Field to Flight: Migration Dynamics Amidst Climate/Weather Driven Crop Yield Fluctuations in Burkina Faso

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Abstract

Climate change is anticipated to significantly affect human migration, driven by factors such as crop failures, rising sea levels, and water insecurity. The African continent is particularly vulnerable due to its population's limited adaptive capacity. However, collecting migration data is challenging, especially in regions lacking reliable demographic and epidemiological census data. Consequently, empirical evidence linking migration patterns to climate variability in Africa is scarce. We analysed data from 196,320 individuals in rural Burkina Faso from 1994 to 2016, assessing the relationship between weather-induced crop yield variations and migration. We found that annual reductions in crop yields were strongly associated with increased out-migration, particularly among male farmers, individuals with lower wealth, and those with prior migration experience. These findings underscore the need for effective climate change adaptation and mitigation strategies to reduce forced migration and displacement in the context of climate change.

Keywords: Climate change, migration, crop yield, agriculture, adaptation

Background

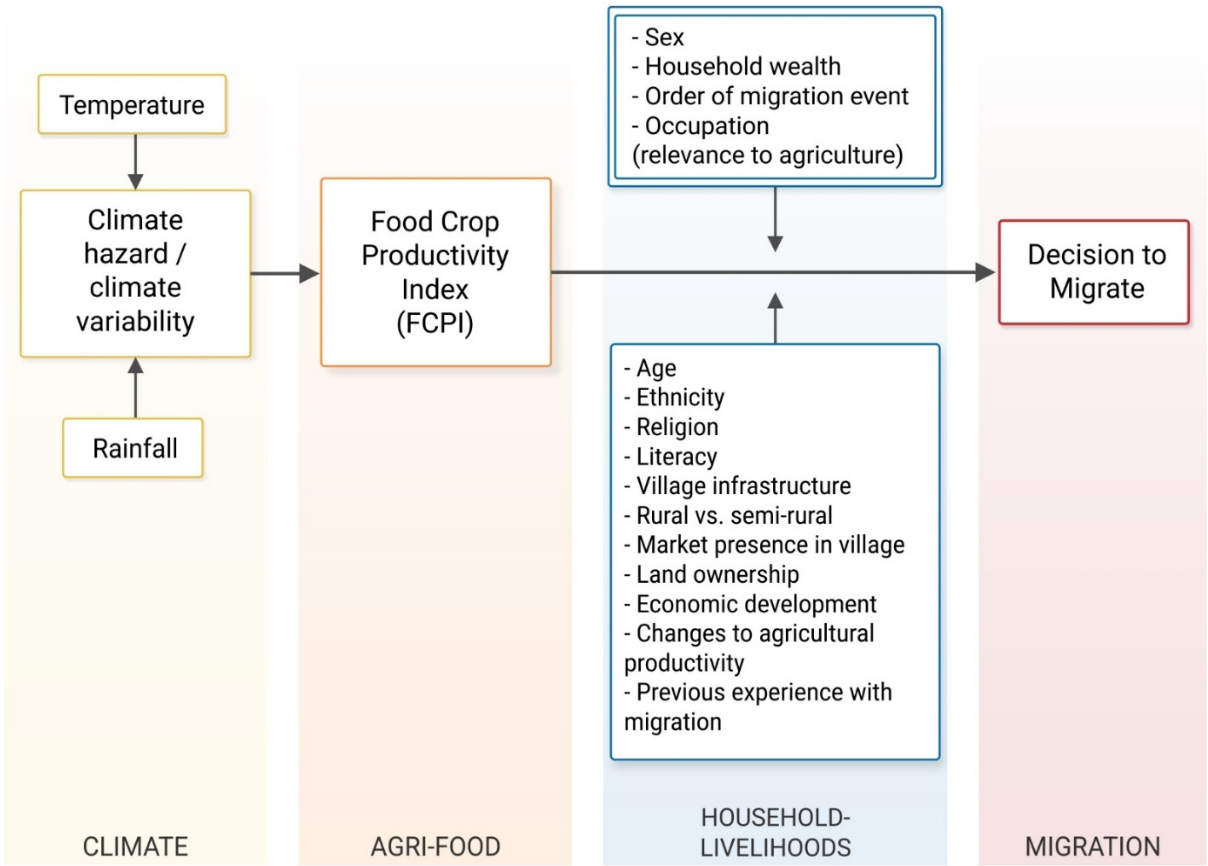
The sudden and slow-onset impacts of climate change including raising temperatures, increased precipitation variability, flooding and droughts will increase rates of migration and displacement (1). As climate change accelerates, involuntary migration from highly exposed regions with limited adaptive capacity is expected to escalate (1), with Sub Saharan Africa anticipated to be particularly affected (2). The IPCC estimated (with high agreement and medium evidence) that by 2050 there could be 17–40 million and 56–86 million additional internal migrants in Sub Saharan Africa alone with 1.7° and 2.5°C warming, respectively (3). The additional burden of migration driven by climate change can pose socio-economic challenges to populations in both sending and hosting communities (4,5). However, climate change-related migration can also be adaptive, and reduce climate-related risks including health risks.

