEACRU et al. 2013). This product is preferred by climatologists for many applications because it overcomes problems associated with bias and missing data from individual weather stations. CRU data are considered to be an accurate source of climate measures in Africa (Zhang et al. 2013), and 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 (approximately 30 meters at the Equator) (Hansen et al. 2013). Specifically, we draw upon the 2000 and 2010 Landsat reanalysis images, from which we extract the percent tree cover for a one kilometer buffer centered on the community.

## Migration measures

We construct our measures of temporary migration using the household roster, which included a question regarding the number of months that a household member was present during the 12 months prior to the interview date. For members who had been absent for at least one month, the roster includes a categorical question on motivation for absence. We consider household members who were present in the household for fewer than 12 months during the previous year to be temporary migrants, and disaggregate this outcome by motivation (labor and non-labor). Records of permanent migration were collected during the 2013 data collection using a retrospective migration module. Because the 2003 questionnaire did not record the names of all individuals, we use a variant of the approach developed by

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Massey and Zenteno (2000) to record any household members who permanently left the community after 2003 and did not return as reported by the interviewee. We also collected the year of departure, the motivation (as a categorical outcome), and whether the destination was rural or urban. Drawing upon these data, our measure of permanent migration is a count of the total number of migrants sent from a household in a given year, which we then disaggregate by motivation (labor or non-labor) and destination (rural or urban).

We also use the household data to control for household and individual factors previously found to predict mobility (White and Lindstrom 2005). We extract our control variables for permanent migration from the 2003 household data and for temporary migration from the 2003 or 2013 data respectively. Our person-level controls include age, gender, marital status, and whether the individual was a child of the household head, while our household-level controls include household size, distance to the nearest market, land tenure status, asset value, livestock value and the age, gender, and educational level of the household head, derived from values self-reported during the household interview.

## Environmental measures

To measure climate anomalies, we transform precipitation and temperature data from the primary growing season in Uganda into z-scores using 1980-2013 as the reference period. The growing season is defined as February through May, the months during which maize and millet (the most widely cultivated crops) are growing (FAO 2018; Kaizzi 2019). Anomalies are advantageous for measuring exposure to climate change because (1) they are universally relevant (as opposed to climate thresholds which in many locations are never experienced), and (2) they are on average uncorrelated with baseline climate and can thus be treated as natural experiments (Nordkvelle et al. 2017). For temporary migration, we generate z-scores using 12 and 120-month moving averages starting with the month of interview, while for permanent migration we generate yearly 12 and 120 month moving averages starting with 2003 and continuing through 2013. These moving averages are then transformed into z-scores that compare these periods to all other 12 and 120 month periods (respectively) in the climate data, generating both short and long-term measures of deviation from the local historical climate.

More precisely, we follow these steps to construct the 12-month climate anomalies: Using a monthly climate dataset from January 1980 to December 2013, we define a 12-month moving average where the mean of months $t$ to $t-11$ is attached to month $t$. We then take the mean and standard deviation of this moving average over the entire dataset, excluding the first 11 months for which these measures are undefined. We then use this moving average, its mean, and its standard deviation to define a z-score representing the deviation of each 12-month period from the historical average of 12-month periods in that location. To construct the 120-month climate anomalies, the same process is repeated using moving averages over a 120 month period instead of 12. We chose to construct both 12-month (1 year) and 120-month (10 year) measures of climate anomalies in order to test for differences between short term coping and long term adaptation to climate stress, as previous research has indicated that the length of a period of climate stress informs the response (Bohra-mishra et al. 2014; Gray and Wise 2016). In Supplementary Material Section B, we explore alternative measures based on the number of extreme months experienced during the same intervals. Finally, we also extract the mean historical temperature and precipitation rate at each location to include as a control, capturing variation in baseline climate within our districts.

