Weather shocks, migration, and in-place adaptation*

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Abstract

Allowing for in-place adaptation when analysing climate migration drastically changes policy implications. Besides sending migrants, Kenyan households react to temperature shocks by transiting to less climate-sensitive (non-agricultural) occupations and by changing livestock species. These in-place adaptations shed light on the mechanisms through which common policies weaken temperature's effect on migration. Better infrastructure catalyses occupational transitions and reduces other adjustment margins such as migration and livestock composition. Random unconditional cash transfers attenuate temperature's effect on migration by softening welfare losses. We rationalise household responses to weather shocks using a model of joint migration, occupation, and livestock choices by households accounting for equilibrium adjustments in local wages. We show that the three coping strategies are substitutes and that infrastructure lowers the effect of temperature shocks on migration at lower costs than several other common policies. Compared to ours, a model that considers migration as the only coping strategy under-estimates the mitigating impact of infrastructure investment on the effect of heat on migration by more than half.

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1 Introduction

Rural emigration is part of economic development. If unmanaged, however, it can overwhelm urban infrastructure, labor markets, and communities (IOM, 2014) as well as increase urban poverty (cf UNDESA, 2018). As such, policies to mitigate migration, particularly as a response to weather shocks, have become a key concern for policy makers (e.g. UNHCR, 2022). However, the effectiveness of any intervention will depend on the types of coping strategies households adopt to deal with weather shocks. An often overlooked fact is that migration is only one possible adjustment option. Alternative responses to climatic shocks include, for instance, sector changes or changes in agricultural practices. In fact, the World Bank's Groundswell reports (2018; 2021) on internal climate migration explicitly stress the importance of policies supporting in-place-adaptation, such as through job creation in less climate-sensitive sectors. If such in-place responses are valid substitutes to migration, this will drastically change policy effectiveness.

This paper examines how different policies affect migration responses to weather shocks whilst accounting for alternative, in-place coping strategies. We focus on the semi-arid regions of northern Kenya, which have experienced frequent heat waves. These same areas were exposed to two common types of interventions: infrastructure development and randomized income support. We first estimate the effect of exogenous unconditional cash transfers and infrastructure development on three common coping strategies for heat shocks: migration, occupational choice, and livestock compositions. To disentangle the underlying mechanisms and to credibly evaluate different policy scenarios, we then estimate a model of joint migration, occupation, and livestock choice that accounts for equilibrium adjustment in wages. Using this setup, we determine the degree to which the three coping strategies are substitutes. Simulating different policies of equal cost, we find that interventions easing occupational transitions (such as infrastructure development or transition subsidies) are markedly more efficient in mitigating climate migration than cash transfers.

We combine granular climatic information with data from a randomised controlled trial and with geo-coded infrastructure information. Specifically, we overlay the geographic location of respondents to the Hunger Safety Net Programme evaluation survey (HSNP, a household panel in northern Kenya spanning 2010 to 2012) with air temperature drawn from the ERA5 database, and calculate local temperature anomalies, which are plausibly exogenous. Indeed, we find no relation with household characteristics.[1]

To explore the role of income support, we exploit the random allocation of unconditional cash transfers under the HSNP. Households in a randomly selected half of locations were

[1]We also explore the role of rainfall and find it not to be the driving dimension in our context.

given an unconditional cash transfer amounting to 28% of median household consumption. Importantly, these transfers are unconditional on households sending a migrant. To investigate the importance of broader infrastructure, we use geo-coded data on several dimensions of infrastructure: overland roads (which ease transport of goods and people), digital infrastructure, such as electricity and mobile phone coverage (which can catalyse all sorts of economic activities), and health and educational infrastructure in each location. For causal identification, we instrument infrastructure using lightning strike frequency (Manacorda and Tesei, 2020) and terrain ruggedness (Nunn and Puga, 2012).

Our results show that in years where local temperature was above its local long-term median,[2] households are 2.8 percentage points more likely to send a member outside the district (of which there are 47 in Kenya). Given a sample mean of 4 percent, these are large effects highlighting the importance of climate for migration decisions. We also find that abnormally hot years decrease household consumption. As such, sending a migrant is a rational response, since for the average household receiving migrant remittances in our data, these transfers contribute 17% of household consumption. We find no effects on the whole household migrating.

Both random income transfers and infrastructure development significantly attenuate the effect of heat shocks on migration. Interacting our two policies with heat shocks shows that unconditional cash transfers from the HSNP or a one standard deviation improvement in local infrastructure offset about 70% of temperature's effect on migration. However, as we show below, the mechanisms behind these two policies are very different. Whereas infrastructure eases local adaptation as an alternative to migration when households are faced with heat shocks, income support alleviates the most severe hardship and offsets adjustment pressure.

To examine the mechanisms via which policies attenuate temperature's effect on migration, we focus on two types of in-place adjustments as alternatives to migration, using detailed information on households' economic activities: occupational sector choice and livestock composition. Our results show that in abnormally hot years, the likelihood of household members entering non-agricultural occupations increases by 4.7 percentage points (which in our equilibrium model rationalizes an effect of climate shocks also on non-agricultural households). Considering the large proportion of households involved with pastoralism (63%), we analyse the type of livestock households own, the importance of which has been pointed out by Bandiera et al. (2017), for instance. We focus on camels, which are more heat resistant than cows, the other commonly owned large kind of livestock. Our estimates show that heat

[2]We show that our results are robust to alternative definitions of shocks. Complementing our analysis with Afrobarometer data on *perceived* climate change shows that actual temperature changes are in line with respondents' perceptions. We also find that the latter correlate with migration intentions both Kenya-wide and on a broader African level.

shocks increase the likelihood of households owning camels by 4.4. percentage points. At the same time, there are strong negative effects on ownership of cattle.

Our results show very different effects of infrastructure and income transfers on in-place adaptation. Whereas infrastructure substantially increases the effect of heat on transitions out of agricultural occupations and attenuates the effect on camel ownership, cash transfers have little effect on either occupational choice or camel acquisitions. We also find no direct effect of HSNP transfers on migration or other mitigation strategies.

An upshot of our reduced form analysis is that any policy prediction requires a joint modelling of migration and sectoral choice, which also accounts for potential equilibrium effects. We do this in the last, structural part of the paper. In our model, households decide between not sending any migrant, sending part of the household to work elsewhere, and relocating entirely. In the first two cases, households furthermore decide on whether its members work in agriculture or in non-agricultural occupations, where equilibrium wages adjust endogenously. Agricultural households, further decide on camel ownership. Reduced form estimates show negative effects of heat shocks on consumption are particularly pronounced for agricultural households not owning camels. In line with these findings, we allow earnings to be affected by temperature differentially by occupational sector and camel ownership. Moreover, we allow the costs of migration, sector changes and camel acquisition to vary with past income as an approximation to financial constraints as well as with local infrastructure. When sending a migrant, the household enjoys remittances, which again vary with exposure to shocks.

The estimated model allows us to estimate to which extent migration, sector choice, and livestock ownership are substitute strategies for dealing with heat shocks. We find that a doubling of the cost of switching from the agricultural to the non-agricultural sector increases the effect of heat on migration by 50%. Similarly, increases in the cost of acquiring camels raises temperature's effect on both households entering the non-agricultural sector and on households sending a migrant. We use the model to quantify the effectiveness of different policies of equal total cost: infrastructure development, unconditional and conditional cash transfers, and occupational transition subsidies. We find that infrastructure improvement leads to the strongest reduction in climate migration among all these alternatives policy options. This is due to the fact that improved infrastructure facilitates sectoral transitions, which allow households to move to less weather-sensitive occupations thus easing the pressure on migration.

We illustrate the importance of jointly modelling migration, occupation, and livestock choices for policy by comparing our full model (accounting for alternative coping strategies and equilibrium effects) to predictions derived from two simpler models: one without alternative coping strategies and one without equilibrium effects. Our policy simulations suggest that a model without considering alternative coping mechanisms would *underestimate* the effectiveness of infrastructure development in curbing temperature's effect on migration by more than 50%. A model that furthermore does not consider labor market equilibrium effects would underestimate the effects of infrastructure by over 70%.

This is the first paper to quantify the role of different policies in mitigating climate migration whilst modelling migration jointly with alternative coping strategies. Our findings have wide-ranging policy implications. By jointly analysing occupational choice and migration, our analysis is able to link infrastructure investment (which catalyses occupational transitions) to migration. Large sums of money are regularly spent on infrastructure projects. For instance, between 2005 and 2018 the World Bank invested 1 billion USD to improve Kenya's overland roads. More recently, the World Bank pledged 390 million USD to improve digital infrastructure in the country. Our analysis highlights—for the first time— that such interventions can have the additional effect of attenuating migration responses to weather shocks. Thus our findings provide novel and important additional rationales for investing in infrastructure in low-income countries.

Our paper contributes to several strands of the literature. In a first instance, our focus on weather fluctuations contributes to the micro-development literature linking migration to climatic shocks such as typhoons (Gröger and Zylberberg, 2016), regional dryness (Albert et al., 2022), heat waves (Mueller et al., 2014), rainfall (Bazzi, 2017; Munshi, 2003; Jayachandran, 2006; Kleemans and Magruder, 2018), temperature (Jessoe et al., 2018), droughts (Gray and Mueller, 2012; Di Falco et al., 2022), or combinations thereof (Bohra-Mishra et al., 2014); see also the surveys by Cattaneo et al. (2019), Cui and Feng (2020), and Ferris (2020). Whilst the omission of other choices does not necessarily bias the reduced form effects of weather shocks on migration, it will affect policy simulations and predictions.

Our paper also advances the fast growing literature on the interaction between migration with other choices. Morten (2019) and Meghir et al. (2021) analyse migration in relation to informal risk sharing, whereas Diop (2022) considers the interdependency between the subsidy and use of fertilizers on the one hand and migration on the other. We add novel insights to this literature by highlighting occupational choice and livestock ownership as important alternative responses of high policy relevance. Labor markets have been identified as a key dimension of adjustment to climatic change (World Bank, 2022). While the importance of rising temperatures as a push factor of migration is well documented (UNDP, 2022), adequate policy responses remain underdeveloped. As shown in our policy simulations mentioned above, the joint modelling of choices significantly alters conclusions about the effectiveness of common policies aimed at mitigating the impact of climate change. Moreover, the importance of the occupation and production technology choices we highlight suggests novel avenues for research.

Our results looking at sectoral choice and type of livestock ownership also speak to the climate-economy literature (see Dell et al., 2014; for an overview, and Hsiang, 2010; Dell et al., 2012; Somanathan et al., 2021; for examples) highlighting the effect of the weather on—among many other things—economic productivity. Our paper contributes to these studies by highlighting two additional and novel adaptation mechanisms that interact with migration decisions.

By highlighting several, different ways in which households respond to weather shocks, our analysis also speaks to a body of research that documents effects of climatic and other events on a larger scale (see, for instance, Cattaneo and Peri, 2016; Marchiori et al., 2012; Conte et al., 2021; Burzyński et al., 2022; Conte, 2022; Bertoli et al., 2022; Waldinger, 2022).

Finally, our paper also speaks to the large literature evaluating the effects of randomized cash transfers on migration (see Clemens, 2021, for a summary). Our analysis differs in two important ways: first, most of the literature considers cash transfers that are conditional on certain choices (such as in Gazeaud et al., 2020), or tied to a specific purpose (such as transportation in Bryan et al., 2014). Instead, receipt is universal in our setting.[3] Second, whereas existing studies evaluate the effects of a transfer itself, our interest is in its interaction with weather shocks. An analysis of general equilibrium effects of cash transfers is provided by Egger et al. (2022). Our investigation of infrastructure development as a policy alternative to direct cash transfers, instead, adds to a nascent literature that links this to migration, such as Fuchs et al. (2023) and Gamso and Yuldashev (2018), who find that World Bank projects and other development aid attenuate emigration pressure in recipient countries.

The remaining paper is structured as follows. Section 2 provides background and describes the data. Section 3 estimates the reduced form effect of weather shocks and also analyses various policy alternatives. Section 4 sets up and estimates our structural model. Section 5 discusses policy relevance and concludes.

2 Background and Data

The setting for our main analysis is the semi-arid region of northern Kenya. Individuals in these areas experience frequent heat waves. In addition, we can exploit experimental variation from a randomized unconditional cash transfer programme that was rolled out in this region by the Hunger Safety Net Programme, as well as geo-coded information on

[3] Since the main migration outcome in our context is the migration of a single household member, transfers, which are paid at the household level, in fact are also not conditional on not migrating.

infrastructure (instrumented via climatic and geographical local features).

2.1 Hunger Safety Net Programme evaluation data

Our main data source is a household panel dataset collected to evaluate the Hunger Safety Net Programme (HSNP), an unconditional cash transfer. In the Kenyan districts Mandera, Marsabit, Turkana and Wajir, 2,436 households in 40 locations were interviewed in three annual waves spanning 2010-2012. See map in figure 1a. Although the HSNP was not designed as a representative sample, the characteristics of its respondents are similar to the local population. Table 1 shows that the characteristics of HSNP households are very similar to those interviewed in the same four districts by the nationally representative 2009 Kenyan Demographic Health Survey (DHS). We define agricultural occupations as livestock production and farming.

Table 1: Descriptives

	(1)	(2)		(3)	(4)	(5)	(6)
	Panel A			**Panel B**			
Data source	HSNP (2010)			HSNP (2010)		DHS (2009)	
	Mean	SD		Mean	SD	Mean	SD
Member migrated (2011-12)	0.04	(0.20)	**Age**	23.7	(20.9)	20.0	(19.0)
Works only in agriculture (2010)	0.60	(0.49)	**HH size**	5.89	(2.28)	5.27	(2.33)
Works only in non-agriculture (2010)	0.25	(0.43)	**Owns livestock**	0.79	(0.40)	0.76	(0.43)
Works in both (2010)	0.13	(0.33)	**Owns mobile phone**	0.16	(0.36)	0.20	(0.40)
Owns camels	0.36	(0.48)	**Owns cart**	0.06	(0.23)	0.07	(0.25)
Mean temperature (2009-11)	32.7	(1.50)	**Owns mosquito net**	0.68	(0.47)	0.66	(0.47)

Notes: Table reports summary statistics of the Hunger Safety Net Programme evaluation data. Panel A: reports summary statistics of key variables used in estimations. Panel B: compares characteristics of Hunger Safety Net Programme respondents with 2009 Demographic Health Survey respondents, a nationally representative survey of Kenyan households.

As part of the HSNP evaluation, half the locations were randomly selected via public lottery to receive unconditional cash transfers—see map (b) in appendix A. After collection of the baseline dataset in 2009/2010, households in treatment locations received bi-monthly unconditional transfers for 24 months. The value of transfers increased from KES 2,150 initially to KES 3,500 (corresponding to USD 65.50 and 92.20, PPP adjusted, respectively). Over a year, the sum of six payments amounts to 28% of median yearly household consumption. Control households received HSNP transfers after completion of the second follow up round in 2012.