Existing research highlights the complex interactions between climate change, food security, and migration, particularly in regions with limited adaptive capacity. Studies in Burkina Faso demonstrate that both socio-demographic and environmental factors influence migration patterns, with economic opportunities and environmental stressors jointly shaping mobility decisions (6). Agent-based modeling approaches further emphasize that migration responses are not solely determined by climate change but are mediated by governance structures and socio-political factors (7). Empirical analyses of historical droughts reveal that livelihood diversification, including migration, is a key adaptation strategy, though it carries risks and is shaped by household resource access (8). Additionally, economic research suggests that climate variability is more likely to drive internal and regional migration rather than large-scale international displacement (9).

The role of environmental hazards in migration patterns varies across regions, with migration predominantly occurring within low- and middle-income countries, particularly in agriculturally dependent economies in Latin America and sub-Saharan Africa (10). Studies also reveal non-linear migration responses to climate hazards, with tipping points where adaptation fails, leading to abrupt displacement (11). Economic analyses further demonstrate that climatic shocks, including temperature and precipitation variability, impact productivity, health, and economic growth, influencing migration decisions (12). Additionally, adaptation strategies such as integrated soil fertility management and agroforestry have been shown to enhance agricultural resilience, potentially mitigating climate-driven migration (13). However, our understanding of the climate – food – migration (and closely related health) nexus is constrained by methodological challenges - recent meta-analyses and systematic reviews have identified difficulties in measuring migration and climatic variables, integrating datasets, and identifying causal relationships (10).

This study builds on our prior research, which provided empirical evidence on the association of child survival and nutritional status with inter-annual crop yield variations in a rural population of Burkina Faso (14). We had established that inter-annual crop yield variation in this setting is largely driven by weather variations (14). Here we examine how these same yield fluctuations influence out-migration. Integrating perspectives from epidemiology and public health into the climate change and migration discourse - traditionally dominated by demography, economics, and agricultural science - our study bridges disciplinary gaps for a more comprehensive understanding of climate-related migration and its health implications. This study adapts the conceptual model from Tuholske et al. (2024) to examine the climate-food-migration nexus, illustrating the key components and linkages that drive migration through the agricultural pathway (See Figure 1) (15) . The model conceptualizes how local climate variability affects agricultural productivity, shaping rural household decisions to migrate in response to changing food security and economic opportunities.

Figure 1: Conceptual Model



Adapted from Tuholske et al, 2024. Legend: Blue unbroken line: Confounders. Blue double link: Mediating factors

This study advances climate migration research by leveraging a detailed continuous individual panel, allowing for more precise, sequential, and nuanced estimates of the climate-migration relationship than studies using broader time intervals. It focuses on agriculture as a key pathway linking climate variability to migration, providing insights into how environmental shocks drive mobility. Additionally, it examines how gender, wealth, and migration experience shape migration responses, improving understanding of differential vulnerabilities. These findings contribute to the empirical evidence base and emphasize the need for targeted adaptation strategies. We sought to answer the question - How do weather-induced fluctuations in crop yields influence out-migration patterns in rural Burkina Faso, and how do these effects vary by gender, wealth, and prior migration experience?

Materials and Methods

Study Area and Population

The study was conducted in the Nouna Health and Demographic Surveillance System (HDSS) site, located in Kossi Province in north-western Burkina Faso. This predominantly rural area, comprising 58 villages and one town, is reliant on rain-fed subsistence farming with a single agricultural season per year. The population has been under longitudinal surveillance since 1992, increasing from 26,626 to approximately 125,000 by 2022, due to natural growth, village incorporation (in 2000 and 2004), and in-migration.

Data Sources and Study Design

We used Nouna HDSS data from 1994 to 2016, excluding 1992–1993 due to data incompleteness and post-2016 due to interruptions in surveillance continuity. HDSS data included quarterly (later 4-monthly) house-to-house surveys registering births, deaths, migrations, and other vital events, complemented by periodic full censuses.

Our primary outcome was out-migration for yield-sensitive reasons: work, crop cultivation, and livestock pasture outside the HDSS area. Migration events unrelated to yield (e.g., marriage, education) were included in the time at risk but censored upon migration. Events with ambiguous yield sensitivity (e.g., health reasons, following family) were excluded from main analyses. Migration was defined as any absence from the HDSS area lasting more than two months.

Exposure Variables

Exposure to agricultural productivity was measured using the Food Crop Productivity Index (FCPI), derived from province-level crop yield data (millet, sorghum, maize, fonio, rice) collected via crop cut estimation by Burkina Faso's Agricultural Statistics Service (1994–2016). FCPI values express annual yield as a percentage of the 1992–2012 average. Lower FCPI values reflect yield deficits linked to climate variability. Two exposure windows were analyzed:

- Preceding harvest – FCPI in the agricultural season prior to each observation period.
- Cumulative FCPI – mean FCPI over the three preceding harvests, reflecting medium-term economic conditions.