For our measure of forest cover we utilize the average percent tree cover of the pixels within a 1 kilometer radius of the community centroid. We selected this radius 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 employ principal components analysis to construct an index of three management-sensitive soil properties that were measured consistently in 2003 and 2013: organic matter, total potassium, and available phosphorus. The results demonstrate that greater than 50% of the variance is explained by the first principal component, and our previous analyses of agricultural production reveal this to be a suitable measure of soil fertility (Call et al. 2019). The value of the first principal component was then rescaled to range from 0 to 10. As our analysis is at the household level, we weight these values by plot area and refer to this measure as soil fertility.

## Regression approaches

To examine the effects of environmental factors on *temporary* migration, we construct a person-period dataset (N = 8,213) by combining cross-sectional data on temporary migration and its predictors from 2003 and 2013. Each case in this dataset is one adult household member observed in a particular survey year (2003 or 2013). We analyze this two-wave stacked dataset using logistic regression and multinomial logistic regression approaches (Hosmer et al. 2013). For *permanent* migration, we analyze a household-year dataset (N = 7,854) consisting of yearly measures of the number of permanent migrants each household sent from 2003 to 2013. Each case in this dataset is one year observation of a particular baseline household. We analyze these data using negative binomial regression, which is appropriate for count outcomes. We include both linear and squared terms for the year to adjust for better recall of more recent migration events, an issue present in retrospective data collection (VanWey 2005). Descriptive statistics from these two datasets are displayed in Table 1 for the most relevant unit of analysis.

In all regressions, we include district fixed effects to adjust for agro-ecological, socio-demographic, and other omitted variable differences between each of the eight original survey districts. Year fixed effects are included to account for national time-varying factors, or alternatively a quadratic time trend in the case of permanent migration. With the inclusion of these fixed effects, the climatic and forest effects are statistically identified by within-district variation over time, consistent with a large literature on how to measure the causal effects of environmental shocks (Hsiang et al. 2013). A generalized version of our analytical approach can be represented in this way:

$$Y_{hct} = \beta E_{hct} + \beta P_{hct} + \alpha + \alpha_d + \alpha_t$$

where $Y_{hct}$ is a household or individual-level migration outcome, $E_{hct}$ is a vector of environmental characteristics at the household and community level, $P_{hct}$ is a vector of control variables at the individual, household and community levels, $\alpha$ is the overall intercept, $\alpha_d$ is a set of indicator variables (fixed effects) for the district, and $\alpha_t$ is an indicator for the year (replaced with linear terms for the year and year squared in the model for permanent migration). This equation is estimated with logistic regression, multinomial logistic regression, or negative binomial regression depending on the outcome as described above.

With regard to the hypotheses described above, the coefficients on $E_{hct}$ should be negative under the environmental risk and amenity hypotheses (H1-H2) for favorable environmental characteristics (precipitation anomalies, soil quality and forest cover), and positive for negative environmental qualities (temperature anomalies), whereas the reverse would be true under the environmental capital hypothesis (H3). This interpretation of which factors are favorable is supported by the Call et al. (2019) study cited above, along with a large literature describing the importance of forest access for rural livelihoods in Africa (Angelson et al. 2014). Under the stream heterogeneity hypothesis (H4), the direction of the coefficients for the same environmental predictor will differ across migration streams.

All regressions are corrected for clustering at the community-level to account for the clustered sampling strategy and adjust for the non-independence of households within communities. Results from the logistic regressions are shown as odds ratios, while values from the negative binomial regressions are shown as incidence rate ratios, both of which have a multiplicative interpretation. (For both odds ratios and incidence rate ratios, if a value is greater than one, this indicates that the odds of migration are increased by a predictor while if a value is less than one, the odds are reduced by that predictor). Soil fertility, household asset values, household livestock values, household agricultural land, and household distance to nearest market are all are strongly right-skewed and thus log-transformed for inclusion in the analysis.

For the case of climate anomalies, the coefficients have a clear causal interpretation. Anomalies represent natural experiments that cannot be meaningfully influenced or predicted by households, and we account for all potential time-stable district-level confounders as well as confounding time trends (Hsiang et al. 2013; Nordkvelle et al. 2017). For forest cover and soil quality, however, the possibility exists that these values reflect unobserved household or community characteristics that influence environmental management and also migration, such as an orientation towards market (as opposed to subsistence) production. Climatic changes could also influence both land quality and migration simultaneously. For this reason, assessing the consequences of land degradation for migration is fundamentally more challenging than climate, an issue we return to in the Discussion.