Migration measurement. We measure migration rates using detailed information on household members' whereabouts contained in the household roster. During baseline, the HSNP collects information on all household members. The two follow up surveys inquired whether each roster member still resides in the household. This is similar to the way migration is measured by Di Falco et al. (2022), and by Gray and Mueller (2012). If a member does not reside in the household anymore, the questionnaire records their new location as any of the following i) *same village*, ii) *same location*, iii) *same district*, or iv) *outside of the district*. Our migration variable takes the value 1 if the household member moved *outside of the district*—see map in figure 2b) for means. For the whole sample, 4 percent of households report that one member has left the district,[4]

2.2 Climate in northern Kenya

Meteorological data are taken from the ECMWF2-ERA5 reanalysis (Hersbach, 2020), which supersede the ECMWF ERA-Interim data.[5] We employ data on monthly averages for surface air temperature (in °C) measured at 12noon. We focus specifically on deviations in dry season temperature, which is important for herding animals (the major occupation of respondents in our context), from local long-run levels. For the HSNP sample, air temperature during the dry seasons of 2010-2012 has a mean of 32.7°C, a median of 32.9°C and a standard deviation of 1.50°C. Figure 1 shows the spatial distribution and trends of these temperatures.

To isolate the causal effect of temperature, we calculate yearly deviations from the local long term conditions (often referred to as anomalies). We focus on temperature during the previous year's dry season (January, February, and June to September) when grazing is at its shortest.[6] For each of the 40 locations covered by the HSNP evaluation data, we calculate the long term median for dry season temperature by using data from 2000 to 2009. For our main specification we then define a variable taking the value 1 if the dry season temperature in the year before interview was higher than the local long term median. We cross-check this specification with alternative quantile cutoffs, with temperature anomalies in °C, and also investigate the role of rainfall (which in appendix table A2 we show is not important for migration decisions). Panel (a) of figure 2 reports the difference between temperatures in 2010 and 2011 (relevant for the years 2011 an 2012) and the long term median for each of the 40 locations.

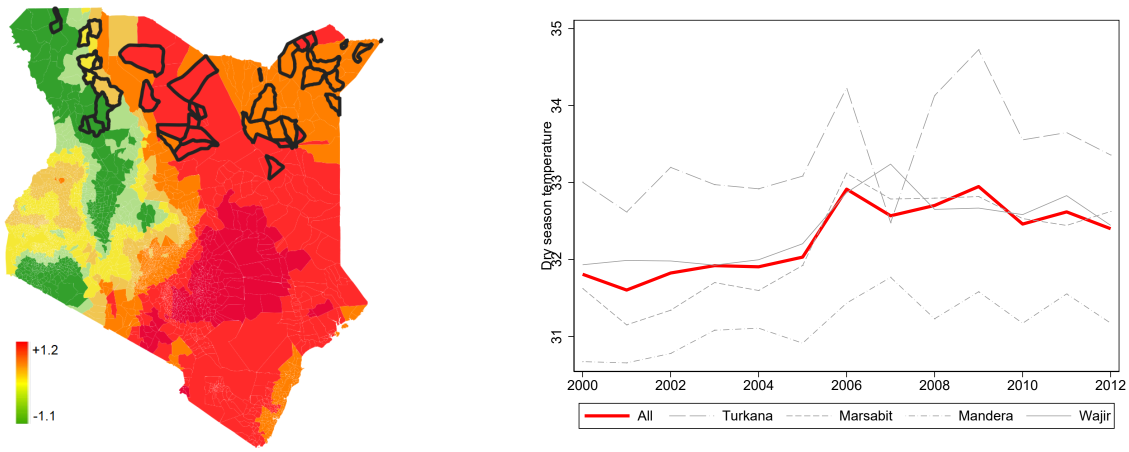
[4] Out of these, only 4.6% of households state *Moved to follow the animals (herding)* as a reason for a member's migration, which may be explained by the large size of districts (61,790km^2 on average).

[5] The data are freely available at `https://cds.climate.copernicus.eu`.

[6] `https://fews.net/east-africa/kenya/seasonal-calendar/december-2013` accessed January 2023.

Figure 1: Temperature in Kenya

(a) Temperature differences 2000 to 2012 (b) Temperature trends (HSNP districts)



Notes: Figure reports dry season temperature trends from 2000 to 2012. Panel a: shows temperature differences between 2000 and 2012 (HSNP locations outlined in black). Panel b: shows dry season temperature trends for 4 districts covered by HSNP (10 locations per district).

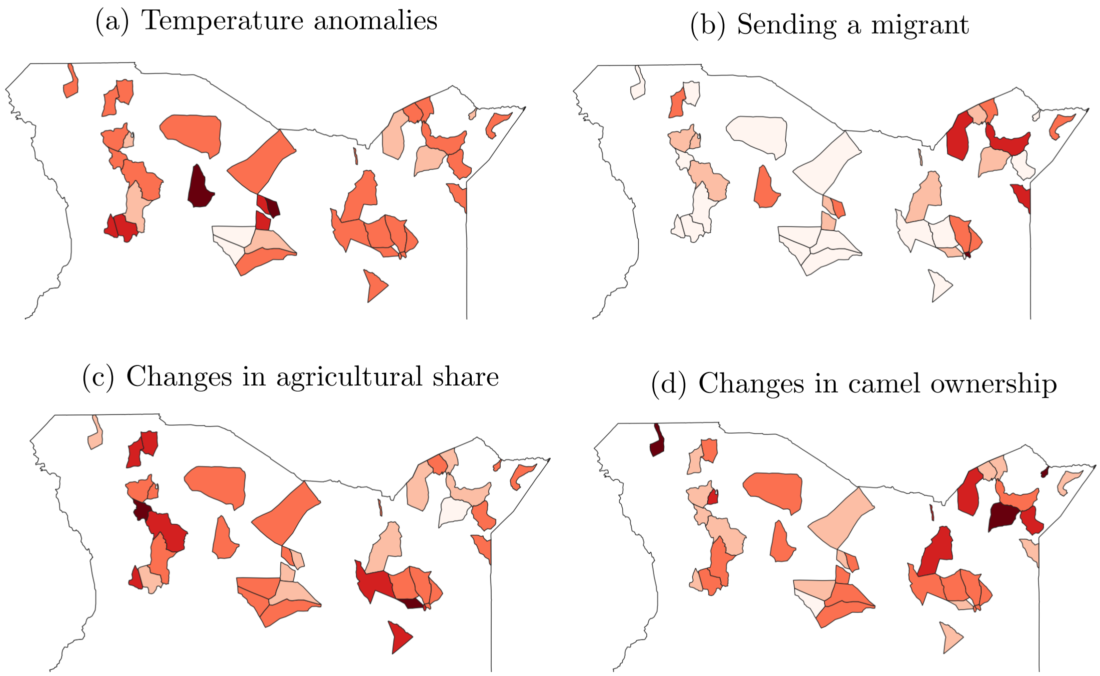
Temperature and migration. Descriptively, we find that agricultural households experiencing a heat shock are more likely to send a migrant in later years. Figure 3b below plots the proportion of households in either sector which send at least one member depending on whether their location had an above median dry season temperature. Due to endogenous sector choice, we do not interpret these results as causal.

Data from the 7^{th} round of the Afrobarometer[7] (2016-2018), moreover, suggest a link between perceived climate and migration intentions on a larger scale. Relating perceived climate to migration intentions we find that in Kenya as a whole individuals perceiving the climate to worsen are also more likely to intend to migrate (column (1) in appendix table A6).[8] The Afrobarometer data also show that observed temperature anomalies increase the likelihood that individuals perceive the climate to worsen (column (2)). When we look at the whole Africa sample covered by the Afrobarometer, we find very similar correlations (columns (3) and (4) of appendix table A6).

[7]Data are available under `https://www.afrobarometer.org/data/data-sets/`.

[8]We use answers to the questions *How much, if at all, have you considered moving to another country to live?* and *In your experience, would you say climate conditions for agricultural production in your area have gotten better, gotten worse, or stayed about the same over the last 10 years or haven't you heard enough to say?*

Figure 2: Temperature, migration, sector choice, and camel ownership



Notes: Figure reports temperature, migration, changes in sector and camel ownership for the 40 locations covered by the HSNP data. Panel a: shows mean deviations in dry season temperature 2010-2012 from local long term median. Panel b: shows the proportion of households for which a member moved out of the district. Panel c: shows the change in households for which at least one member works in the agricultural sector. Panel d: shows the change in households that own at least one camel.

2.3 Livelihoods and infrastructure in northern Kenya

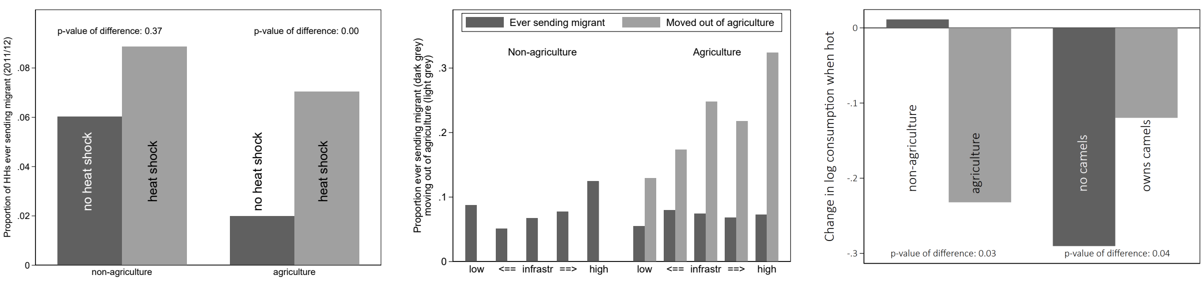
With the highest level of absolute rural poverty rates in the country (KNBS, 2007), individuals living in the semi-arid regions of northern Kenya are persistently impoverished

The baseline HSNP quantitative survey reveals that livestock rearing, pastoralism, and (to a lesser extent) agriculture were the primary sources of livelihood: 73 percent (60 percent exclusive and 13 percent partly, see table 1) of households have at least one member working in these occupations; 79 percent of all households owning some livestock and 36 percent owning camels.

Infrastructure measurement. We consider a range of infrastructure dimensions, which catalyse economic activities in different ways. First, we use geo-coded information on GSM mobile phone network coverage from the GSMA and provided by Collins Bartholomew, which uses submissions from mobile operators to construct maps of GSM networks, which as the dominant standard in Africa during our sample period has a near 100% market share. Less

Figure 3: Temperature, migration, and consumption by occupational sector

(a) Migration (b) Infrastructure (c) Consumption



Notes: Panel a reports average proportion of households sending at least one migrant between 2011 and 2012, distinguishing agricultural from non-agricultural households and those experiencing a heat shock from those that do not. Panel b reports average proportion of households sending at least one migrant between 2011 and 2012, distinguishing agricultural from non-agricultural households and quintiles of the infrastructure distribution. Sample consists of households having experienced at least one heat shock. Panel c plots changes in log household consumption expenditure net of remittances and cash transfers when local dry season temperature exceeds the local long term median, controlling for year and household fixed effects. Reported p-values of the differences in each case are based on HAC Conley standard errors (Conley, 1999) with 50km radius and two year lag.

than half the locations were covered by GSM networks. Second, using maps denoting major and minor roads, we calculate road density as the kilometres of roads by square kilometre for each sub-location.[9] The average value for our sample is less than 3 meters of paved road per square kilometer. Third, we identify whether each sub-location has access to electricity via kv11 or kv33 cables or via mini-grids.[10] Figures 4a and 4b provide maps for these three aspects of infrastructure. We complement these three geo-coded features with the number of educational and health facilities as reported by the HSNP. Appendix C shows that our main results are robust to different infrastructure measures.

Figure 3b provides descriptive evidence for the interplay between migration, occupational choice, and infrastructure. The dark grey bars show the proportion of households ever sending a migrant after having experienced a heat shock for agricultural and non-agricultural households, by level of local infrastructure. For non-agricultural households, migration slightly increases with better infrastructure (aside from the lowest quintile). For agricultural households, conversely, migration slightly decreases with better infrastructure (again, aside from the lowest quintile).[11] One possible reason for this divergence is that better infrastructure allows agricultural households to transition to less climate sensitive non-agricultural occupations thus weakening the need to migrate. The light grey bars in

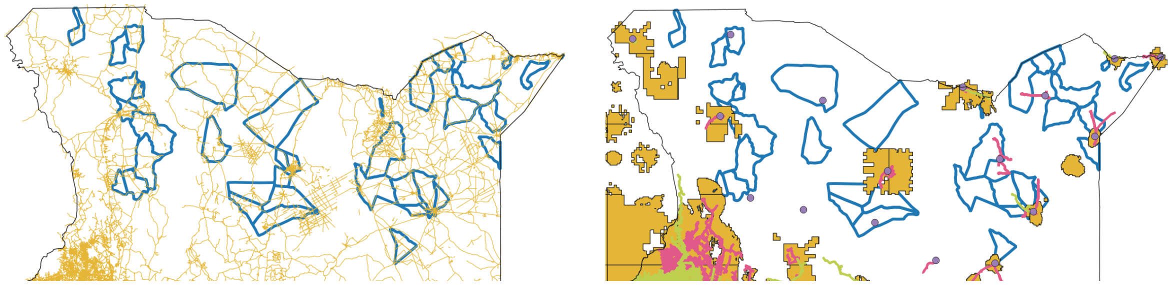
[9]Source: Digital Chart of the World (`https://www.diva-gis.org/gdata`)

[10]Source: The World Bank Kenya Off-Grid Solar Access Project (`https://energydata.info/dataset/kenya-overview-of-off-grid-electricity-service-areas`.)

[11]This decrease is markedly stronger when conditioning on household fixed effects, as we do in the estimations below.

Figure 4: Infrastructure in northern Kenya

(a) Road network (b) GSM coverage and electricity



Notes: Figure reports road, electricity, and mobile phone network in northern Kenya. 40 HSNP locations are denoted in blue. Panel a) reports major and secondary roads in Kenya in yellow (Source: Digital Chart of the World). Panel b) reports electricity access (via cable or minigrid, Source: World Bank Off-Grid Project) in pink and green and GSM second generation mobile phone network coverage in yellow (Source: Bartholomew Collins).

figure 3b show exactly this to be the case.

3 Responses to weather shocks

This section estimates the extent to which the effect of temperature shocks on migration can be mitigated by policy interventions. Thereafter, we explore the role of two alternative coping strategies: occupational sector choice and livestock ownership.

For each household, we use information from the household roster to define a variable $migrant_{it} = 1$ if at least one member has left household i in year t to move out of the district (see Section 2.1 for details), and estimate the following regression:

$$migrant_{it} \quad = \quad \beta_1 hot_{l_i,t-1} + \beta_2 hot_{l_i,t-1} \times policy_{l_i} + \iota_i + \tau_t + \epsilon_{it}, \tag{1}$$

where $hot_{l_i,t-1} = 1$ if the temperature during the dry season in individual i's location l_i in the year prior to interview was above the long term median in location l_i, and $policy_{l_i}$ denotes either location l_i's treatment status in the randomized unconditional cash transfer programme or the level of local infrastructure. Throughout, we condition on household (ι_i) and year (τ_t) fixed effects. Since all household members are present at baseline by construction, the estimation is based on the years 2011 and 2012. We estimate equation (1) by OLS with Spatial HAC (Conley, 1999) standard errors.[12]

Throughout this section, we carry out a large number of identification and robustness

[12]We allow for spatial correlation within a 50km radius and two years lag.

checks. We investigate the causal interpretation of our coefficients by providing evidence for the exogeneity of temperature shocks and of HSNP transfers (appendix figure A4) as well as by instrumenting local infrastructure using lightning strike frequency and terrain ruggedness (table 2). We also examine different measurements for climatic shocks including alternative definitions of $hot_{i,t-1}$, using temperature anomalies in ^oC, temperature quantiles, and rainfall anomalies (appendix tables A2 and A3). Additionally, we experiment with alternative definitions for the dependent variable ($migrant_{it}$, in appendix table A2) and with different ways of clustering (appendix table A1).