Covariates

Covariates were derived from HDSS individual, household, and village-level data:

- Demographic and socioeconomic variables: age, sex, literacy, religion, ethnicity, occupational status.
- Occupational relevance to agriculture: categorized as (a) crop farming, (b) other agri-food work, (c) non-agricultural work, (d) unoccupied/unemployed, or (e) unknown.
- Household wealth index: based on 2009 data on housing and asset ownership, dichotomized above/below the median.
- Village infrastructure: an index constructed via principal component analysis (e.g., presence of health facility, market, road type).
- Migration history: order, permanence (return vs non-return), and duration (<1 year or ≥1 year) of out-migration events.

Statistical Analysis

Out-migration was modeled as a recurrent event. Subjects were at risk from birth but included from September 1, 1994. We applied Prentice-Williams-Peterson models using age as analysis time to estimate associations between FCPI and migration, adjusting for intra-subject correlation. Cumulative hazard plots were used for visual comparison of high vs low FCPI exposure. Models were adjusted for time-invariant individual and contextual confounders (ethnicity, religion, literacy, village type, market access, infrastructure index) and a linear time trend to account for secular changes. Effect modification was assessed for sex, household wealth, agricultural occupation, and migration order, including two-, three-, and four-way interaction terms based on improvements in model fit (Akaike Information Criterion) and Wald test significance.

Sensitivity Analyses

We conducted three sensitivity analyses:

I. including all migration events regardless of reason;
II. restricting to original HDSS villages (excluding those added in 2000/2004);
III. restricting to individuals born after September 1, 1994 (with complete migration history).

Details are provided in Supplementary Tables S6–S8. Statistical analyses were performed using Stata 17 (StataCorp LLC, College Station, TX, USA).

Ethics Statement

This study involved human participants and received ethical approval from the Ethics Committee of the Medical Faculty of Heidelberg University, Germany, and the Comité Institutionnel d'Éthique du Centre de Recherche en Santé de Nouna, Burkina Faso. The approval reference number is 2022-11-240. Written informed consent was obtained from all participating households enrolled in the ongoing dynamic longitudinal cohort. All participants were adults over the age of 18; no children were involved in the study.

Results

Our dataset includes 196,320 people under observation with records of 59,745 out-migration events, corresponding to 45 events per 1,000 person-years of observation over 1994 until 2016. The out-migration rate was highest in the age group of 18 - < 30 years and among those from the wealthiest households (measured using a wealth index derived from an exhaustive socio-economic census on household assets and housing quality) and from villages with the highest level of infrastructural development (i.e., villages with highest presence of health-care facilities, drilled water wells, markets, and quality road connections).

Table 1. Number of people, out-migration events, person-years, and out-migration rates according to individual characteristics (n=196,320 people), Nouna Health and Demographic Surveillance System, Burkina Faso, 1994-2016

The vast majority of the observed migration events were singular for the out-migrating individuals; only 8% of events were repeated (up to five repetitions per individual). Reasons for out-migration that were "possibly yield sensitive" – namely health reasons, returning to parents to give birth and for reasons other than giving birth, and following family or someone else, unknown reasons, and reasons recorded as "other" – were the most prevalent. There were more out-migration events for "yield sensitive" reasons, i.e., for work and farming outside of the HDSS area (24%), than for "non-yield sensitive" reasons, i.e., marriage, divorce, studies, to create a household, funeral (15%). Most of the out-migration events were recorded as permanent, i.e., without a return during the study period (78%). However, this is likely due to the limitations of the HDSS system in identifying returning migrants. Of the temporary migration events, there were more long-term than short-term migration events, which may also be an artefact of data limitations. Median duration of out-migration episodes (for temporary out-migration) was 2 (p10-90: 1, 6) years. Median age at out-migration was 17 (p10-90: 4, 34) years. Tables 1 and 2 present characteristics of the study population and out-migration events, respectively.

Table 2. Number of out-migration events according to the event characteristics (n= 59,745 events), Nouna Health and Demographic Surveillance System, Burkina Faso, 1994-2016

Inter-annual yield variability was expressed using the Food Crop Productivity Index (FCPI), which reflects weighted variation of key food crops (millet, sorghum, maize, rice and fonio – a local type of cereal). 100% FCPI equals the mean yield level over the study period (16). We previously estimated that 72% of variation in FCPI can be explained by variation in weather parameters of physiological significance to crop growth (16).

We related every migration event and the corresponding number of people staying to: 1) FCPI values of the preceding agricultural harvest and 2) cumulative (mean) FCPI over the preceding last three harvests. The median values of FCPI for our study population over the preceding year's and cumulative exposure windows for this study were 103 (p10-90: 81, 118) % and 102 (p10-90: 85, 116) %, respectively. Further details on FCPI variation in this area are reported elsewhere (16).

The cumulative hazard plots showed that the outmigration rate was highest at the age of 15-25 years. Out-migration was consistently higher among those exposed to below-average FCPI than those exposed to above-average FCPI. This pattern applied to both – FCPI in the single preceding year and cumulative FCPI over the past three years (Figure 2).

Figure 2. Cumulative hazard plots of all outmigration events in relation to preceding FCPI (on the right) and cumulative FCPI over the last three years (on the left) preceding each observation episode (n=196,320 people), Nouna Health and Demographic Surveillance System, Burkina Faso, 1994-2016. The red solid line shows the cumulative hazard in those exposed to FCPI< 100%; the blue dashed line shows the cumulative hazard in those exposed to FCPI ≥ 100%. Red/blue shaded areas show the 95% confidence intervals, correspondingly.