## Results

The regression results are presented in Tables 2-5. We first consider the results for all temporary moves combined (Table 2) and then separated by motivation (Table 3). Table 2 reveals that the odds of temporary migration increase by 79% with each standard deviation increase in the 1-year temperature ($p < 0.001$; short-term specification) and also increase by

42% with each standard deviation increase in the 10-year precipitation rate ($p = 0.002$; long-term specification). Other environmental factors had non-significant effects that were close to zero. The effects of control variables in these models are jointly significant but somewhat weaker than expected, though while acting in the expected directions. Decomposing these moves by motivation reveals that the main effects are acting through the more-common non-labor-related moves (Table 3). Paralleling the main effects, the odds of non-labor-related temporary migration increased by 136% with each standard deviation increase in the 12-month temperature ($p < 0.001$; short-term specification) and also increased by 75% with each standard deviation increase in the 10-year precipitation rate ($p < 0.001$; long-term specification). In contrast, the odds of labor-related temporary moves decrease by 83% with each standard deviation increase in the 1-year precipitation and are not significantly influenced by other environmental characteristics.

These results suggest a dynamic in which households are pushed to send temporary, non-labor migrants (e.g., to live with family elsewhere) in response to temperature shocks (supporting the environmental risk hypothesis) but also benefit from long-term precipitation increases, enabling favorable forms of non-labor-related movement (supporting the environmental capital hypothesis). At the same time, they also retain temporary migrants when short-term conditions are wet and thus productive for agriculture (also supporting the environmental capital hypothesis). These distinctions across migration streams also support the stream heterogeneity hypothesis. The effects of forest cover and soil quality are non-significant in all specifications, suggesting a minimal role for land degradation in temporary migration decisions in this context.

The results for permanent migration are displayed in Tables 4 and 5. Table 4 reveals that, contrary to temporary migration, environmental factors have jointly non-significant effects on all permanent moves combined, and no environmental coefficient is statistically significant at $p < 0.05$. The effects of the control variables are again somewhat weaker than expected but are also in the expected directions. Decomposing permanent moves by motivation and destination, however, reveals that the environmental effects are jointly significant for most streams, indicating that combining all streams masks these influences. The long-term temperature anomaly and soil fertility are the most influential factors. The odds of labor-related ($p < 0.001$) and urban-bound ($p = 0.029$) permanent migration both increase by 20-30% with each standard deviation increase in the 10-year temperature. In contrast, soil fertility increases the odds of non-labor related ($p = 0.067$) and rural-bound ($p = 0.038$) permanent moves by approximately 40% per unit of soil fertility. Short-term climate anomalies and forest cover do not have significant effects on any permanent migration stream.

These results suggest that households are pushed by long-term temperature increases to permanently send labor and urban-bound migrants (supporting the environmental risk hypothesis), paralleling the way in which temporary moves increase with short-term temperatures. In contrast, soil fertility appears to be used as natural capital to support non-labor-related permanent moves as well as rural-bound moves (supporting the environmental capital hypothesis 3). This may reflect an inability to easily convert soil quality into financial capital that can support urban-bound and labor-related moves, or it might reflect a stronger orientation towards agriculture in households with high soil quality. The distinctions across permanent migration streams, as well as the contrast with temporary migration, again support the stream heterogeneity hypothesis. Below, we discuss why different environmental factors affect migration in different ways, and what the implications are for understanding environmental migration more broadly.

## Discussion

Examining environmental migration in Uganda by simultaneously considering both climate anomalies and land quality; temporary and permanent migration; and long and short-term climate exposures provides evidence in support of certain findings of the broader literature while providing no, or opposing, evidence for others. Taken together, the results provide partial support for the environmental risk and capital hypotheses (H1, H3), strong support for the stream heterogeneity hypothesis (H4), and no support for the environmental amenity hypothesis (H2). Both displacement and trapping processes are occurring, with the balance of the two dependent on the time scales of movement and exposure in question. This represents a significant challenge to unitary narratives of involuntary environmental displacement that cannot accommodate such heterogeneity, as well as to scholarly approaches to environmental migration that focus solely on labor-related moves to urban areas. We emphasize two main sets of findings.