3.1 Temperature shocks and migration in Kenya

Identifying variation in $hot_{l_i,t-1}$ is based on yearly temperature deviations from long term local climatic conditions. Whilst the latter are likely to be associated with numerous underlying factors, such as, for instance, institutional quality (Acemoglu et al., 2002; Rodrik et al., 2004), short-run deviations from these long term values are plausibly exogenous. Appendix figure A4 investigates the exogeneity of temperature anomalies by estimating the correlation between $hot_{l_i,t-1}$ and characteristics of location l_i, always conditioning on year and household fixed effects; and finds no correlation.

Column (1) of table 2 shows a positive effect of temperature shocks on migration with a 2.8 percentage point higher propensity for households to send a migrant in abnormally hot years. Compared to the sample mean of 4 percent, this is a large effect in line with policy reports highlighting climate to be a major driver of migration (IOM, 2020). Instead, we find no effect on the (low) rate at which entire households leave the sample, see column (1) in appendix table A2. Column (2) of that table estimates the effect of a temperature shock on the migration of household members irrespective of destination and finds a smaller effect (relative to the sample mean).

Robustness. In appendix table A2, we explore different measurements of temperature shocks. Column (3) of that table estimates the effect of dry season temperature in degrees Celsius. Since we include household fixed effects (which are nested in locations), this variable can be interpreted again as deviations from the local long term temperature. The results remain similar. Columns (4) and (5) use rainy (rather than dry) season temperature and show no effect. Columns (6) and (7) use stricter definitions of heat shocks, with the 80^{th} and 90^{th} percentile of the local long term dry season temperature distribution as cutoffs rather than the median. As expected, the effects with these specifications are larger. Column (8) estimates the effect of temperature anomalies on migration semi-parametrically by defining indicators for the second, third, and fourth quartile. The results show strong increases in migration along the temperature anomaly distribution. Finally columns (9) and (10) show that our effects remain robust when controlling for leads and lags of temperature shocks.

Rainfall. Appendix table A3 investigates the importance of rainfall (rather than temperature) shocks and shows that these are not important in our context. The coefficients on rainfall anomalies during the dry and rainy seasons are small in size and their inclusion does not reduce the size of the temperature coefficients.

Table 2: Temperature, migration, and common policy choices

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Dependent variable = 1 if at least one household member migrated (mean: 0.04)							
	Panel A: Reduced form effect				**Panel B:** Mechanisms			
Estimator	OLS	OLS	OLS	IV	OLS	OLS	OLS	OLS
Sample	all	all	all	all	poor	rest	poor	rest
High temperature	0.028	0.051	0.044	0.041	−0.010	0.050	0.046	0.051
	(0.013)	(0.007)	(0.010)	(0.010)	(0.008)	(0.009)	(0.008)	(0.010)
High temperature		−0.035			0.048	−0.052		
× **UCT**		(0.009)			(0.001)	(0.002)		
High temperature			−0.038	−0.030			−0.045	−0.046
× **Infrastructure (SD)**			(0.008)	(0.009)			(0.006)	(0.004)
Kleibergen-Paap F-Stat				32.4				
HH and year effects	YES	YES	YES	YES	YES	YES	YES	YES
Households	2,436	2,436	2,436	2,436	609	1,827	609	1,827

Notes: Table reports effect of temperature on migration in northern Kenya; dependent variable takes value 1 if at least one household member left the district of residence; data are drawn from the follow up 1 (2011) and follow up 2 (2012) of the HSNP; *High temperature* = 1 if the dry season temperature in the location is above the long run median for that location; *UCT* = 1 if the location was randomly chosen to receive unconditional cash transfers (UCT) under the Hunger Safety Net Programme; *Infrastructure (SD)* is the first principal component of road network, electricity grid, GSM mobile telephone, education and health infrastructure in a location (normalised to have minimum value = 0 and standard deviation = 1); sample in columns 1, 2, 3, and 4 consists of whole HSNP sample, sample in columns 5 and 7 consists of households in lowest quartile of 2010 consumption distribution, sample in columns 6 and 8 consists of households in highest three quartiles of 2010 consumption distribution, column 4 instruments infrastructure with first principal component of lightning strikes and terrain ruggedness, HAC Conley standard errors (Conley, 1999) with 50km radius and two year lag reported in parentheses.

3.2 Policy responses to temperature shocks

Temperature shocks affect output in climate sensitive sectors (see Dell et al., 2014; for an overview). The ensuing negative impact on household consumption (more on this below) acts as a direct push factor for migration. As such, any policy that helps households to attenuate the negative consequences of higher temperatures has the potential to decrease the effect of temperature shocks on migration. For $policy_{l_i}$ in equation (1), we consider two commonly advocated types of policy interventions: income transfers and infrastructure improvements (World Bank, 2020).

Income transfers and infrastructure improvements as policy options. First, to examine whether disposable income influences the effects of climate on migration, we exploit the random allocation of unconditional cash transfers to households by the HSNP. Hence $policy_{l_i} = 1$ if location l_i was randomly chosen to receive HSNP transfers. The results in column (2) of table 2 show that receiving unconditional cash transfers under the HSNP almost completely offsets the effects of temperature on migration. Note that due to household fixed effects (ι_i), we cannot estimate the direct effect of unconditional cash transfers. However, column (1) of appendix table A4 suggests that (controlling for district fixed effects) HSNP transfers themselves have no significant direct effect on migration in our context.

Second, we investigate the importance of infrastructure development. We extract the first principal component from indicators reflecting a broad array of infrastructure dimensions. Specifically, we use geo-coded data on the overland road network, geo-coded data on mobile phone coverage and electricity (mainland electricity lines and electricity minigrids), and information drawn from the HSNP on educational and health facilities in each location (see section 2.3). For interpretability, we normalize this principal component to have a minimum value of 0 and a standard deviation of 1. Column (3) of table 2 shows that when interacting this index with $hot_{l_i,t-1}$, infrastructure significantly attenuates the effect of temperature on migration. A one standard deviation improvement in infrastructure from the lowest value decreases the effect of temperature by around 86%. In columns (1) to (3) of appendix table A5, we use the three broad components of our infrastructure (roads, electricity/GSM, and education/health facilities) separately and find that also individually they each reduce the effect of temperature shocks. Appendix figure A2 further shows that both random cash transfer receipts and infrastructure attenuate the effect of heat shocks along the temperature anomaly distribution.

Instrumenting infrastructure. Whilst receipt of randomized unconditional cash transfers is exogenous by design, there is a concern that infrastructure is endogenous with respect to migration. To address this, we instrument infrastructure in location l_i using two local geographical features. First, lightning strike frequency has been shown to damage electrical infrastructure such as telephone antennae used for GSM and electrical grids, which both are parts of our infrastructure measure (Manacorda and Tesei, 2020). Second, terrain ruggedness makes overland transportation hard (Nunn and Puga, 2012) and is thus related to our measure for roads. We extract the first principal component of these two geographical features, interact it with the hot dummy and use this interaction as an instrument for the $hot_{l_i,t-1} \times policy_{l_i}$ interaction. Note that all our estimations condition on household (and year) effects, which pick up any time-constant location characteristics. Therefore, the instrument's identifying variation only derives from the interaction with the time-varying hot dummy. As column (4) of table 2 shows, the instrumental variables parameter estimates are remarkably similar to their OLS counterparts in column (3). One possible interpretation of this is that—with respect to migration—infrastructure can be considered as conditionally exogenous in our context. Consequently, we use causal language when discussing the OLS estimates. First stage estimates are reported in appendix table A5 and illustrated graphically in appendix figure A3.

Heterogeneity by income at baseline. For some households, cash transfers may help overcome binding financial constraints. We thus assess whether the impact of our two policies varies by income, distinguishing poor households based on consumption expenditure in 2010 (before migration choices are made). Column (5) of table 2 shows that receiving unconditional cash transfers under the HSNP increases (rather than decreases) the effect of temperature shocks for the poorest quartile. This is in line with studies documenting that at low levels, additional income is used to fund migration (Clemens, 2021). For comparably richer households, by contrast, UCT receipt attenuates the effect of heat shocks (see column 6).[13] Instead, the effect of infrastructure on temperature's impact in columns (7) and (8) does not vary with income levels in 2010.

3.3 Sector and livestock choice as alternative coping strategies

The negative effect of temperature on household welfare varies significantly with the sector household members work in and with the livestock they own. Figure 3c shows the effect

[13] This does not contradict the generally higher migration rates among richer households. In fact, we do document such a positive relation in appendix figure A8, which our model presented below is able to replicate.

of abnormally high temperatures on per capita consumption, a common proxy for welfare (Deaton, 1997). The left set of bars show that following high temperatures, per capita consumption for households working in agriculture decreases substantially but does not change for non-agricultural households. While, due to household's endogenous sector choice, we do not interpret these changes as causal, they are (like the estimates in table 2) net of household and year effects. The two bars on the right of figure 3c further indicate a milder loss in consumption following a heat shock for households that own camels. The differences between each set of bars are statistically significant.

Given these differential impacts, occupational and livestock composition changes are plausible alternatives to emigration. In fact, several papers highlight sectoral transitions as an important adjustment mechanism, see, for instance, Colmer (2021), Macours et al. (2022), and Liu et al. (2023). Given that most respondents are pastoralists (see Section 2.3), we consider two alternative coping mechanisms for households, which we model explicitly in Section 4: i) change the sector in which they work and ii) buy camels, which have a higher heat tolerance than other common livestock, such as goats, sheep and particularly cattle.

Temperature and sector choice. We investigate the effect of temperature shocks on sector choice by re-estimating equation (1) using the dependent variable $agriculture_{it} = 1$ if at least one member of household i in year t works in the agricultural sector.[14] Panel (c) of figure 2 visualizes the proportions of households moving out of agricultural occupations geographically. The estimate in column (1) of table 3 shows that in years when dry season temperature is above the long run median, households are 4.7 percentage points less likely to be active in the agricultural sector, conditional on household and year effects.

Temperature and livestock choice. To assess the effect of temperature on camel ownership, we re-estimate equation (1) using $camels_{it}$ as a dependent variable, which takes the value one if household i owns at least one camel in year t.[15] Changes in the shares of households owning camels are shown in panel (d) of figure 2. The estimate in column (2) of table 3 indicates that during years when the dry season temperature exceeds the long run median, households are 4.4 percentage points more likely to own at least one camel. We also estimate temperature's effect on cattle, which are the least heat resistant type of commonly owned livestock. Column (3) shows a negative effect. Together with column (2) this result points towards households selling cattle in order to buy camels. These patterns also suggest

[14]Since occupational information is provided in all three rounds, we use the years 2010, 2011, and 2012 for this estimation.

[15]Since livestock ownership information is provided in all three rounds, we use the years 2010, 2011, and 2012 for this estimation.

that credit constraints are no significant obstacles to changes in livestock composition. This tallies with other results showing neither a direct effect of cash transfers on camel or cattle ownership (columns (3) and (4) of appendix table A4), nor a change in the effect of heat by receipt of the transfers (columns (6) and (8) of table 3).

Table 3: Temperature, occupation, and livestock

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Dependent variable = 1 if at least one household member								
	works in agricult.	owns camel	owns cattle	works in agriculture		owns camel		owns cattle	
Sample mean	0.65	0.36	0.22	0.65		0.36		0.22	
High temperature	−0.047	0.044	−0.073	−0.037	−0.032	0.039	0.078	−0.074	−0.065
	(0.017)	(0.025)	(0.027)	(0.027)	(0.019)	(0.028)	(0.025)	(0.033)	(0.038)
High temperature × UCT				−0.019		0.011		0.002	
				(0.029)		(0.020)		(0.027)	
High temperature × Infrastructure (SD)					−0.044		−0.094		−0.022
					(0.015)		(0.020)		(0.033)
HH and year effects	YES	YES	YES	YES	YES	YES	YES	YES	YES
Households	2,436	2,436	2,436	2,436	2,436	2,436	2,436	2,436	2,436

Notes: Table reports effect of temperature on occupational sector choice and camel ownership in northern Kenya; dependent variable in columns 1, 3, and 4 takes value 1 if at least one household member works in agricultural occupations (herding or agriculture); dependent variable in columns 2, 5, and 6 takes value 1 if household owns at least one camel; dependent variable in columns 3, 8, and 9 takes value 1 if household owns at least one cattle; data are drawn from baseline (2010), follow up 1 (2011), and follow up 2 (2012) of the HSNP; *High temperature* = 1 if the dry season temperature in the location is above the long run median for that location; *UCT* = 1 if the location was randomly chosen to receive unconditional cash transfers (UCT) under the Hunger Safety Net Programme; *Infrastructure (SD)* is the first principal component of road network, electricity grid, GSM mobile telephone, education and health infrastructure in a location (normalised to have minimum value = 0 and standard deviation = 1); HAC Conley standard errors (Conley, 1999) with 50km radius and two year lag reported in parentheses.

Sector choice, livestock and infrastructure. As with migration, we investigate whether the effect of temperature on occupational sector choice and on camel and cattle ownership varies by randomized transfer receipt and local infrastructure. Intuitively, changing sector, in particular towards non-agricultural occupations, may be easier for households in areas that are well connected economically.

The parameter estimates in column (5) of table 3 show that the effect of temperature shocks on households moving out of the agricultural sector is significantly stronger for households living in locations with better infrastructure. A one standard deviation increase from the lowest infrastructure level roughly doubles occupational sector changes. By the same token, in column (7) of table 2 we find that increases in camel ownership are significantly weaker in areas with better infrastructure. A one standard deviation increase from the lowest infrastructure level fully offsets camel acquisitions. Column (9) further shows that temperature's effect on cattle sales is stronger (although statistically insignificant) in areas with better infrastructure, again pointing towards households exiting the agricultural sector.

Taken together the estimates in column (5) of table 3 suggest that better infrastructure allows households to respond to temperature shocks by changing occupational sector. This, in turn, may decrease the need for household members to migrate or to change their livestock composition (as confirmed by column (7)). We explore the inter-relationships between choices in detail using the structural model in Section 4.

Sector choice, livestock and cash transfers. In contrast to above, we find that the effect of temperature shocks on occupational sector choice or livestock ownership does not vary with random receipt of cash transfers. Columns (4), (6), and (8) of table 3 show small and statistically insignificant point estimates on the interaction between the $hot_{i,t-1}$ dummy and cash receipts. In columns (2) to (4) of appendix table A4 we also estimate the direct effect of HSNP transfers on sector choices and on livestock ownership and find no changes.

4 A Model of Temperature, Migration, Sector, and Livestock Choices

4.1 Intuitive overview

The purpose of our model is to credibly predict the effects of common policy interventions on climate migration whilst accounting for alternative coping mechanisms, as well as for potential equilibrium effects. Households maximise their income via three costly choices: emigration (of a member or the entire household), sector of occupation (agriculture or non-agriculture), and livestock ownership (whether to own heat resistant camels). The cost of each option varies with local infrastructure, a household's previous sector of economic activity, and—to approximate financial constraints—with household income in the previous period. In each sector and location, employees earn their marginal product of labor, which, in turn, depends on the number of employees in that particular sector and location. If households send a migrant, they receive remittances. We allow for high temperature to affect transfers from migrants and other sources, and to change the marginal product of labor. Crucially, the extent to which heat alters productivity, depends the household's occupation and the livestock the household owns. For instance, high temperature shocks depress the marginal product of labor less in non-agricultural than in agricultural occupations. In addition, our model allows infrastructure to have a sector-specific effect on productivity.