We present hazard ratios (HRs) of out-migration in relation to reductions in FCPI from its 90th to 10th centile, i.e., the relative change in the rate of out- migration adjusted for potential confounders at the individual, household, village levels and across time, for every combination of sex, relevance of occupation to agriculture, household wealth level, and order of migration event for the migrating individuals. We found evidence for association between FCPI and out-migration for some but not all combinations of these characteristics (See Table 3, and Supplement 2 - Tables S1-5).

Of the occupational categories, the association held among farmers, particularly male (e.g., HR 1.54 (95% CI 1.41, 1.69) for the first out-migration of poorer male farmers), and the unoccupied (e.g., HR 1.60 (95% CI 1.41, 1.81) for the first out-migration of poorer male unoccupied) but not among those in non-agricultural occupations (e.g., HR 0.84 (95% CI 0.69, 1.03) for the first out-migration of poorer males in non-agricultural sector). For those occupied in the wider agricultural and food sector, the association only held for migrants' second out-migration events either for both last year's and cumulative FCPI or only for last year's FCPI, depending on migrants' sex, e.g., HR 1.66 (95% CI 1.16, 2.85) for poorer male workers (See Supplement 2 - Table S2).

The central estimate of the hazard ratio was consistently higher among men than women, among those with lower than higher household wealth, for migrants' second and third than for their first, fourth or fifth out-migration (the latter two were rare, limiting statistical power), and in relation to the last years' than cumulative FCPI.

Hence, for the first out-migration, the highest hazard ratio was found in relation to the preceding years' FCPI among the poorer male farmers: 1.54 (95% CI 1.41, 1.69) and the unoccupied: 1.60 (95% CI 1.41,1.81) for a 90^{th} to 10^{th} centile reduction in FCPI. This, for example, translates into 84% (95% CI 62, 109%) increase in the rate of out-migration among poorer male farmers in the year of the lowest observed crop yield level (2000) as compared to the year with the highest observed yield level (2015), or 47% (95% CI 36, 59%) if the year 2000 is compared to the period average yield over the study period.

Table 3. Association of outmigration for reasons that are likely to be sensitive to inter-annual crop yield variation with the preceding food crop yield and with cumulative (mean) food crop yield for the migrants' ***first*** out-migration by sex, household wealth, relevance of occupation to agriculture (n = 168,089 people), Nouna Health and Demographic Surveillance System, Burkina Faso, 1993-2016.

Discussion

This study provides empirical evidence linking weather-induced fluctuations in crop yields to out-migration patterns in rural Burkina Faso over a 22-year period. Our findings demonstrate a clear association between reductions in the FCPR and increased out-migration rates, particularly among poorer male farmers and individuals without stable employment. The differential effects observed across gender, wealth levels, and migration history highlight the complex interplay of socio-demographic factors in shaping climate-related migration decisions.

In the Burkinabè subsistence-farming population relying on rain-fed agriculture, years of poor crop yield were significantly associated with increased rates of out-migration for work and farming elsewhere. This finding is consistent with some studies in other ecological contexts. For example, in Mexico, each additional month of drought increases the odds of rural-urban migration by 3.6% (17). Similarly, a study in Bangladesh suggested that increased rainfall uncertainty would raise net out-migration rates by 20% in 2030, relative to 1990, assuming no adaptation measures are implemented (18).

Yet, not all prior studies show a consistent association between environmental stressors and increased out-migration. For instance, a single study showed an increase in migration with excessive precipitation in Senegal, but a decrease with heatwaves. Both effects were intensified when exposures were considered over the crop growing season, suggesting agricultural mediation (19). Hence, our findings likely highlight the context-specific complex interplay between climate stressors and migration patterns in rural Burkina Faso.

Our results showed that increases in out-migration were somewhat higher in response to the preceding single year's FCPI than cumulative FCPI. This suggests that socio-economic processes and coping strategies, such as selling disposable assets to cope with low yields, may mitigate out-migration over the long term. A systematic review found that migration decisions are closely linked to access to agricultural means for climate change adaptation and vary by landholdings (20). Research in Mexico demonstrated that climate shocks might lead to immediate migration responses, but migration may also be delayed until in-situ adaptive strategies are exhausted (21).

The association between FCPI and out-migration was stronger in **poorer households**. 'Distress migration' is more often pursued by socioeconomically vulnerable individuals (22) and is less planned compared to economic or investment migration, which is more strategic. Distress migration can undermine livelihoods and exacerbate vulnerability, leading to negative outcomes such as withdrawing children from school and eroding resilience against future shocks (23,24). This is supported by a study in Burkina Faso, documenting first time migration in the absence of other options, despite its erosive effects (4). However, other studies show that households require some degree of wealth to migrate and that poorer households can become immobile or trapped (21). This highlights the importance of addressing socio- economic inequalities in climate change adaptation to ensure equitable outcomes for high- risk populations. Implementing weather-based crop insurance targeted at poor farmers provides financial support during climate shocks (25), reducing inequities. Targeted social support measures, such as grants and cash for lower-income groups, can protect against forced migration and negative health effects from climate shocks, aligning with forecast- based financing strategies to minimize disaster displacement (25).