First, while there is a general consensus in the scientific literature that different environmental factors affect migration differentially (Bohra-Mishra et al. 2014), few studies have as of yet have tested the effect of both climate anomalies and land quality. Our findings reveal that, contrary to earlier claims (Black et al. 2011a), high land quality does not reduce outmigration. We observe almost no effect of forest cover on Ugandan migration processes while high soil fertility provides the natural capital necessary to support permanent migration, as others have observed (Gray 2011). This finding supports the current focus of the literature on climate, and further undermines poorly-supported claims that land degradation is a major contributor to migration. In contrast, our findings for climate (detailed below) suggest that ongoing warming is likely to result in incremental increases in internal migration, layered onto the ongoing process of urbanization that Uganda is already experiencing. Nonetheless, our conclusions about consequences of land degradation are limited by the possibility that that measures are endogenous to unobserved household and community characteristics, an issue that we cannot fully address here.

Second, few previous studies of climate migration have had the capacity to disaggregate mobility into temporary and permanent migration, nor have they examined varying durations of climate exposure. Our findings suggest that temporary and permanent migration are both shaped by climate anomalies. However, this relationship clearly differs by migration motivation and destination. Households respond to excessively hot years by engaging in the temporary moves that are a staple of rural livelihoods. In the long run, however, extended heat waves push household members to engage in permanent migration. Households also increase temporary labor migration during short periods of drought when crop yields decline, but after long periods of drought they lose their ability to send temporary migrants. As others have observed, households are able to cope successfully with short periods of climate stress through livelihood diversification but struggle to adapt to long term climate pressures (Call et al. 2019). These findings suggest that temporary migration might be serving as an important undetected relief valve against climate stress, which would help to explain the weak and mixed effects found by previous studies focusing on long-term moves. However, our findings for long-term climate shocks also suggest that, by primarily examining the effects of year-to-year shocks on year-to-year moves, previous studies are likely missing many of the longer-term consequences of climate change for migration.

Given this finding, what can be done to measure migration responses at very short time scales, while also expanding the temporal scale of exposure to multiple decades? Creating more long-term household panel datasets, as we have described here, is one approach (see also Davis et al. 2017). This approach is limited by attrition between survey rounds. At the same time, the rapid expansion of publicly-available microdata from censuses covering multiple decades (Thiede et al. 2016) as well as from population surveillance sites with monthly time resolution (Call et al. 2017) has already opened new avenues to address these issues. Existing, well-worn household surveys and country-to-country bilateral flow datasets have served migration-environment research well, but to provide a more comprehensive view of this process it is time the broaden the types of migration that we consider, as well as the nature of the data that we use.

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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**Table 1.**