4.2 Model setup

Households are heterogeneous in size and their initial location and sector of economic activity, and all choices depend on idiosyncratic preferences. Locations are differentially exposed to shocks, and further differ in the level of infrastructure and treatment status in the randomized cash transfer programme. Temperature shocks affect consumption both through a direct impact on productivity, a potential change in the level of transfers received from migrant members or households' broader network, and through an equilibrium wage effect arising from an endogenous response in labour supplied to different sectors. Households have three adjustment options: (i) migration of either a member or the entire household, (ii) changing to a sector of employment where incomes are less affected by temperature shocks, and (iii) purchasing camels. This joint modelling of choices allows us to examine the distinct channels through which common policies such as cash transfers or infrastructure development affect migration.

Notation. Each period t, household i chooses $m_{it} \in \{0, 1, E\}$, indicating whether no member migrates, a household member is sent as migrant,[16] or the entire household migrates. In the former two cases, the household further decides on the sector $s_{it} \in \{A(griculture), N(on-agriculture)\}$ in which its members are economically active, and agricultural households choose whether their animals include camels or not, indicated by $a_{it} \in \{C(amels), O(ther)\}$. Each of these choices will respond to heat shocks. To be consistent with the estimations in Section 3, we use the same indicator $hot_{l_i,t}$ for dry season temperature being above the local long run median in location l_i.

Earnings and remittances. Households value per capita consumption c_{it}, which is financed through per capita income y_{it}. This income derives from wages w_{it} earned in a given sector, migrant remittances $r^m(hot_{l_i,t})$ or other transfers $r^o(hot_{l_i,t})$ from their social network, each of which may vary with temperature shocks. Finally, a household enjoys unconditional cash transfers $hsnp_{l_i,t}$ from the HSNP, if its location is randomly allocated to the treatment group. Per capita consumption in a household of size n_i, which has sent at

[16]We do not observe any household in our data that sends more than one member to migrate.

most one migrant (so that $m_{it} \in \{0,1\}$), then is given by $c_{it} = y_{it} = w_{it} + r^m(hot_{l_i,t})m_{it}/(n_i - m_{it}) + (r^o(hot_{l_i,t}) + hsnp_{l_i,t})/n_i$.

Wages in each sector s_{it} are given by the marginal product of labour, derived from a non-linear function of the number of workers $L_{s_{it}}$ in that sector as

$$w_{it} = \phi_{it}\theta L_{s_{it}}^{\theta-1} e^{v_{it}}, \tag{2}$$

where $\theta \in (0,1]$ determines the elasticity of labour demand, and v_{it} denotes an idiosyncratic wage component. Productivity, in turn, varies with

$$\phi_{it} = \phi_{s_{it},a_{it},0}\phi_{s_{it},a_{it},h}^{hot_{l_i,t}}\phi_{s_{it},d}^{d_{l_i}},$$

which differs by sectors of economic activity s_{it} and for agricultural households by whether their livestock a_{it} includes camels. In addition, productivity is a function of the local level of infrastructure development d_{l_i} and of temperature shocks $hot_{l_i,t}$, the impacts of which again vary with sector and camel ownership. For consistency, we use the same measure for infrastructure introduced in Section 3.2, which summarizes a set of indicators ranging from road network density to digital infrastructure. The wage w_{it} in each sector and location hence is an equilibrium outcome, and depends on the exogenous shocks both directly and indirectly through the endogenous labour supply to different sectors.[17] Solving the model thus requires that we iterate until wages and the distribution of the labour force converges.

Since we observe that both migrant and non-migrant transfers vary with households' exposure to heat shocks, we predict transfers received through a household's non-migrant network as

$$r_{l_i,t}^o = \hat{\rho}_0^o + \hat{\rho}_1^o \ hot_{l_i,t}, \tag{3}$$

based on a regression of observed transfers on the temperature shocks. When a household sends a member to migrate, its income is further augmented by migrant remittances

$$r_{l_i,t}^m = \hat{\rho}_0^m + \hat{\rho}_1^m \ hot_{l_i,t}. \tag{4}$$

Households in our model thus care about remittance receipt rather than migrants' potentially under-estimated total income (Baseler, 2023) or their disutility from migration (Imbert and Papp, 2020).

[17]Note that identification relies on the parametrization of the model, which makes local productivity a function of observables s_{it}, a_{it}, $hot_{l_i,t}$, d_{l_i} and $L_{s_{it}}$ only.

Migration, sector change and livestock costs. Migration, sector changes and camel acquisition are costly, with costs depending both on a household's previous sector of economic activity s_{it-1} and the level of development d_{l_i} in its location l_i. Given the literature on financial constraints to migration (see, for instance, Bryan et al., 2014; Bazzi, 2017; Gazeaud et al., 2020; Clemens, 2021; Görlach, 2023), we let migration (as well as the other) costs be a function of a household's previous income y_{it-1}. Lagged income is the closest approximation to the stock of assets, which is the key variable in financial constraints. Studies in this literature face the common problem of separately identifying the direct effect of income on consumption on the one hand and the effect it has on financial constraints on the other. We rely on a timing assumption, which amounts to assuming that costs are to be paid upfront and can be covered by past incomes, whereas choices are made based on expected utility in the current period. We denote costs by $\delta^m_{it} = \delta^m(d_{l_i}, y_{it-1}, s_{it-1})$ for migration choice m, $\eta^s_{it} = \eta^s(d_{l_i}, y_{it-1}, s_{it-1})$ for the choice of sector s, and $\kappa_{it} = \kappa(d_{l_i}, y_{it-1})$ for camel acquisition.[18]

Choices. Households decide on migration, sector of economic activity and livestock composition. Given the above cost functions, the household's problem is given by

$$\max_{m \in \{0,1,E\}} \quad V_{it}(m) - \delta^m_{it} + \varepsilon^m_{it}, \tag{5}$$

where the values of migration choices $m \in \{0, 1\}$ entail a value maximizing choice of sector $s \in \{A, N\}$,

$$V^m_{it}(m \in \{0,1\}) \;=\; \max\{V^A_{it} - \eta^A_{it} + \varepsilon^A_{it}, u(c_{it}) - \eta^N_{it} + \varepsilon^N_{it}\}. \tag{6}$$

When a household chooses the agricultural sector, it further decides on having camels among its livestock,

$$V^A_{it}(m \in \{0,1\}, s = A) = \max_{a \in \{C,O\}} u(c_{it}) - \kappa_{it} + \varepsilon^a_{it}. \tag{7}$$

Flow utility is given by $u(c) = \frac{(c-\alpha_c)^{1-\gamma}-1}{1-\gamma}$, with minimum consumption level α_c and risk aversion γ. The terms ε^m_{it}, ε^s_{it} and ε^a_{it} capture unobserved idiosyncratic taste shocks for each option. Since we do not observe outcomes if an entire household migrates, we estimate an overall expected payoff $\omega_E \equiv V_{it}(m = E) - \delta^E_{it}$ from that choice.

[18] We assume that the cost of staying in the same sector ($s = s_{it-1}$) is zero. For sector changes, as well as for migration and livestock choices, we assume that costs are log linear functions of d_{l_i} and y_{it-1}, see appendix F.

In line with the reduced form estimations in Section 3, we assume that households use the previous period's temperature realization $hot_{l_i,t-1}$ as a basis for their choices.

4.3 Identification and estimation

We first estimate equations (3) and (4) for transfers. Appendix figure A5 shows the estimated parameters of these relations. All preference, wage and cost parameters are then estimated jointly by method of simulated moments, targeting observed (conditional) migration, sector and livestock choices, log expenditure per capita by sector, infrastructure, heat exposure and camel ownership, the variance of log expenditure and the correlation between log expenditure and the log share of the workforce active in a given sector by location and year. This latter moment identifies the curvature parameter parameter θ.[19] See below and Appendix F for details. Solving for the choice probabilities implied by the model requires a specification of the distributions of preference shocks ε^a_{it}, ε^m_{it} and ε^s_{it}. We assume that these shocks are extreme value distributed with spread parameters σ_a, σ_m and σ_s, leading to logistic closed form solutions for agents' choice probabilities. Finally, we assume that idiosyncratic shocks v_{it} to log wages are normally distributed with variance σ^2_v.

Identification. We estimate the model's 29 structural parameters by targeting 30 empirical moments from the HSNP data. Our vector of moments includes (I) the reduced form estimates from columns (2) and (3) of table 2. While all moments jointly identify the set of parameters, these reduced form coefficients contribute most directly to the identification of preference parameters γ, α_c and σ_m. (II) We target coefficients from a regression of an indicator $\mathbb{1}[m_{it} = 1]$ for sending a migrant on HSNP treatment status, d_{l_i}, and indicators $\mathbb{1}[s_{it-1} = A]$ and $\mathbb{1}[s_{it-1} = N]$. These coefficients identify the cost $\delta^m(d_{l_i}, y_{it-1}, s_{it-1})$ of sending a migrant. (III) The fraction of households leaving the panel identifies the value ω_E of an entire household migrating. (IV) The coefficients in columns (1) and (2) of table 3 identify σ_a and σ_s. (V) We also target coefficients from two regressions of, respectively an indicator $\mathbb{1}[s_{it} = N]$ for switching to non-agriculture among households with $s_{it-1} = A$ and an indicator $\mathbb{1}[s_{it} = A]$ for switching to agriculture among households with $s_{it-1} = N$, each on HSNP treatment status, d_{l_i}, and a constant, identifying the costs $\eta^s(d_{l_i}, y_{it-1}, s_{it-1})$ of changing sector. (VI) coefficients from a regression of an indicator $\mathbb{1}[a_{it} = C]$ for owning a camel on HSNP treatment status, d_{l_i} and a constant. These identify the cost $\kappa(d_{l_i}, y_{it-1})$ of

[19]Note that because wages in each sector are an equilibrium outcome that depends on endogenous sector choices, we cannot pre-estimate the wage equation. Rather, we solve the model numerically by iteration to find the equilibrium wage in each sector.

acquiring a camel. (VII) Mean log per capita expenditure[20] for non-agricultural households and for agricultural households by camel ownership identifies the productivity level parameters $\phi_{s_{it},a_{it},0}$. (VIII) The effect of heat on log per capita expenditure as well as the differences by sector and camel ownership, corresponding to the differences between the bars displayed in figure 3c. These identify the change $\phi_{s_{it},a_{it},h}$ in productivity due to heat shocks by sector and camel ownership.[21] (IX) Coefficients from regressions of log per capita expenditure on infrastructure by sector identify the sector-specific contribution $\phi_{s_{it},d}$ of infrastructure to productivity. (X) The correlation between log per capita expenditure and the log share of the workforce active in a given sector, location and year identifies the curvature parameter θ. (XI) We also target the variance of log per capita expenditure (conditional on year and location effects) to identify the variance σ_v^2 of idiosyncratic shocks to log wages. Figure A6 visualizes the gradient matrix of moments with respect to parameters. The fact that this matrix has full rank, formally demonstrates local identification of all parameters under the model. Appendix figure A7 and table A7 show that the model fits these moments well. Figure A8 in the appendix further shows a good fit also for important moments not targed in the estimation.

Parameter estimates. We list all structural parameter estimates of our model in appendix table A8. We estimate strong negative effects ($\phi_{A,O,h} < 1$) of heat on earnings by agricultural households that do not own camels, but little direct effect on other households ($\phi_{A,C,h} \approx \phi_{NA,h} \approx 1$). Yet, in equilibrium, decreasing marginal returns to labor ($\theta < 1$) indicate that endogenous labor supply adjustments across sectors will lead to spillovers of temperature shocks also on non-agricultural households. The cost of sending a migrant is similar for agricultural and non-agricultural households ($\delta_A \approx \delta_{NA}$), but slightly decreases with lagged earnings ($\delta_y < 0$). In line with panel B of table 2 hints at the existence of weak financial constraints for migration.[22] Transitions from agricultural to non-agricultural occupations are more costly than vice versa ($\eta_A^{NA} > \eta_{NA}^{A}$), but decrease strongly with the quality of infrastructure ($\eta_d^{NA} < 0$). More specifically, a one standard deviation improvement in infrastructure amounts to a $1 - \exp(\eta_d^{NA}) \approx 85\%$ decrease in the baseline cost of

[20]We use households' consumption expenditure, since it is measured more precisely than income. In particular, since many households in our context are self-employed, reported income may not be net of expenditure on input factors. We subtract from these expenditures income from transfers, such as remittances and HSNP cash transfers.

[21]We condition on year and household fixed effects. In general, all targeted regression coefficients are net of year effects as well as the finest possible cross-sectional variation. For instance, the first set of moments (I) can condition on year and household effects, whereas moments (II) only condition on year effects because d_{l_i} varies on the location level. Moments (III) condition on year and location effects etc.

[22]We measure income per capita in 100 USD PPP. That is, each USD PPP of lagged income per capita lowers the cost of migration by $1 - \exp(\delta_y) \approx 0.1\%$.

entering a non-agricultural occupation. Our estimate for α_c indicates an annual minimum level of consumption of 128 purchasing power adjusted USD per adult-equivalent household member. Finally, our estimate for relative risk aversion $\gamma = 3.1$ is well in line with classical estimates in the literature, such as Friend and Blume (1975).

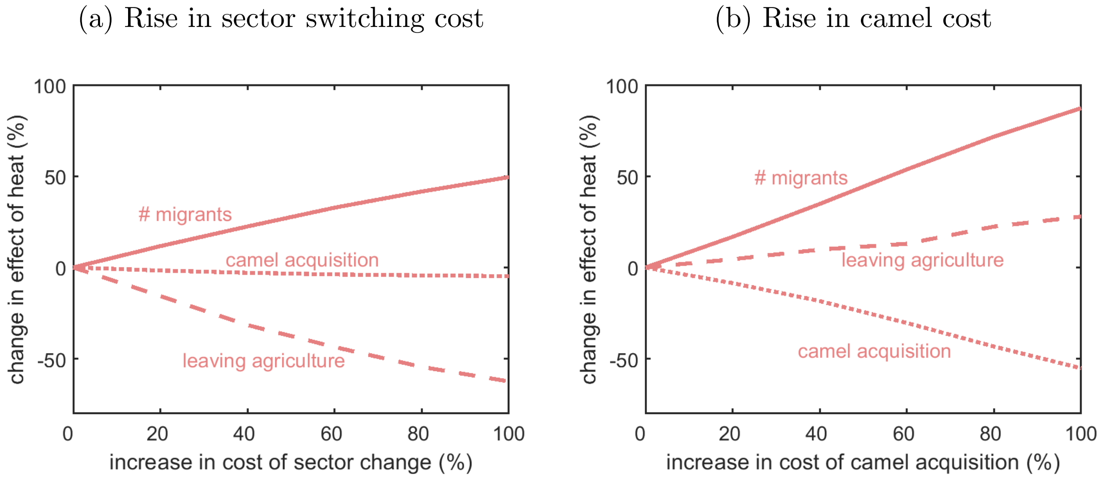
4.4 Results

Importance of alternative coping strategies. The descriptive evidence in figure 3b suggests that occupational transitions may act as an alternative to climate migration. To investigate the substitution patterns between migration and alternative choices in detail, we use our model to predict how the response in each would change if the cost of different choices increased. Panel (a) of figure 5 shows that an increase in the cost of transiting to non-agricultural occupations raises the effect of temperature shocks on migration (solid line), with a doubling of the total cost of changing to non-agricultural activities raising the effect of a heat shock on migration by 50%. This indicates that migration and sectoral change are strong substitutes in the response to shocks. Camel acquisition, instead, remains unaffected (dotted line). The corresponding patterns for a rise in the cost of camel acquisition are displayed in panel (b) of the figure. We find that the predicted effect of heat on migration is boosted by 87% as the cost of camel livestock acquisition doubles. The share of households leaving agriculture in response to a shock increases by 28% (dashed line).[23] Taken together, figure 5 highlights the importance of modelling migration jointly with alternative margins of adjustments.