Our study reveals gender disparities in the migration response to declining crop yields. Men exhibit a stronger association between lower yields and out-migration compared to women. This may be attributed to traditional gender roles in rural Burkina Faso, where men are often primary income earners and thus more likely to seek employment opportunities elsewhere when local livelihoods are threatened. Additionally, the finding that individuals with prior migration experience are more responsive to yield fluctuations suggests the role of social networks and migration pathways in facilitating mobility, consistent with migration systems theory (26). This aligns with other research indicating that climate change-related migration is highly gendered (27). For example, a study in Pakistan found that heat stress increased long-term migration among male but not female farmers (28). These findings highlight the need for gender-specific policies to address the distinct capability of migration in response to climate stressors and ensure equity in benefits brought by such responses across genders.

The results suggest a cumulative impact of migration experience on migration behaviour, with individuals who have previously migrated being more likely to respond to crop yield reductions by migrating again. The influence of past migration on future migration behaviour is poorly understood due to the lack of longitudinal studies in climate migration research. Yet, some evidence indicates that migration is a learned behaviour. For instance, a study of 15 European countries found that decisions to migrate are embedded within a longer migration history and the influence of past moves diminishes as individuals progress in their migration “careers” (29). This suggests that past migration experiences shape individuals' adaptive strategies, emphasizing the need for longitudinal studies to capture the evolving dynamics of migration in response to climate change.

We observed that not only farmers but also those employed in the wider agricultural and food sector may out-migrate more in years of poor yield, if they have a general predisposition to migration, such as prior experience of out-migration. While many studies on migration and slow-onset events focus on populations with directly resource-dependent livelihoods, such as farmers, there is a growing body of research examining the risk of environment-related migration and displacement among other occupational groups, which constitutes a novel aspect of this study.

Our time-to-event analysis applied to 23 years of HDSS cohort data introduces an innovative approach. This approach provides empirical evidence meeting multiple causality criteria, often lacking in previous climate and migration studies. By accounting for the timing of agricultural harvest and migration events with monthly precision, we ensured accurate temporality, which eliminates the possibility of reverse causality in the association of crop yield variability with out-migration. Using continuous exposure (FCPI) and outcome (migration rate) measures allowed us to assess the association gradient and investigate the association in specific occupational, demographic, and socio-economic groups, controlling for confounders, thus, contributing to the specificity and plausibility of our results. The high effect size and corroborating qualitative evidence from farmers in our study area (4,30) further support the weight of evidence for a causal interpretation of our findings.

Our results have significant implications for policy interventions aimed at mitigating climate-induced migration. First, enhancing agricultural resilience through climate-smart practices such as integrated soil fertility management and agroforestry could reduce the vulnerability of rural households to climatic shocks (13). Investments in rural infrastructure, access to credit, and diversification of income sources can also strengthen adaptive capacity and reduce the necessity of distress migration. Further, migration should be recognized as a legitimate adaptation strategy within national climate change policies. Facilitating safe and orderly migration, supported by legal frameworks and social protection measures, can help maximize the adaptive benefits while minimizing the risks associated with forced displacement. Regional cooperation will be essential, given the transboundary nature of climate impacts and migration flows in West Africa.

While this study advances understanding of the climate-migration nexus, several areas warrant further investigation. Longitudinal studies incorporating more granular climate data and diverse socio-economic indicators could elucidate causal pathways more precisely. Additionally, qualitative research exploring the lived experiences of migrants can provide deeper insights into decision-making processes and the role of non-economic factors in migration. Future research should also examine the health impacts of climate-induced migration, considering both the risks associated with displacement and the potential health benefits of reduced exposure to environmental hazards. Integrating health metrics into migration studies would offer a more comprehensive view of the climate-food-migration-health nexus, informing holistic adaptation strategies.

Some limitations need to be acknowledged. (i) The cohort study compared the population against itself over 23 years, minimizing time-invariant confounding but allowing for residual confounding from time-varying factors. No relevant time-variant factors were identified as potential confounders. (ii) Historical crop yield data were only available at the provincial level; higher spatial resolution could have improved the analysis. (iii) Household wealth data were only available for 2009, we had to assume household wealth stability over the study period. (iv) Migrant identification issues in the Nouna HDSS may have led to underestimations of temporary and overestimations of permanent migration, introducing some bias, particularly, in the role of the order of migration as a modifier leading to a lower-bound estimate of the associations. HDSSs should integrate data on crop production, migration events, and climate parameters for better understanding (31).

The variation in crop yields in this setting is largely attributable to weather. Poor crop yields are projected to worsen in the future, even under the aspirational target of 1.5°C global warming. Consequently, out-migration from the study area is likely to increase under any climate scenario. This future will necessitate increased local and national adaptation measures.

Development of adequate adaptation measures requires robust and context-specific projections of migration flows under different climate change and socio-economic scenarios based on high-quality empirical evidence. Estimating the number of people projected to migrate or be displaced due to climate change presents significant challenges. The variability of climate impacts across regions complicates uniform predictions, while models must account for complex interactions between environmental, economic, and social factors, which are often nonlinear, unpredictable, and context-specific. Migration data, particularly in developing regions, is scarce, fragmented, often outdated, leading to gaps and biases in projections and since most environmental displacements are internal, they are harder to track than cross-border movements (32).