Descriptive statistics and definitions for all variables used in analysis

| Variable | Mean | St Dev | Min | Max | Definition |
|---|---|---|---|---|---|
| **Migration outcomes** | | | | | |
| Temporary migration [a] | 0.17 | --- | 0 | 1 | Individual present in household fewer than 12 months |
| Labor migration | 0.04 | --- | 0 | 1 | Individual states migration was for labor purposes |
| Non-labor migration | 0.13 | --- | 0 | 1 | Individual states that migration was for non-labor purposes |
| Permanent migrants [b] | 0.08 | 0.38 | 0 | 10 | Number of permanent migrants per household per year |
| Economic migrants | 0.04 | 0.23 | 0 | 6 | Number of labor migrants per household per year |
| Non-economic migrants | 0.04 | 0.28 | 0 | 10 | Number of non-labor migrants per household per year |
| Urban destination | 0.04 | 0.28 | 0 | 9 | Number of urban migrants per household per year |
| Rural destination | 0.04 | 0.24 | 0 | 8 | Number of rural migrants per household per year |
| **Environmental factors** [b] | | | | | |
| Precipitation (12-month) | 0.13 | 1.01 | −2.14 | 3.07 | Z-score of 12 mo growing season precipitation relative to 1980-2013 |
| Temperature (12-month) | 0.94 | 0.60 | −0.24 | 1.99 | Z-score of 12 mo growing season temperature relative to 1980-2013 |
| Precipitation (120-month) | −0.34 | 0.84 | −2.22 | 2.04 | Z-score of 120 mo growing season precipitation relative to 1980-2013 |
| Temperature (120-month) | 0.60 | 0.40 | −0.19 | 1.12 | Z-score of 120 mo growing season temperature relative to 1980-2013 |
| Average monthly precipitation | 104.0 | 13.1 | 75.6 | 135.6 | Average monthly precipitation, 1980-2013 (mm) |
| Average monthly temperature | 22.13 | 2.37 | 16.57 | 25.93 | Average monthly temperature, 1980-2013 (C) |
| Soil fertility | 2.45 | 1.50 | 0.03 | 8.47 | Average soil fertility index derived from PCA of measured soil characteristics weighted by plot area |
| Tree cover | 21.7 | 6.6 | 6.6 | 43.6 | Tree cover percentage for 1 kilometer community buffer |
| **Individual characteristics** [a] | | | | | |
| Unmarried | 0.73 | --- | 0 | 1 | Marital status of individual |
| Child of head of household | 0.55 | --- | 0 | 1 | Individual is the child of head of household |
| Female | 0.51 | --- | 0 | 1 | Gender of individual |
| Age | 46 | 14 | 14 | 105 | Age of individual |
| **Household characteristics** [c] | | | | | |
| Female head of household | 0.22 | --- | 0 | 1 | Head of household is female |
| Education of head of household | 0.86 | --- | 0 | 1 | Head of household has no completed education |
| Household size | 6.27 | 3.05 | 1 | 26 | Number of household members |
| Secure land tenure | 0.33 | --- | 0 | 1 | Land tenure is either owned through freehold or leased (vs mailo, customary) |
| Household asset value | 5,292 | 9,140 | 138 | 61,273 | Total value of household assets in USD |
| Household livestock value | 621 | 1,720 | 0 | 21,853 | Total value of household livestock in USD |
| Distance to market | 3.67 | 3.47 | 0.05 | 17.19 | Distance to the nearest market in kilometers |
| Agricultural land area | 0.96 | 1.25 | 0.02 | 8.12 | Total agricultural land area in hectares |

[a] N=8,213 person-periods

[b] N=7,854 household-years

[c] N=1,240 household-periods (636 from 2003, 604 from 2013)

**Table 2.**

Logistic regression of temporary migration (person-period dataset)

| Predictors | Short term climate anomaly | Long term climate anomaly |
|---|---|---|
| **Environmental factors** | | |
| Precipitation | 1.11 | 1.42** |
| Temperature | 1.79*** | 0.98 |
| ln(Soil fertility) | 0.90 | 0.81 |
| Tree cover | 1.02 | 1.02 |
| **Individual characteristics** | | |
| Unmarried | 1.10 | 1.10 |
| Child of head of household | 1.17 | 1.15 |
| Female | 0.88* | 0.88* |
| Age | 1.04 | 1.04 |
| Age*Age | 1.00 | 1.00 |
| **Household characteristics** | | |
| Female head of household | 1.40+ | 1.40+ |
| Education of head of household | 0.98 | 0.98 |
| Household size | 1.02 | 1.02 |
| Secure land tenure | 1.05 | 1.01 |
| ln(Household asset value) | 0.75 | 0.79 |
| ln(Household livestock value) | 1.19* | 1.17* |
| ln(Distance to market) | 1.02 | 1.02 |
| ln(Agricultural land area) | 1.22 | 1.23 |
| Observations | 8,213 | 8,213 |
| *Joint test of environmental factors* | *51.77*** | *28.16**** |
| *Joint test of individual characteristics* | *13.21** | *12.78*** |
| *Joint test of household characteristics* | *19.84*** | *15.69** |

*** p<0.001

** p<0.01

* p<0.05

+ p<0.1

Constants, district, and year fixed effects and average monthly temperature and precipitation included but not shown.