Equilibrium effects. The inclusion of equilibrium effects in our model implies that temperature shocks primarily affecting the climate sensitive agricultural sector can have spillover effects on the non-agricultural sector. While such effects are likely to be small, they are an important aspect to consider when scaling up policies. Figure 6 plots a worker's marginal productivity in each sector (averaged across locations) against the local population share working in agriculture. In our model, where workers are paid their marginal product, these curves are akin to inverse labour demand curves. The figure indicates a labour demand elasticity in non-agriculture (dashed red line) of -0.28, and of -0.14 in agriculture (solid green line). These magnitudes are much in line common estimates, both for high and low income countries (Borjas, 2003; Hasan et al., 2007). This implies, for instance, that a 10 percent (or 3.3 percentage point) increase in the share of non-agricultural households lowers earnings in that sector by a little less than 3 percent, or 17 USD PPP per capita.

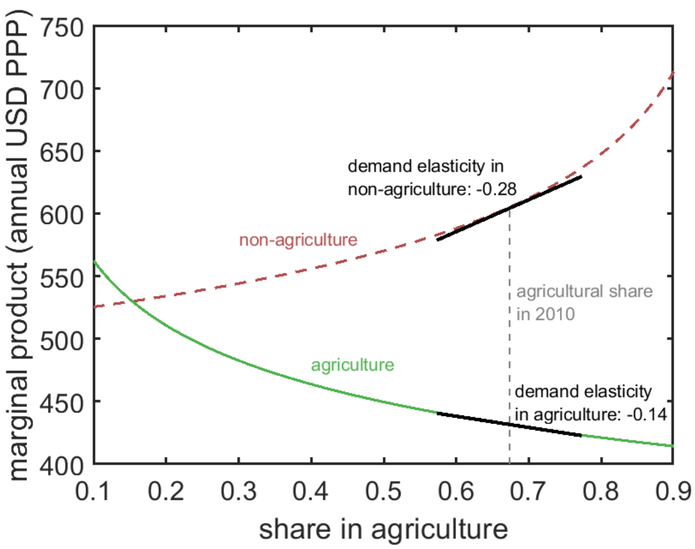
[23] At median levels of infrastructure and household income, the total cost of camel acquisition (250 USD PPP) exceeds that of sector switching by 58%.

Figure 5: The effect of heat on alternative shock coping strategies



Notes: Figure shows the substitution patterns between different response margins to a temperature shocks. Panel a: Change in the effect of above median local dry season temperature on alternative choices as the cost of entering the non-agricultural sector increases; panel b: Change in the effect of above median local dry season temperature on alternative choices as the cost of camel acquisition increases.

Figure 6: Equilibrium effects



Notes: Figure shows an average worker's marginal productivity in agricultural and non-agricultural occupations as a function of the local population share working in agriculture. The solid green line indicates the marginal productivity in agriculture; the dashed red line shows te same for non-agriculture.

Policy and cost analysis. We use our estimated model to assess how different policies alter the effect of heat shocks on migration. In particular, we consider spending one billion Kenyan shillings[24] (KES) to develop infrastructure, transferring the same amount as unconditional or conditional cash transfers directly to households, or to subsidize sector transitions. Compared to the reduced form analysis, our structural model allows for a more credible extrapolation to policies other than the ones actually in place.

Four ways to spend 1bn KES. For the first policy, infrastructure, we focus on building overland roads for which reliable cost estimates are readily available from the World Bank's Road Costs Knowledge System (ROCKS) Database and other sources that we describe in appendix G. Based on the estimates for Kenya, 1bn KES spent on roads in the four HSNP districts Mandera, Marsabit, Turkana and Wajir would raise our infrastructure measure by 0.0088 standard deviations. The World Bank estimates that roads in Africa have a life span of about 20 years, after which they typically require resurfacing. Hence, to account for the longer-run effect of infrastructure investment, we multiply the above number with 20. As a second policy, the same 1bn KES paid out as unconditional cash transfers in these districts would imply a transfer of about 576.89 KES (15.19 USD PPP) per adult equivalent capita. Third, we consider the same policy, but targetting payments to agricultural households. This policy will lower both the effect of temperature shocks on migration and on transitions out of agriculture. On the upside, 1bn KES allows larger payments when these focus on agricultural households only. Finally, 1bn KES is used as a subsidy to agricultural households which enter non-agricultural activities. This policy provides an economic incentive for individuals to move into new, less climate sensitive sectors.

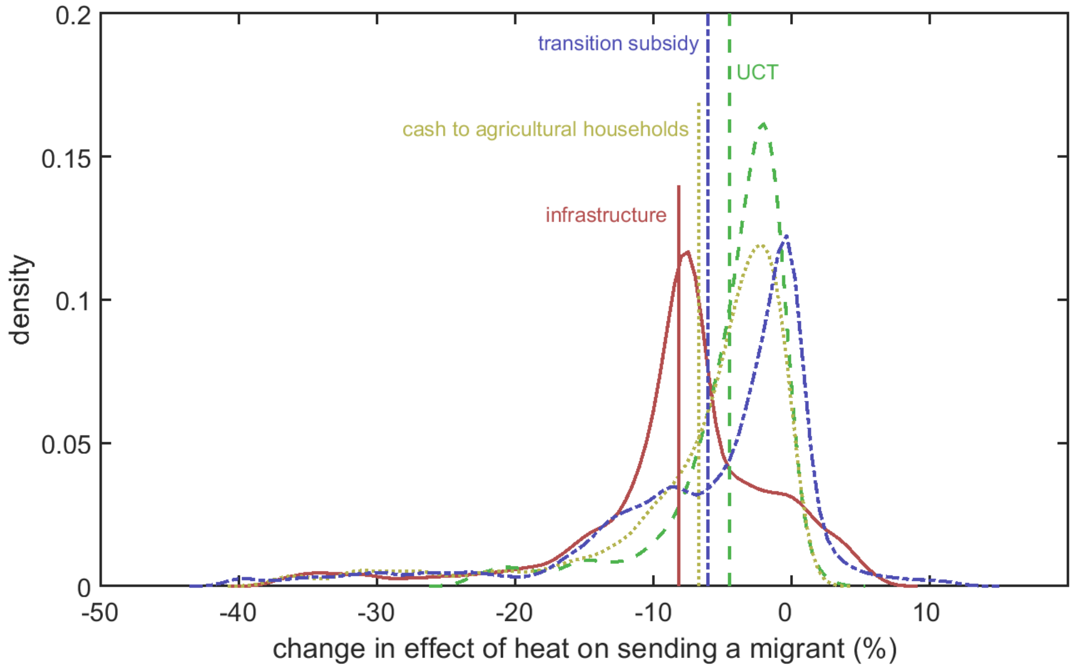
Policy simulations. Panel (a) of Figure 7 shows the means and distributions of the impact of these four policies on the response in migration to temperature shocks. In line with our regression analysis in table 2, we focus on the choice of sending a migrant. 1bn KES invested in infrastructure improvement reduces the effect of heat on sending a migrant by an average of 8.2% (solid red vertical line). The mean mitigating effect of unconditional cash transfers of the same costs (dashed green line) amounts to 4.5%.

When channelling cash transfers to purely agricultural households only, the same total of 1bn KES make for transfer of 23.60 USD PPP per (adult equivalent) capita in agricultural households. This larger amount accelerates the change in the effect of temperature shocks on migration, which under this policy is reduced by 6.7% (dotted yellow line). Finally, we consider a subsidy for sectoral transition. Since the amount that each household receives depends on the number of households choosing to enter non-agricultural activities, we solve for the actual amount through iteration. These subsidies lower the cost of entering a non-

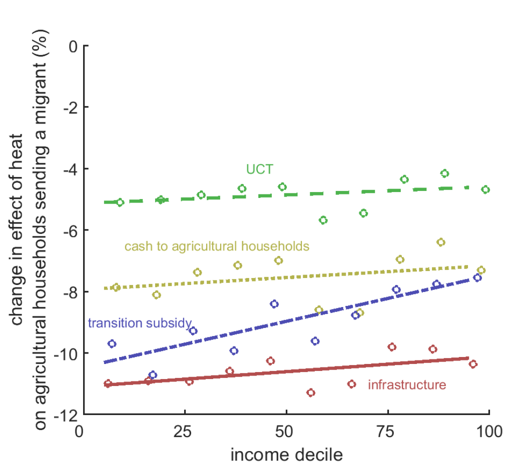
[24]Equivalent to about 12 million nominal USD or 26 million PPP adjusted USD in 2012.

Figure 7: The impact of 1bn KES on the effect of heat on migration

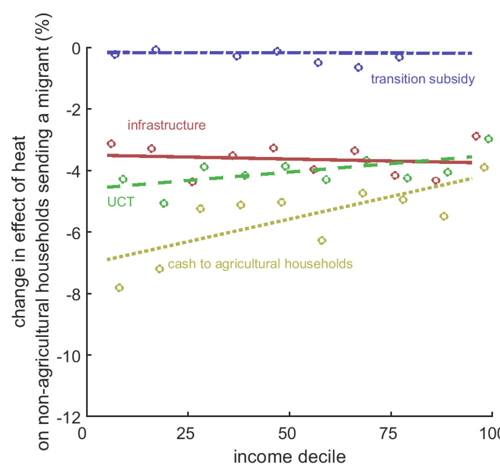
(a) Unconditional effects



(b) By income: Agriculture



(c) By income: Non-agriculture



Notes: Figure shows changes in the effects of above median local dry season temperature on migration if 1bn KES are spent through four different policies: (i) infrastructure development in the districts Mandera, Marsabit, Turkana and Wajir (solid red lines); (ii) unconditional cash transfers to all households in these districts (dashed green lines); (iii) transfers to agricultural households only (dotted yellow lines); or (iv) spending half of the amount as unconditional transfers to all households and the other half as a subsidy for entering non-agricultural activities (dash-dotted purple lines). Panel (a) shows means and distributions of changes when 1bn KES through these policies. Panel (b) shows mean changes within income deciles as well as fitted lines.

agricultural occupation by 354 USD PPP in 2011 and 365 USD PPP in 2012, implying a cost reduction for the average household by 72%. Transition subsidies boost sectoral change as an adaptation channel alternative to migration, thus lowering the effect of a temperature shock on migration by 6.0% (dash-dotted purple line).

Effects by sector and along the income distribution. Panels (b) and (c) of Figure 7 plot the effectiveness of our policies against the distribution of household incomes, separately for agricultural and non-agricultural households, with fitted lines for each policy. This exercise allows us to shed light on how each policy changes the composition of migrants. The two panels show similar relative effects of unconditional cash transfers for all types of households (green dashed lines). Cash transfers targeted at agricultural households, in turn, reduce the effect of temperature shocks both on migration and on sector transitions. The latter raises non-agricultural incomes through equilibrium effects. These spillover effects mitigate also part the (weaker) effect heat has on the share of non-agricultural households sending a migrant (yellow dotted lines). Instead, the two policies that ease sectoral transition (infrastructure improvement and transition subsidies) have the strongest impact for agricultural households, whose shock coping strategies are directed towards sectoral transition and away from migration. In particular, transition subsidies (dash-dotted purple lines) have zero effect for non-agricultural households. For agricultural households, the linear fitted line indicates that the impact of transition subsidies is strongest for lower income households. Infrastructure improvement, instead, besides easing sectoral transition, also boosts incomes, in particular for non-agricultural households. It thus offsets part of the effect of heat on migration also for the latter, albeit to a lower degree than for agricultural households (red solid lines).

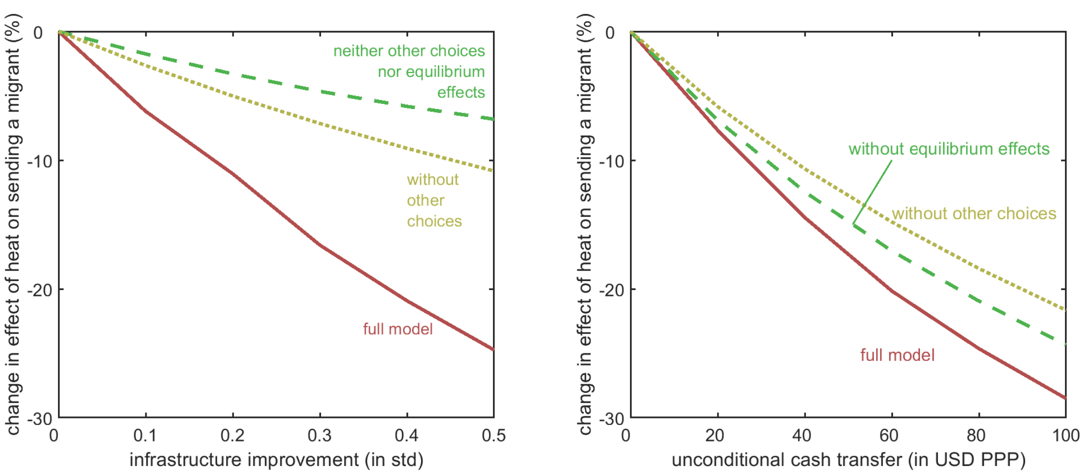
Policy predictions in alternative models. Whilst the estimates in table 2 show that income support programs such as the HSNP or infrastructure development both dampen the effect of temperature shocks on out-migration, table 3 also suggests that the mechanisms behind these effects are very different. Supporting households through direct assistance can help alleviate most severe hardship; the development of local infrastructure, by contrast, can ease transitions out of agriculture after temperature shocks. Predictions of the effectiveness of different policies hence crucially hinge on the modelling of migration in conjunction with other coping strategies.

We demonstrate the importance of this by re-estimating a version of our model in which migration of either individual household members or migration by entire households are the only choices. The direct effect of cash transfers on households' income and consumption, as well as the productivity enhancing effect of infrastructure development soften households' welfare loss following temperature shocks, and thus reduce the effect of migration, as in our full model with sector and livestock choices as alternative shock coping strategies. In a model without these choices, however, the additional cost reduction effect—in particular of infrastructure on transitions to non-agricultural occupations—is absent. Accordingly, such a model would under-estimate the impact infrastructure investments have on the effect of heat on migration. We illustrate this for our two core policies (infrastructure and unconditional cash transfers), by predicting counterfactual effects on migration for an expansion in infrastructure using both our full model with multiple choices, and the (re-estimated) constrained model with migration choices only. The red solid line in panel (a) of figure 8 shows the average effect of infrastructure in the full model, corresponding to the red solid lines in figure 7. Instead, the yellow dotted line indicates the same for the constrained model as described above. This constrained model without alternative choices under-estimates the change in the effect of heat on migration when infrastructure improves by 0.1 standard deviations by 3.6 percentage points or 58%. Panel (b) shows the corresponding effect for unconditional cash transfers. While also cash transfers ease sectoral transitions, this effect is weaker than for infrastructure improvement. Accordingly, a model without alternative choices under-estimates the mitigating impact of cash transfers on households' migration response to heat shocks to a smaller degree, by 24% at an annual level of cash transfers of 100 USD PPP. These counterfactual simulations highlight that constrained models under-estimate the mitigating effect of both types of policies—and primarily of infrastructure development—on the migration response to temperature shocks.