Building a more comprehensive evidence base for attribution, projections, and development of suitable policies requires further research on similar associations in other areas. There are >60 HDSS sites globally, which follow a standardised methodology and pass quality-assurance. All HDSS sites are in low-income countries vulnerable to climate change (32–34). Hence, our approach is scalable and, if expanded, can be used to substantially improve the empirical evidence for the attribution and projections of climate migration.

If adequately managed, migration can constitute an adaptation strategy (35–37). Migration decisions are influenced by individual characteristics, household composition, social networks, and broader historical, political, and economic factors. Migration can be part of household strategies to diversify risk (33,38,39), which may be what our results reflect given poorer households are more likely to migrate in response to weather-related crop loss. Understanding whether, to what extent and how out-migration in response to low crop yield currently constitutes an effective adaptation strategy and what factors influence its effectiveness, is important. Further research is needed to determine what strategies, policies, and other interventions could benefit sustainable management of migration flows in both sending and host locations, ensuring the health and wellbeing of migrants.

A recent policy synthesis suggested key principles for stewarding safe, orderly and regular migration in the context of climate change, including: avoiding the universal promotion of migration as an adaptive response to climate risk; preserving cultural and social ties of mobile populations; enabling the participation of migrants in decision-making in sites of relocation and resettlement; strengthening health systems and reduce barriers for migrant access to health care; and optimizing of social determinants of migrant health with attention to immobile and trapped populations (40). However, effective climate change mitigation action should remain the priority to help minimise the stress that climate change imposes on requiring people to leave their homes.

Conclusion

In conclusion, in the rural population of Burkina Faso studied, out-migration appears to increase with crop yield reductions, particularly among farmers, and especially among poorer male farmers with prior experience of migration. There is also some evidence that those occupied in the wider agricultural and food sector and the unoccupied out-migrate more during the years of poor yield. These findings are particularly important in the context of the projected reductions and increased unpredictability of crop yields with future climate change in this and similar settings. Our findings provide an important basis for further research and projections of possible out-migration flows under future climate change and socio-economic scenarios. It is important to understand whether, to what extent and how out-migration in response to poor crop yield constitutes an effective adaptation strategy in different settings and what policies and programs are necessary to improve the migrant health and the health of sending and host communities. Finally, this research emphasises the need for urgent action on climate change mitigation to prevent further exacerbation of the climate change-driven stressors that necessitate migration in subsistence farming communities in Africa.

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Supplementary Information: Please see Supplement 1 for Technical Results, Supplement 2 for Extended Results, and Supplement 3 for Sensitivity Analysis Results.

Author Contributions: KB conceived, designed, and developed the methodology of the study with input from JR and RS. PZ, AS performed data collection. KB performed data analyses. KB, PNS, RB, JR, PZ assisted with interpretation of the study results. KB, PNS drafted the paper incorporating editorial changes and comments from all authors. All authors reviewed and approved the submitted manuscript.

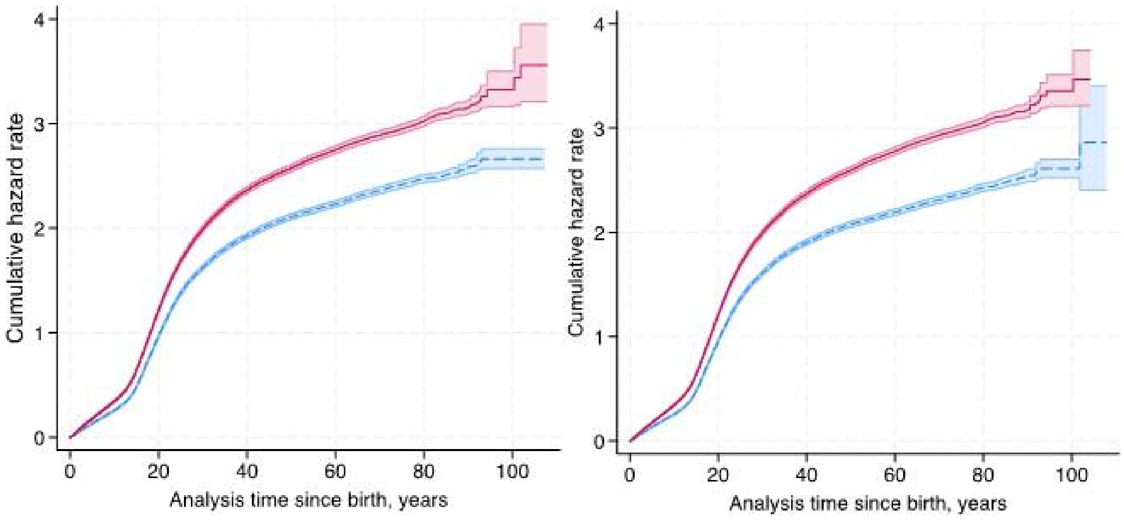
Competing Interests: The authors declare no competing interests

Supplementary Material

- Table S1: Full version of Table 3. First out-migration.
- Table S2: Association of out-migration, undertaken for "yield-sensitive" reasons, with food crop yield. Second out-migration.
- Table S3: Association of out-migration for reasons, undertaken for "yield-sensitive" reasons, with food crop yield. Third out-migration.
- Table S4: Association of out-migration for reasons, undertaken for "yield-sensitive" reasons, with food crop yield. Fourth out-migration.
- Table S5: Association of out-migration for reasons, undertaken for "yield-sensitive" reasons, with food crop yield. Fifth out-migration.
- Table S6: Results of Sensitivity Analysis 1.
- Table S7: Results of Sensitivity Analysis 2.
- Table S8: Results of Sensitivity Analysis 3.