## Table 3.

Multinomial logistic regression of temporary migration by motivation (person-period dataset)

| Predictors | Motivation | |
|---|---|---|
| | **Labor** | **Non-labor** |
| **Short term climate anomaly** | | |
| Precipitation | 0.17*** | 1.62 |
| Temperature | 1.33 | 2.36*** |
| ln(Soil fertility) | 1.04 | 0.98 |
| Tree cover | 1.01 | 1.02 |
| *Joint test of environmental factors* | *104.2**** | |
| **Long term climate anomaly** | | |
| Precipitation | 1.01 | 1.75*** |
| Temperature | 0.87 | 0.98 |
| ln(Soil fertility) | 1.01 | 0.83 |
| Tree cover | 1.02 | 1.01 |
| *Joint test of environmental factors* | *63.16**** | |

N=8,213

*** p<0.001

** p<0.01

* p<0.05

+ p<0.1

All other variables from full specification included in models but not shown.

**Table 4.**

Negative binomial logistic regression of the number of permanent migrants from a household in a given year (household-year dataset)

| **Predictors** | **Short term climate anomaly** | **Long term climate anomaly** |
|---|---|---|
| **Environmental Factors** | | |
| Precipitation | 0.94 | 1.06 |
| Temperature | 0.99 | 1.11 + |
| ln(Soil fertility)(2003) | 1.11 | 1.10 |
| Tree cover (2000) | 1.01 | 1.01 |
| **Household Characteristics** | | |
| Female head of household (2003) | 0.97 | 0.97 |
| Education of head of household (2003) | 0.85 | 0.85 |
| Household size (2003) | 1.05 * | 1.05 * |
| Secure land tenure (2003) | 1.015 | 1.02 |
| ln(Household asset value)(2003) | 0.80 | 0.81 |
| ln(Household livestock value)(2003) | 1.13 * | 1.12 * |
| ln(Distance to market)(2003) | 1.02 | 1.02 |
| ln(Agricultural land area)(2003) | 1.06 | 1.06 |
| Observations | 7,854 | 7,854 |
| *Joint test of environmental factors* | *9.41* | *7.31* |
| *Joint test of household characteristics* | *22.04* ** | *21.69* ** |

*** p<0.001

** p<0.01

* p<0.05

+ p<0.1

Constants, district, year, and year squared fixed effects and average monthly temperature and precipitation included but not shown.

### Table 5.

Negative binomial logistic regression of the number of permanent migrants from a household in a given year by motivation and destination (household-year dataset)

| Predictors | Motivation | | Destination | |
|---|---|---|---|---|
| | Labor | Non-labor | Urban | Rural |
| **Short term climate anomaly** | | | | |
| Precipitation | 0.98 | 0.91 | 0.95 | 0.93 |
| Temperature | 1.00 | 0.98 | 0.99 | 0.98 |
| ln(Soil fertility)(2003) | 0.88 | 1.42 + | 0.93 | 1.43 * |
| Tree cover (2000) | 1.00 | 1.02 | 1.02 | 1.00 |
| *Joint test of environmental factors* | *23.82* ** | *8.74* | *11.28* + | *14.13* * |
| **Long term climate anomaly** | | | | |
| Precipitation | 0.91 | 1.25 | 1.13 | 0.96 |
| Temperature | 1.31 *** | 0.97 | 1.21 * | 1.02 |
| ln(Soil fertility)(2003) | 0.87 | 1.38 + | 0.91 | 1.43 * |
| Tree cover (2000) | 1.00 | 1.01 | 1.02 | 1.00 |
| *Joint test of environmental factors* | *22.67* ** | *12.4* + | *20.48* ** | *9.86* |

N=7,854

*** $p<0.001$

** $p<0.01$

* $p<0.05$

+ $p<0.1$

All other variables from full specification included in models but not shown.