An additional benefit of the structural analysis is that it accounts for equilibrium effects. These imply that decreases in agricultural earnings after a heat shock are counteracted by wage increases resulting from households leaving agricultural occupations either for the local non-agricultural sector or to destinations outside the district. Since infrastructure facilitates these moves, it also magnifies equilibrium effects. In particular, a positive effect on agricultural incomes following an improvement in infrastructure implies that the effect of heat on migration is muted further. To quantify the importance of this for the evaluation of different policies, we estimate a third version of our model, in which in addition to sector and livestock choices, we also eliminate any equilibrium adjustments. Panel (a) of figure 8 shows that absent equilibrium adjustments, we would under-estimate the reduction in the effect of heat on temperature by an additional 0.9 percentage points, accumulating to a total underestimation by 72% when infrastructure improves by 0.1 standard deviations (green dashed line). Instead, cash transfers reducing the movement of households out of agriculture implies that equilibrium effects put downward pressure on agricultural incomes, offsetting part of the mitigating impact cash transfers have for the effect of temperature shocks on migration. Panel (b) shows that abstracting from equilibrium adjustments in addition to alternative choices strengthens the mitigating effect of cash transfers.

Figure 8: Mitigating effects of different policies

(a) Infrastructure improvement (b) Cash transfers



Notes: Figure shows changes in the effects of above median local dry season temperature on migration, for different levels of infrastructure developments and unconditional cash transfers. The figure shows predictions of the full equilibrium model (red solid lines), as well as for alternative models which successively abstract from choices other than migration (yellow dotted lines) and also equilibrium effects (green dashed lines). Panel a: Change in effect on share of households having at least one member migrate by infrastructure improvement (in standard deviations); panel b: Change in effect on share of households having at least one member migrate by level of cash transfers (in annual USD PPP).

5 Conclusion

The International Organization for Migration (IOM, 2020) recognises that climate change drives migration by thinning resources and making areas inhospitable. This paper highlights the importance of considering migration responses to weather shocks jointly with other coping strategies. Aside from emigration, weather shocks also increase changes out of agricultural occupations and livestock ownership of households. We show that common types of interventions—pecuniary transfers and infrastructure development—significantly weaken the effect of heat on out-migration, albeit via different channels. A key finding of our paper is that modelling migration jointly with other choices has crucial implications for the predicted impact of common policy alternatives. Models not considering other coping strategies strongly under-estimate effects of common policies in curbing climate change's effect on migration. In particular, we also show that investments in local infrastructure are considerably more cost effective in terms of their mitigating impact than direct cash payments. This difference is obscured if migration is investigated in isolation. The finding that climate change is seen as a major diver behind population movements stresses the importance of modelling migration jointly with other choices and accounting for equilibrium effects. The latter are particularly important when programmes are scaled up. Our results clearly show that policies can offset push factors such as weather shocks to a significant degree. In particular the occupational transition supported by infrastructure investments is in line with Sustainable Development Goal 9 of developing resilient and sustainable infrastructure.

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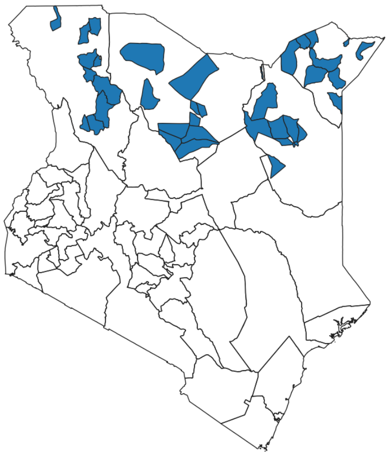
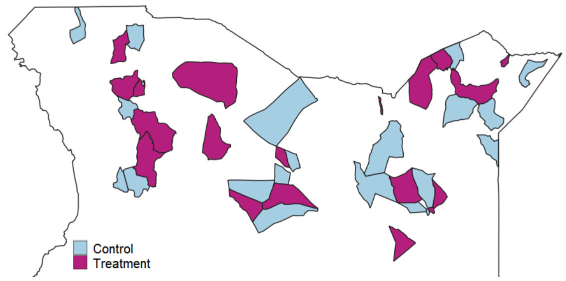
A Additional maps

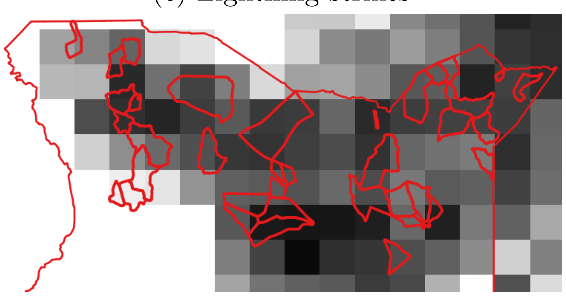
(a) Locations in Kenya



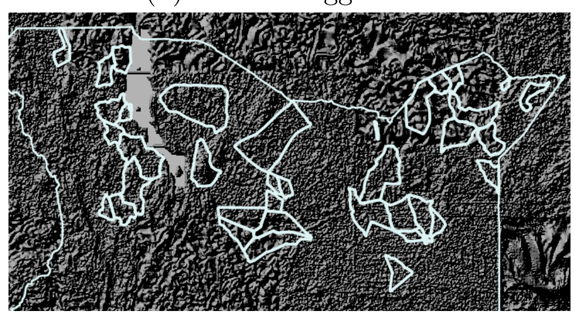
(b) HSNP random treatment status



(c) Lightning strikes



(d) Terrain ruggedness



Notes: map a) shows the 40 locations covered by the HSNP along with Kenya's 40 districts. map b) shows the 40 locations covered by the HSNP by random receipt of unconditional cash transfer (treatment) and no receipt (control). map c) shows the 40 locations covered by the HSNP along with number of lightning strikes as reported by NASA. map d) shows the 40 locations covered by the HSNP along with terrain ruggedness.

B Robustness

Table A1: Alternative clustering methodologies

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Dependent variable = 1 if at least one household member migrated (mean: 0.04)							
Sample	all	all	all	all	poor	rest	poor	rest
High temperature	0.028	0.051	0.044	0.041	−0.010	0.050	0.046	0.051
Conley 50km, 2 lags	(0.013)	(0.007)	(0.010)	(0.010)	(0.008)	(0.009)	(0.008)	(0.010)
Conley 100km, 2 lags	(0.010)	(0.008)	(0.009)	(0.009)	(0.007)	(0.010)	(0.007)	(0.009)
Conley 50km, no lags	(0.009)	(0.004)	(0.006)	(0.005)	(0.005)	(0.006)	(0.006)	(0.006)
Clustered at location	(0.014)	(0.008)	(0.012)	(0.011)	(0.007)	(0.010)	(0.008)	(0.011)
High temperature × UCT		−0.035			0.048	−0.052		
Conley 50km, 2 lags		(0.009)			(0.001)	(0.002)		
Conley 100km, 2 lags		(0.009)			(0.001)	(0.002)		
Conley 50km, no lags		(0.006)			(0.001)	(0.001)		
Clustered at location		(0.009)			(0.001)	(0.002)		
High temperature × Infrastructure (SD)			−0.038	−0.030			−0.045	−0.046
Conley 50km, 2 lags			(0.008)	(0.009)			(0.006)	(0.004)
Conley 100km, 2 lags			(0.007)	(0.010)			(0.005)	(0.004)
Conley 50km, no lags			(0.005)	(0.007)			(0.005)	(0.003)
Clustered at location			(0.008)	(0.009)			(0.007)	(0.004)
HH and year effects	YES	YES	YES	YES	YES	YES	YES	YES
Households	2,436	2,436	2,436	2,436	609	1,827	609	1,827

Notes: Table replicates results in table 2 using different clustering methodologies: Conley standard errors with 50km radius and 2 years lag, Conley standard errors with 100km radius and 2 years lag, Conley standard errors with 50km radius and no lags, and standard errors clustereed at the location level. Same notes as table 2 apply.

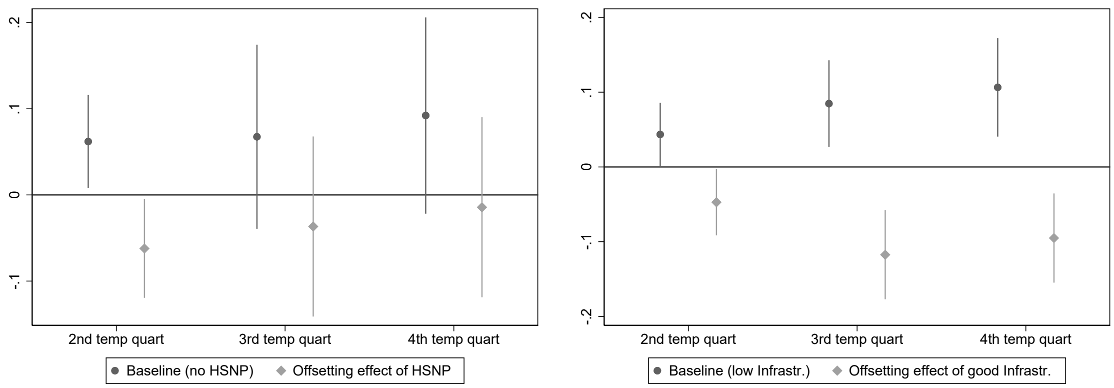
Table A2: Alternative migration and temperature measurements

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
			Dependent variable =1 if							
	HH leaves	Mem leaves (any dest.)	household member migrates out of district							
Sample mean:	0.029	0.174	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040
High temperature	0.012	0.077							0.039	0.037
	(0.010)	(0.029)							(0.012)	(0.012)
Temperature in ^{o}C (dry season)			0.083		0.080					
			(0.036)		(0.038)					
Temperature in ^{o}C (rainy season)				−0.027	−0.011					
				(0.025)	(0.029)					
High temperature (> 80 pctl)						0.037				
						(0.017)				
High temperature (> 90 pctl)							0.097			
							(0.045)			
2nd temperature quartile								0.035		
								(0.019)		
3rd temperature quartile								0.055		
								(0.032)		
4th temperature quartile								0.090		
								(0.038)		
High temperature (1 year lag)									0.016	0.018
									(0.007)	(0.007)
High temperature (1 year lead)									−0.023	−0.029
									(0.028)	(0.029)
High temperature (2 years lag)										−0.033
										(0.020)
HH & Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Households	2,583	2,436	2,436	2,436	2,436	2,436	2,436	2,436	2,436	2,436

Notes: Table reports effect of climate shocks on migration in northern Kenya; dependent variable in column (1) takes value 1 if household leaves sample the following period; data for column (1) are drawn from the baseline (2010) and follow up 1 (2011) of the HSNP; dependent variable in column (2) takes value 1 if at least one household member left the households (irrespective of destination); dependent variable in columns (3)-(8) takes value 1 if at least one household member left the district of residence; data for columns (2)-(9) are drawn from the follow up 1 (2011) and follow up 2 (2012) of the HSNP; *High temperature* = 1 if the dry season temperature the year before interview in the location is above the long run median for that location; *Temperature in $^o C$ (dry season)* denotes dry season temperature in degree Celsius; *Temperature in $^o C$ (rainy season)* denotes rainy season temperature in degree Celsius; *High temperature (> 80 pctl)* and *High temperature (> 80 pctl)* = 1 if the dry season temperature the year before interview in the location is above the long run 80th and 90th percentile, respectively; *2nd temperature quartile*, *3rd temperature quartile*, and *3rd temperature quartile* = 1 if dry season temperature anomalies fall into the second, third, or highest quartile, respectively; *High temperature (1 year lag)*, *High temperature (2 year lags)*, and *High temperature (1 year lead)* are 1, 2 year lags and 1 year lead of *High temperature (dry season))*, respectively; HAC Conley standard errors (Conley, 1999) with 50km radius and two year lag reported in parentheses.

Figure A2: Effect of temperature quartiles by HSNP and infrastructure

(a) By HSNP (b) By Infrastructure



Notes: Figures show estimates based on equation (1). Circles and diamonds denote point estimates; Circles denote coefficient estimates on 2nd, 3rd, and 4th quartile of temperature anomalies; diamonds denote coefficient estimates on 2nd, 3rd, and 4th quartile of temperature anomalies interacted with dummy for HSNP receipt (panel a) and with dummy for infrastructure in top third of sample (panel b); vertical lines denote 95% confidence intervals based on HAC Conley standard errors (Conley, 1999) with 50km radius and two year lag.

Table A3: Temperature and rainfall

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Dependent variable =1 if household member migrates out of district (mean: 0.040)							
Rainfall, z-score	−0.003	0.001	−0.003				−0.000	−0.005
(dry season)	(0.005)	(0.005)	(0.005)				(0.007)	(0.005)
Rainfall, z-score				−0.001	−0.003	−0.003	−0.003	−0.005
(rainy season)				(0.007)	(0.004)	(0.006)	(0.006)	(0.007)
Temperature		0.120			0.120		0.116	
z-score (dry season)		(0.055)			(0.052)		(0.057)	
High temperature			0.027			0.030		0.028
(dry season)			(0.014)			(0.013)		(0.013)
Temperature							−0.016	−0.028
z-score (rainy season)							(0.044)	(0.038)
HH & Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Households	2,583	2,436	2,436	2,436	2,436	2,436	2,436	2,436

Notes: Table reports effect of climate shocks on migration in northern Kenya; dependent variable takes value 1 if at least one household member left the district of residence; *High temperature* = 1 if the dry season temperature the year before interview in the location is above the long run median for that location; *Temperature (dry season)* denotes z-score of dry season temperature in degree Celsius; *Temperature in ^oC (rainy season)* denotes z-score of rainy season temperature in degree Celsius; *Rainfall in mm (dry season)* denotes z-score of rainfall in millimetres during dry season; *Rainfall in mm (rainy season)* denotes z-score of rainfall in millimetres during rainy season; HAC Conley standard errors (Conley, 1999) with 50km radius and two year lag reported in parentheses.

Table A4: Direct effect of HSNP transfers

	(1)	(2)	(3)	(4)
	Dependent variable =1 if household			
	mem migrates	works in agri.	owns camels	owns cattle
HSNP	0.009	−0.017	−0.002	−0.005
	(0.009)	(0.031)	(0.019)	(0.027)
District & Year FE	YES			
HH & Year FE		YES	YES	YES
Households	2,436	2,436	2,436	2,436

Notes: Table reports effect of unconditional cash transfers under the HSNP on migration, occupations, and livestock ownership in northern Kenya; dependent variable takes value 1 if at least one household member left the district of residence (column 1), if household works in agriculture (column 2), and if household owns any camels (column 3) or cattle (column 4); $HSNP = 1$ if household's location was randomly chosen to receive unconditional cash transfers under the HSNP from 2011 onwards; sample in column 1 consists of rounds 2011 and 2012 only (since we do not measure migration at baseline); HAC Conley standard errors (Conley, 1999) with 50km radius and two year lag reported in parentheses.