FIGURES

Figure 2. Cumulative hazard plots of all out-migration events in relation to the FCPI exposure at different times: Panel a – in the single preceding harvest, panel b – cumulatively over the preceding three harvests. (n=196,320 people), Nouna Health and Demographic Surveillance System, Burkina Faso, 1994-2016. The red solid line shows the cumulative hazard in those exposed to FCPI< 100%; the blue dashed line shows the cumulative hazard in those exposed to FCPI ≥ 100%. Red/blue shaded areas show the 95% confidence intervals, correspondingly. X-axis: Analysis time since birth of the migrant (years).



TABLES

Table 1. Number of people, out-migration events, person-years, and out-migration rate according to individual characteristics (n=196,320 people), Nouna Health and Demographic Surveillance System, Burkina Faso, 1994-2016.

Characteristic	No of individuals	% of people	No of out-migration events				P-Y at Risk	Rate of out-migration per 1,000 P-Y			
			All	Yield-sensitive	Non-yield-sensitive	Maybe yield-sensitive		All	Yield-sensitive	Non-yield-sensitive	Maybe yield-sensitive
Age while under observation											
<5	82,726	42	7,721	22	35	7,664	253,524	30	0	0	30
5-<18	99,820	51	24,195	5,508	4,484	14,203	479,127	50	11	9	30
18-<30	61,759	31	19,736	6,499	3,896	9,341	246,650	80	26	16	38
30-<50	35,936	18	6,189	2,187	393	3,609	220,713	28	10	2	16
50-<70	15,436	8	1,545	296	41	1,208	107,730	14	3	0	11
≥70	5,344	3	359	30	6	323	29,868	12	1	0	11
Sex											
Male	91,644	47	27,000	9,790	2,886	14,324	668,930	40	15	4	21
Female	104,676	53	32,745	4,752	5,969	22,025	668,705	49	7	9	33
Ethnicity											
Bwamu	48,435	25	13,066	3,661	2,083	7,322	329,018	40	11	6	22
Dafing	69,492	35	17,639	5,992	2,166	9,480	509,647	35	12	4	19
Mossi	36,532	19	14,056	2,587	2,290	9,180	238,910	59	11	10	38
Fulani	18,615	9	6,258	823	1,056	4,379	120,657	52	7	9	36
Samo	16,084	8	5,306	944	818	3,545	107,798	49	9	8	33
Other	6,988	4	3,383	529	440	2,414	30,901	109	17	14	78
Unknown	174	0	37	6	2	29	705	52	9	3	41
Religion											
Animist	9,796	5	2,954	1,110	341	1,504	77,746	38	14	4	19
Catholic	53,893	27	16,210	4,403	2,535	9,272	355,818	46	12	7	26
Muslim	121,748	62	37,140	8,279	5,387	23,474	833,278	45	10	6	28
Other	450	0	132	39	18	75	2,799	47	14	6	27
Protestant	10,209	5	3,212	696	564	1,952	67,169	48	10	8	29
Unknown	224	0	97	15	10	72	826	117	18	12	87
Relevance of occupation to agriculture											
Non-agricultural	8,514	4	2,624	988	391	1,207	74,009	35	13	5	16
Farmers	35,601	18	10,630	5,651	995	3,983	369,299	29	15	3	11
Wider agricultural/ food sector	3,557	2	868	219	131	518	36,676	24	6	4	14
Unoccupied	118,226	60	28,425	3,725	5,483	19,174	725,065	39	5	8	26
Unknown	30,422	15	17,198	3,959	1,855	11,467	132,587	130	30	14	86
Literacy											
Literate	60,387	31	10,458	3,188	1,427	5,725	524,235	20	6	3	11
Illiterate	5,964	3	1,447	599	313	556	68,775	21	9	5	8
Unknown	129,969	66	47,840	10,755	7,115	30,068	744,625	64	14	10	40
Wealth											
Lower	55,628	28	13,609	5,224	1,831	6,569	457,038	30	11	4	14
Higher	74,502	38	25,082	5,465	4,999	14,588	562,520	45	10	9	26
Unknown	66,190	34	21,054	3,853	2,025	15,192	318,078	66	12	6	48
Market present in the village											
No	50,662	26	14,308	3,763	1,851	8,701	350,491	41	11	5	25
Yes	145,658	74	45,437	10,779	7,004	27,648	987,144	46	11	7	28
Village infrastructure level											
Level 1 (lowest)	51,186	26	13,835	4,009	1,622	8,209	362,546	38	11	4	23
Level 2	55,773	28	14,970	4,792	1,754	8,417	402,531	37	12	4	21
Level 3	18,767	10	5,779	1,578	938	3,261	150,135	38	11	6	22