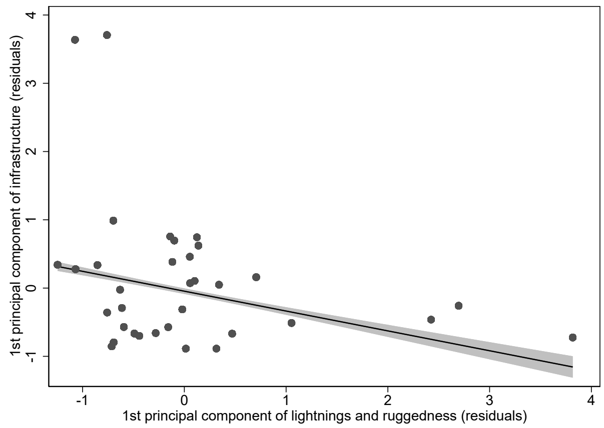
C More detail on our infrastructure measure

Table A5: Infrastructure - measurements and first stages

	(1)	(2)	(3)	(4)	(5)
	Dependent variable				
	=1 if member left hh			infrastr index	
High temperature	0.076	0.039	0.045	1.102	
	(0.011)	(0.010)	(0.014)	(0.123)	
High temperature × Roads (SD)	−0.117				
	(0.037)				
High temperature × Digital (Dummy)		−0.037			
		(0.008)			
High temperature × Facilities (SD)			−0.018		
			(0.006)		
High temperature × IV				1.415	−0.268
				(0.255)	(0.060)
HH & Year FE	YES	YES	YES	YES	YES
Households	2,436	2,436	2,436	2,436	2,436

Notes: Table reports alternative measures for infrastructure and first stages. Dependent variable in columns (1), (2), and (3) takes value 1 if at least one household member left the district of residence; dependent variable in columns (4) and (5) is our infrastructure index in standard deviations. High temperature × Roads (SD) denotes the interaction between the hot dummy and the number of roads per area in standard deviations. High temperature × Digital (Dummy) denotes the interaction between the hot dummy and a dummy = 1 if the location has either electricity (via kv11 or k33 cable or via minigrid) or GSM coverage. High temperature × Facilities (SD) denotes the interaction between the hot dummy and the number of health or education facilities in a location in standard deviations. High temperature × IV denotes the interaction between the hot dummy and the first principal component of lightning strikes and terrain ruggedness. Conley standard errors (Conley, 1999) with 50km radius and two year lag.

Figure A3: First stage illustration



Notes: Figure illustrates the relationship between infrastructure and our instrument. The vertical axis denotes our infrastructure index net of time and year effects. The horizontal axis denotes the first principal component of the number of lightning strikes and terrain ruggedness net of time and year effects. Line denotes slope coefficient with 95% confidence interval in grey.

D Balance checks

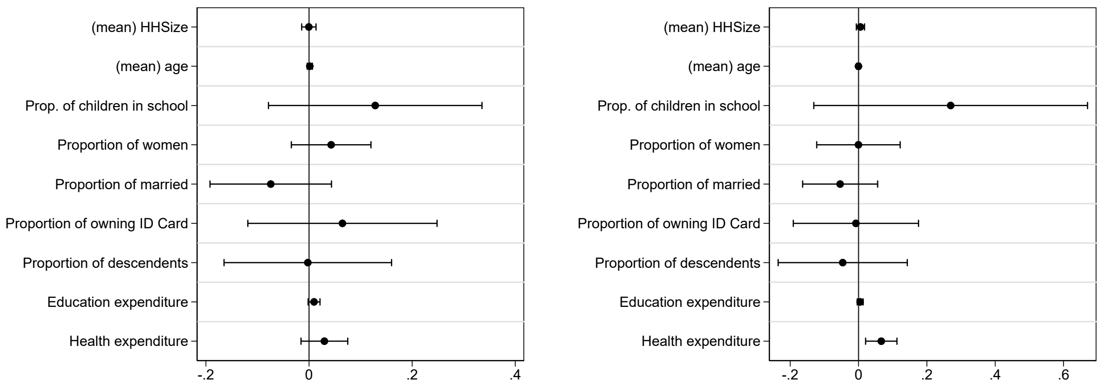
This appendix provides evidence for the randomness of temperature shocks and of unconditional cash transfers under the HSNP. To that end, we regress both shocks (two dummies for HSNP receipt and for dry season temperature being above long-term median) occurring in 2011 and 2012 on a number of household characteristics drawn from the baseline survey in 2010.

High temperature dummy. For each of the 40 HSNP locations, we compute the long run median of temperature during the dry season using the years 2000 to 2008. Whilst the long run temperature during dry seasons is likely to be correlated with various unobservable factors, such as institutions, for instance. Whether temperature in each particular year is above (or below) the median is likely to be exogenous. Panel a) shows correlations between the *High temperature* dummy and household characteristics.

HSNP tansfers. Half of the 40 HSNP locations were assigned to the treatment group, which received unconditional cash transfers from follow up 1 onwards (in 2011). Treatment status was assigned via public lottery. Panel b) shows correlations between the *HSNP transfer* dummy and household characteristics.

Figure A4: Balancing tests

(a) High temperature dummy (b) HSNP transfer



Notes: Figures report correlations between high temperature and cash transfer dummies on the one hand and household characteristics on the other; circles denote point estimates and horizontal lines 95% confidence intervals based on HAC Conley standard errors (Conley, 1999) with 50km radius and two year lag; data are drawn from the follow up 1 (2011) and follow up 2 (2012) of the HSNP; Panel a: dependent variable = 1 if the dry season temperature in the location is above the long run median for that location; Panel b: dependent variable = 1 if location was randomly selected to receive unconditional cash transfers under HSNP scheme.

E Climate perception in Kenya and Africa-wide

Table A6: Observed and perceived climate and migration intentions

	(1)	(2)	(3)	(4)
	=1 if respondent			
	intends to migrate	perceives climate worsening	intends to migrate	perceives climate worsening
Mean	0.34	0.51	0.35	0.48
Perceives climate worsening	0.049		0.035	
	(0.023)		(0.009)	
Temperature (actual)		0.105		0.028
		(0.055)		(0.012)
Sample	Kenya	Kenya	Africa	Africa
Country FE	NO	NO	YES	YES
Year, month, day FE	YES	YES	YES	YES
Observations	1,599	1,599	40,904	40,904

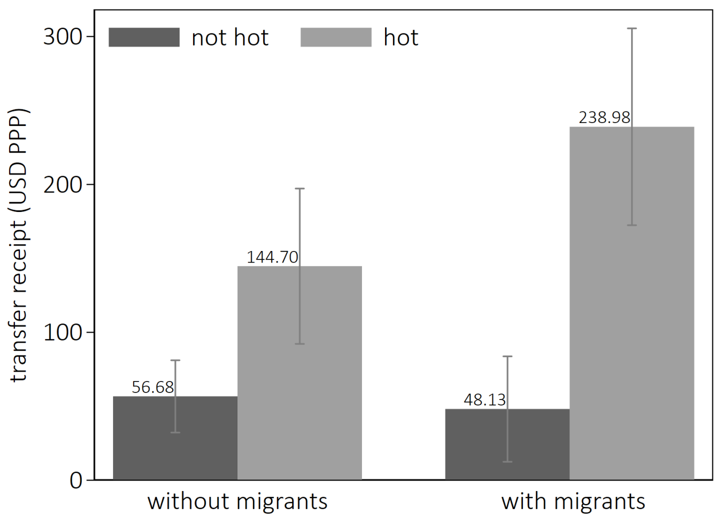
Notes: Table reports associations between actual temperature, perceived temperature, and migration intentions; dependent variable in columns 1 and 3 = 1 if respondent reports intention to migrate in future; dependent variable in columns 2 and 4 = 1 if respondent believes climatic conditions for agriculture are worse than in the past; *Perceives climate worsening* = 1 if respondent believes that climatic conditions for agriculture are worse than in the past; *Temperature (actual)* is growing season temperature anomaly (difference to long run median) in degrees Celsius; covariates are dummies for respondent being female, being black, living in formal house, living in rural area, age and indicators for primary, secondary, and tertiary education, being Muslim, being unemployed, age, longitude, and latitude ; HAC Conley standard errors (Conley, 1999) with 180km radius and two year lag reported in parentheses. Source: Afrobarometer 2017.

F Model appendix

F.1 Specification details and structural parameter estimates

We assume that the costs of sending a household member to migrate, entering a new sector or acquiring a camel, each depends on lagged income y_{it-1} and on the level of infrastructure development d_{l_i}. The cost of acquiring a camel, which enters the livestock choice (7), is given by $\kappa_{l_i,y_{it-1}} = \exp(\kappa_0 + \kappa_y y_{it-1} + \kappa_d d_{l_i})$. The cost of entering a new sector s, which enters the household's sector choice problem (6), is given by $\eta^s_{l_i,y_{it-1},s_{it-1}} = \exp(\eta^s_{s_{it-1}} + \eta^s_y y_{it-1} + \eta^s_d d_{l_i})$. We assume that staying in the same sector is costless. That is, $\eta^s_{l_i,y_{it-1},s} = 0$. Finally, the cost of sending a migrant, which enters the household's migration choice problem (5), is given by $\delta^1_{l_i,y_{it-1},s_{it-1}} = \exp(\delta_{s_{it-1}} + \delta_y y_{it-1} + \delta_d d_{l_i})$. Since we do not observe outcomes at the destination, the cost of moving the entire household is not separately identified from the payoff of doing so. The net payoff from this choice option is summarized by a parameter ω_E. Column (2) of table A8 lists these sets of parameters. The pre-estimated relation between remittance receipt and temperature shocks is shown in figure A5. Figure A7 shows the fit of the model to the empirical moments targeted in the estimation, which are also listed in table A7. Figure A8 shows the model fit for migration rates by earnings groups, which are not targed in the estimation.

Figure A5: Transfer receipt by migrant and non-migrant households



Notes: Figure reports effect of temperature shocks on transfer receipt in northern Kenya; the left set of bars shows the amount of transfers received from migrants for households of which at least one household member left the district of residence; the right set of bars shows the total amount of transfers received for households of which no member left the district of residence; data are drawn from the follow up 1 (2011) and follow up 2 (2012) of the HSNP; *not hot* and *hot* distinguish whether dry season temperature in the location the year before the interview was above the long run median for that location; whiskers indicate 95% confidence intervals with clustering at location level. Source: Hunger Safety Net Programme 2017.

Figure A6: Gradient matrix of moments (in standard deviations) with respect to parameters.

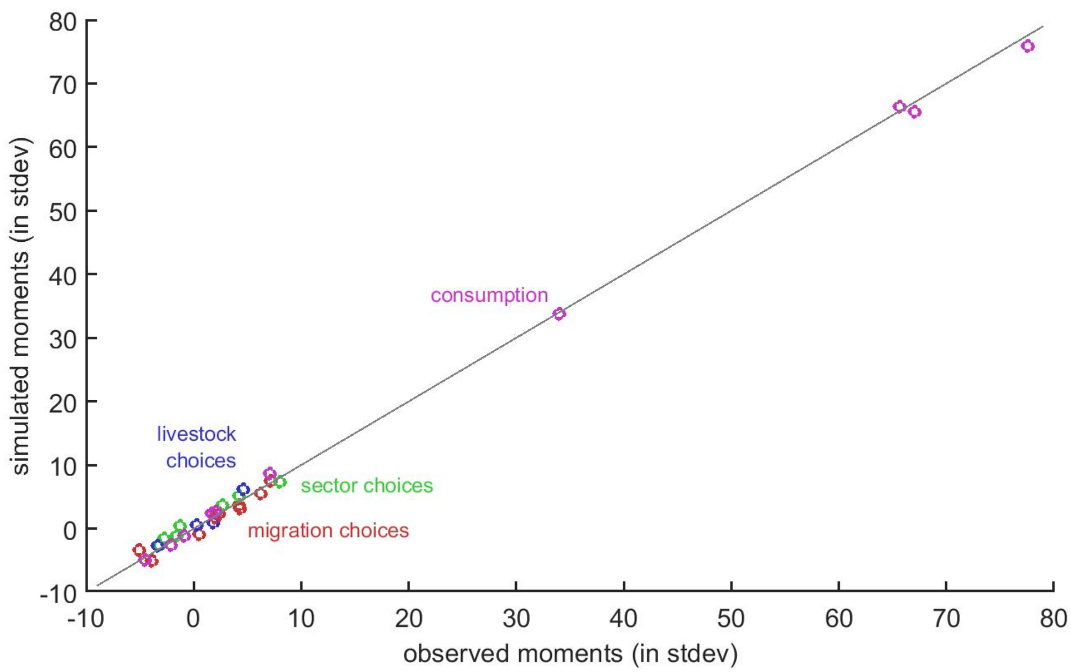
MOMENTS (see description in Section 4.3)

PARAMETERS	(III)	(I)				(IV)		(II)				(V)					
$\phi_{A,0}$	-8.1	-196	81.4	-139	162	23.4	-13.1	-31	-16.1	47.7	37	7.5	5.3	-3.3	2.1	2.1	-0.2
$\phi_{A,h}$	-21.4	-129	31.7	-113	131	35	-11.6	-21.1	-12.2	33	22.9	6.4	5.7	-3.1	-0.4	3.3	1.1
$\phi_{A,d}$	-6.7	12.7	0	8.8	0	7.9	2.2	-10.7	-8	8.9	13.7	-0.1	8.5	-4.8	-2.1	5.1	1.2
$\phi_{C,0}$	-2.3	3.2	0	2.2	0	-8.2	2.4	-11.1	-7	9	16.5	-2.4	7.4	-2.1	1.9	2.8	-1.4
$\phi_{C,h}$	-2.3	3.2	0	2.2	0	2.4	1.9	-11.1	-7	9	16.5	-1.4	6.4	-1.4	0.5	4.6	-2.1
$\phi_{NA,0}$	-7.9	68.7	-52.5	26.6	-32.4	1.2	0.3	-6.3	6.4	1.3	13	-4.2	3.2	2.8	0.8	0.1	-0.8
$\phi_{NA,h}$	-9	3.2	0	2.2	0	0.9	0.1	-7.3	5	2.5	16	-2.4	3.4	0.7	1.1	0.3	-1.3
$\phi_{NA,d}$	-9	1.6	0	1.1	0	-0.8	0.5	-2.2	14.6	-4	2.5	-6.5	9	2	0	1.3	-0.4
θ	-14.6	-143	29	-124	130	32	-6.2	-14.5	-0.8	28.9	15.3	6.1	1.7	-0.5	0.7	-0.8	1.2
σ_y	6.6	-483	392	-182	248	7.1	-8.9	-46.3	-31.7	70.7	41.8	-9.7	-0.9	7.3	3	3.2	-4.1
δ_A	0	60.5	-72.3	29.5	-95.9	1.9	-0.1	-6.9	10.1	-8.9	-0.8	2.9	1.6	-4.2	-0.1	-0.3	0.3
δ_{NA}	0	-1.6	0	-1.1	0	1.3	0	-12	-27.6	17.8	-7.7	2.2	1.7	-3.5	-0.3	-0.3	0.7
δ_y	-1.1	19	22.6	89.8	-198	-1.8	-1.3	17	-45.7	-23	-21.1	2.8	-0.6	-2.7	1.1	-0.2	-1.6
δ_d	3.4	3.2	67.8	64.5	-68.5	-1.8	-1.3	6.3	-4.8	-14.2	-12.9	1.2	-1.4	-0.5	0.9	-0.4	-1.1
ζ_0	12.2	4.7	68.6	9.6	108	-2.3	2.3	-14.2	2.2	10.2	3.4	0.3	-0.9	-1.4	-0.8	-0.4	1.2
σ_ϵ	16.6	-8	92.9	-90.5	440	8.3	-5.1	-29.9	23.3	28.7	-6.3	0.1	-0.5	-0.9	-1.7	0.2	0.6
η^A_{NA}	12.2	65.2	88.4	-17.8	363	-2.9	-2.2	-14.8	1.9	10.5	2.9	3.4	2.6	-5.1	-0.8	5.4	-7.6
η_y	13.6	-368	439	-180	582	7.6	-14.3	-8.9	-0.2	0.5	-28.7	11.3	19.1	-16.5	1.6	9.7	-25.3
η_d	12.3	1.6	138	-42.4	394	3.4	-4.7	-14.6	-11.3	10.3	7.2	6.9	16.3	-14.7	-1.9	-9.9	2.7
η^{NA}_A	-3.3	6.4	0	4.4	0	3.6	0.6	-0.7	-1.2	2.6	0	6.9	6.5	-14	-0.2	-0.2	0.8
η_y	-2.3	183	-149	68.2	-93.8	-26.9	6.8	-1	-3.2	6.5	9.7	-3.1	2	-11.6	-1.5	1.5	-0.6
η_d	0	-4.8	0	-3.3	0	2.6	-0.3	3.4	0.5	-2.7	3.4	4.2	-7.5	-0.9	0.7	-0.6	-0.6
σ_η	-5.6	-185	127	-62.1	29.1	-6.1	2.3	-3.5	-20.8	5.5	9.1	-3.7	13.2	-2.8	0	3.3	0.9
κ_0	-1.1	6.3	0	4.4	0	-1.8	-3.7	-3.8	1.1	2.2	5.6	-1.2	9.6	-4.2	-1	0.3	1.4
κ_y	6.7	-4.8	0	-3.3	0	24.5	-17.9	1.1	-7.6	1.4	11.2	-4.7	-7	10.2	0.2	-1.3	-6
κ_d	3.4	-12.7	0	-8.8	0	7.9	-2.3	4.7	-3	-0.1	-2.4	2.7	-9.1	3.5	-1.4	-2.4	0.5
σ_κ	-1.2	9.5	0	6.6	0	2.1	2.5	-4.8	6.8	1.6	-7.2	1.9	7.5	-10.1	-3	2.4	5.3
α_c	-1.2	-45	55.1	-8.6	33.5	12.7	-6.5	-20.7	-9.1	33.1	23.7	-4.4	2.8	3.7	1.9	0.4	-2.9
γ	-1.1	9.5	0	6.6	0	-1	1.5	-5.9	-1.6	7.7	10.2	-1.9	-0.1	0	-0.1	-1.3	0.5

PARAMETERS	(VI)			(VII)			(VIII)			(IX)		(X)	(XI)
$\phi_{A,0}$	1.1	1.7	-3.3	-0.4	7.3	-0.1	1.3	6.4	-0.4	-0.3	0.6	4.6	0.1
$\phi_{A,h}$	1.4	1.6	-3.7	-1.7	9.3	-0.9	5.5	17.2	-15.3	0.5	2.1	14.1	-5.1
$\phi_{A,d}$	-1.4	0.5	1.5	0	4.4	2.8	0	2.5	2.2	3.6	1.6	4.7	-5.8
$\phi_{C,0}$	-4	0.1	4.9	-0.3	1.6	4	0	-15.7	0.3	-1.1	1.7	13.2	-4.6
$\phi_{C,h}$	-5.2	-0.9	6.8	-0.7	1.6	3.5	1.5	2.6	11.8	-0.6	1.6	9.6	-4.7
$\phi_{NA,0}$	0.3	0.4	-0.5	5.2	0.4	0	0	-8.9	0.4	0.1	0.4	-13.7	3.9
$\phi_{NA,h}$	0.4	0.5	-0.7	4.2	0.2	0	1.4	-8	-2	0.1	1.2	-9.2	2.7
$\phi_{NA,d}$	2	-1.4	-1.8	4.8	0.6	0.2	0.2	-11.7	-1	0.4	16.4	0.5	-1
θ	-3.1	1.7	1.8	4.7	7.9	3.6	1.6	-5.5	-1.5	-1	2.2	2.7	0.4
σ_y	-2.8	0.6	3.6	-0.5	1.4	1.6	3.4	1.7	1.2	-0.9	1.1	7.9	38.1
δ_A	-0.3	0	0.4	0.9	-0.8	-0.1	0	-0.3	0.3	0.1	-0.5	-1.6	0.3
δ_{NA}	0	0	0	0.7	-0.7	0	0	0	0	0.1	-0.4	-1	0.1
δ_y	2	1.9	-3.4	0.2	-0.8	0.8	0.1	0	-0.6	0	0.3	1.2	0
δ_d	0.8	1.3	-1.5	0.2	-0.2	0.7	0.1	0.1	0.1	0	0.1	0.8	0.2
ζ_0	-0.6	-0.7	1.9	1.3	0.4	-0.8	1.3	-4.7	-1.6	0.3	-0.4	-0.8	1.1
σ_ϵ	-1.1	-0.6	1.4	1.2	0.6	-0.2	2.8	-3.5	-2.1	0.3	-0.3	0.3	1.6
η^A_{NA}	-1.3	-5.6	0.9	-0.5	1.7	0.7	2.2	-7.7	-5.8	1.9	-1.7	-1.5	1
η_y	-3.2	3	-6.2	-4.9	3.4	5.4	4.7	22.5	-2.7	5.9	-6.9	-18.7	0.8
η_d	0	-2.7	-0.2	0.7	-0.3	0.7	2.7	-4.1	-4.5	3.8	-5.5	-11.9	1.2
η^{NA}_A	-2.3	-2.2	3.4	2.2	-1.5	-1	0.2	-14.8	0.4	-0.1	-0.3	-1.3	1.1
η_y	-0.7	1	0.9	2.8	-2.1	-1.1	-1.5	1.3	2.6	-0.5	0.7	1.8	0.5
η_d	-1.2	1.5	0.8	1	-0.7	-0.2	0	8.5	0.4	-0.2	-0.3	-2	-0.2
σ_η	2.6	-1.7	-2	-0.8	-0.1	0.3	1	4.8	-1.9	-0.7	1.6	8.8	-1.4
κ_0	0.8	-1	-0.9	0.2	-1	1.9	0.4	0.9	-0.6	0.1	-0.4	2	-0.4
κ_y	3.1	-5.8	-1.2	-1.9	1	2.1	1.5	23.1	-2.4	1.7	-1.7	-5.8	-0.3
κ_d	1.3	-4.3	-1.3	-0.1	0.5	0	0.2	16	-1.3	1.6	-1.6	-7.9	0.6
σ_κ	-1.6	0	1.9	2.7	-2.3	-0.2	0	-16	1.2	-1.3	1.1	2.1	-0.5
α_c	-0.2	0.8	-0.2	-1.4	0.6	1.5	0.3	-4	2	-0.1	0.1	4.6	-0.7
γ	-1.5	-1.3	2.4	0	0.7	-0.9	0	-14.3	0.2	0.1	0	1.7	0.4

Notes: Figure visualizes the responsiveness of targeted moments (hear measured in standard deviations) with respect to the model's structural parameters. Darker shading indicates stronger absolute dependence of moments with respect to parameters.

Figure A7: Model fit.



Notes: Figure plots moments simulated from the model against the same moments observed in the data, each in standard deviations of the empirical moments.

G Estimating the cost of infrastructure in Kenya

In our model, costs and earnings are functions of a location's level of infrastructure, measured in standard deviations. We calculate the monetary cost of this measure as follows. First, we draw on the detailed estimates for country specific road construction costs provided by the World Bank's Road Costs Knowledge System (ROCKS) Database.[25] The median cost for a two-lane bituminous road in Kenya in the listed projects is 419,381 USD per kilometer. The total area of the districts Mandera, Marsabit, Turkana and Wajir extends over

Table A7: Estimation moments

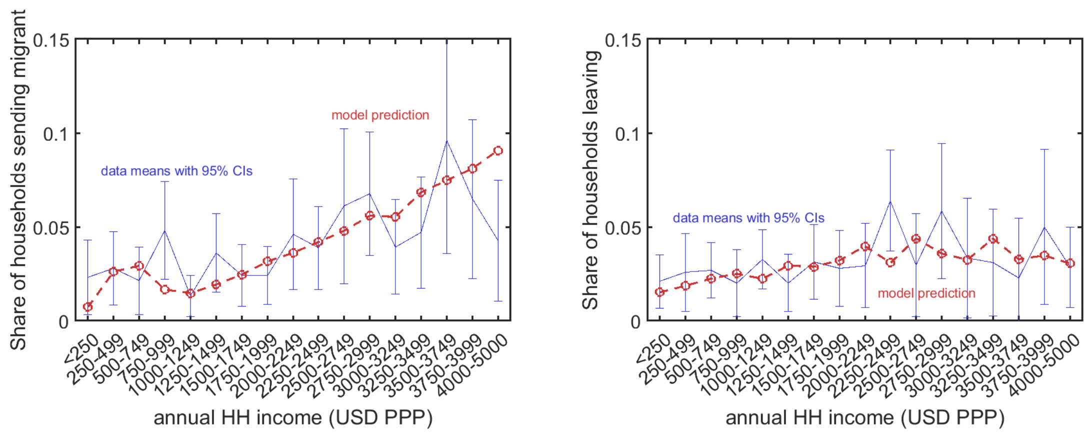
Moment group	Data moment	Standard error	Model moment	Moment group	Data moment	Standard error	Model moment
(I)	0.051	(0.007)	0.054	(VI)	0.010	(0.042)	−0.010
	−0.035	(0.009)	−0.029		−0.045	(0.013)	−0.041
	0.044	(0.010)	0.048		0.155	(0.034)	0.233
	−0.038	(0.008)	−0.034	(VII)	6.3665	(0.095)	6.2332
(II)	0.0038	(0.009)	−0.003		5.8767	(0.076)	5.8248
	0.0196	(0.004)	0.028		5.9303	(0.090)	5.9972
	0.0176	(0.007)	0.031	(VIII)	−0.159	(0.182)	−0.172
	0.0181	(0.009)	0.009		−0.243	(0.112)	−0.218
(III)	0.0288	(0.005)	0.0292		0.171	(0.084)	0.216
(IV)	−0.047	(0.017)	−0.022	(IX)	0.2292	(0.133)	0.1144
	0.044	(0.025)	0.021		0.2088	(0.031)	0.1585
(V)	−0.045	(0.027)	−0.012	(X)	−0.114	(0.025)	−0.138
	0.066	(0.025)	0.085	(XI)	0.4170	(0.013)	0.4130
	0.104	(0.025)	0.121				
	−0.106	(0.081)	0.019				
	−0.069	(0.021)	−0.058				
	0.410	(0.051)	0.368				

Notes: Moments targeted in the estimation of the model detailed in Section 4.2. The first and the fifth column indicate the group of moments (see also text of Section 4.3): (I) reduced form estimates from columns (2) and (3) of table 2; (II) coefficients from a regression of an indicator $\mathbb{1}[m_{it} = 1]$ for sending a migrant on HSNP treatment status, d_{l_i}, and indicators $\mathbb{1}[s_{it-1} = A]$ and $\mathbb{1}[s_{it-1} = N]$; (III) fraction of households leaving the panel; (IV) coefficients in columns (1) and (2) of table 3; (V) coefficients from two regressions of, respectively an indicator $\mathbb{1}[s_{it} = N]$ for switching to non-agriculture among households with $s_{it-1} = A$ and an indicator $\mathbb{1}[s_{it} = A]$ for switching to agriculture among households with $s_{it-1} = N$, each on HSNP treatment status, d_{l_i}, and a constant; (VI) coefficients from a regression of an indicator $\mathbb{1}[a_{it} = C]$ for owning a camel on HSNP treatment status, d_{l_i} and a constant; (VII) mean log per capita expenditure for non-agricultural households and for agricultural households by camel ownership; (VIII) effect of heat on log per capita expenditure as well as the differences by sector and camel ownership, corresponding to the differences between the bars displayed in figure 3c; (IX) coefficients from regressions of log per capita expenditure on infrastructure by sector; (X) correlation between log per capita expenditure and the log share of the workforce active in a given sector, location and year; (XI) variance of log per capita expenditure (conditional on year and location effects). Columns respectively list the empirical moments, their standard error, and the corresponding model predictions.

[25]See `https://collaboration.worldbank.org/content/sites/collaboration-for-development/en/groups/world-bank-road-software-tools.html`, last accessed 25 July 2023.

Figure A8: Fit to non-targeted moments

(a) Sending migrant (b) Household leaves



Notes: Figure compares migration rates predicted by the model (red dashed lines) to those observed in the data (in blue, with 95% confidence intervals), each by earnings groups. Panel a: shows shares of households sending a migrant. Panel b: shows shares of households leaving the panel. Source: HSNP evaluation data 2010-2012.

222,847 square kilometers, so that an additional kilometer of road network raises road density by $1/222,847 = 4.487 \cdot 10^{-6}$ kilometers of road per square kilometer. Conditional on the other dimensions of infrastructure we consider (electricity access, GSM coverage, presence of education and health facilities), one standard deviation of additional road density ($3.791 \cdot 10^{-3}$

Table A8: Structural parameter estimates

	(1)			(2)	
	Earnings and preferences			Cost parameters	
$\phi_{A,0}$	6.144	(0.124)	δ_A	1.962	(0.551)
$\phi_{A,h}$	0.667	(0.085)	δ_{NA}	2.409	(0.308)
$\phi_{A,d}$	1.205	(0.099)	δ_y	-0.131	(0.019)
$\phi_{C,0}$	5.940	(0.204)	δ_d	-0.003	(0.145)
$\phi_{C,h}$	1.018	(0.187)	η^A_{NA}	1.557	(0.163)
$\phi_{NA,0}$	5.858	(0.284)	η_y	0.051	(0.027)
$\phi_{NA,h}$	1.069	(0.489)	η_d	0.080	(0.131)
$\phi_{NA,d}$	1.331	(0.121)	η^{NA}_A	3.039	(0.435)
θ	0.861	(0.114)	η_y	-0.351	(0.215)
σ_y	0.695	(0.015)	η_d	-1.905	(0.810)
γ	3.123	(0.364)	κ_0	1.156	(0.166)
α_c	1.284	(0.407)	κ_y	-0.056	(0.141)
σ_ϵ	1.192	(0.119)	κ_d	-0.012	(0.368)
σ_η	3.913	(0.495)	ω_E	0.8250	(1.120)
σ_κ	4.049	(0.226)			

Notes: Structural parameters of the model detailed in Section 4.2. Asymptotic standard errors in parentheses.

kilometers of road per square kilometer) raises our standardized measure for infrastructure on average by 0.258 standard deviations. One additional kilometer of road constructed in the districts Mandera, Marsabit, Turkana and Wajir thus raises our infrastructure as measured in our model by $3.060 \cdot 10^{-4}$ standard deviations. Correspondingly, billion KES (12 million USD) spent on infrastructure in these Northern Kenyan districts raises infrastructure by $8.755 \cdot 10^{-3}$ standard deviations. If paid out as unconditional cash transfers, the same 1 billion KES would imply a transfer of 577 KES or 15.19 USD PPP per adult equivalent in these districts.