Level 4 (highest)	70,594	36	25,161	4,163	4,541	16,462	422,423	60	10	11	39
Rural *vs* semi-urban residence											
Rural	130,796	67	35,820	10,727	4,549	20,543	951,928	38	11	5	22
Semi-urban	65,524	33	23,925	3,815	4,306	15,806	385,708	62	10	11	41

Table 2: Number of out-migration events according to the event characteristics (n= 59,745 events), Nouna Health and Demographic Surveillance System, Burkina Faso, 1994-2016

Characteristic	No of events	% of events
Distribution of the observations according to the Number of out-migration(events)		
1	55,182	92.4
2	4,172	7.0
3	358	0.6
4	31	0.1
5	2	0.0
Reason for leaving		
Yield-sensitive	**14,542**	**24.3**
To cultivate	263	0.4
To work	13,988	23.4
For pasture	291	0.5
Not yield sensitive	**8,855**	**14.8**
Divorce	551	0.9
Funeral	8	0.0
To study	4,585	7.7
Returning to parents to give birth	39	0.1
To form a household	17	0.0
Marriage	3,654	6.1
Possibly/maybe yield sensitive	**36,349**	**60.8**
Returning to parents for other reasons than giving birth	7,257	12.1
Following family/someone	16,681	27.9
Health reasons	150	0.3
Other	11,781	19.7
Unknown	480	0.8
Migration type		
Short term	3,473	5.8
Long term	9,497	15.9
Permanent	46,775	78.3
Age at migration		
<5	7,721	12.9
5-<18	24,195	40.5
18-<30	19,736	33.0
30-<50	6,188	10.4
50-<70	1,545	2.6
≥70	360	0.6

Table 3: Association of migrants' first out-migration, undertaken for yield-sensitive reasons, with FCPI in the single preceding harvest and with cumulative FCPI over the preceding three harvests by sex, wealth index, and relevance of occupation to agriculture (n = 168,089 people), Nouna Health and Demographic Surveillance System, Burkina Faso, 1994-2016

Characteristics			HR of Δ90p–10p in single preceding FCPI	95% CI	HR of Δ90p–10p in cumulative FCPI	95% CI
Sex	Relevance of occupation to agriculture	Wealth level				
Men	Farmers	Low	1.54	1.41, 1.69	1.41	1.23, 1.62
		High	1.40	1.27, 1.54	1.40	1.22, 1.61
	Wider agricultural/food sector	Low	1.32	0.94, 1.87	1.62	0.91, 2.87
		High	1.20	0.85, 1.69	1.61	0.91, 2.86
	Non-agricultural occupation	Low	0.84	0.69, 1.03	0.71	0.55, 0.92
		High	0.76	0.63, 0.92	0.71	0.56, 0.89
	Unoccupied	Low	1.60	1.41, 1.81	1.33	1.10, 1.61
		High	1.44	1.29, 1.62	1.32	1.11, 1.57
Women	Farmers	Low	1.37	1.20, 1.55	0.96	0.80, 1.16
		High	1.24	1.08, 1.41	0.96	0.79, 1.15
	Wider agricultural/food sector	Low	1.17	0.83, 1.65	1.10	0.62, 1.96
		High	1.06	0.75, 1.50	1.10	0.62, 1.95
	Non-agricultural occupation	Low	0.74	0.61, 0.91	0.48	0.37, 0.63
		High	0.67	0.56, 0.81	0.48	0.38, 0.61
	Unoccupied	Low	1.41	1.25, 1.60	0.90	0.75, 1.09
		High	1.28	1.14, 1.43	0.90	0.77, 1.06

Abbreviations: Δ90p–10p, decrease from 90th to 10th centile; CI, confidence interval; FCPI, food crop productivity index; HR, hazard ratio.

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Supplementary Files

Supplement 2: Supplementary Information on Methods

Study area and population

For our study, we selected a rural subsistence farming population in the North-Western province of Burkina Faso. This population comprises 58 villages and one town. It has been followed-up since 1992 as an open dynamic continuous cohort by the Nouna Health and Demographic Surveillance System (HDSS) (41,42). The population under surveillance has increased from 26,626 in 1992 to 125,000 in 2022 through natural population growth, incorporation of additional villages in the years 2000 and 2004 (16), and in-migration. Households rely almost entirely on rain-fed subsistence agriculture with one agricultural season per year, with the harvest time around September.

We obtained the following data:

Outcome

We acquired the Nouna HDSS data on the entire population that was under uninterrupted surveillance from 1992 until 2016. The surveillance was done through house-to-house vital event registration surveys every 3 months from 1992 until 2006 and every 4 months thereafter, which recorded the event dates and self-reported reasons for migrating. Full population control censuses were conducted every 5 to 6 years. In 2017, the surveillance was interrupted to change from paper to digital data collection. Although surveillance was in 2019, there remained a gap in its continuity. Therefore, data from 2019 onwards are not used in this study. Data from the years 1992–1993 were also omitted from our analyses because of concerns over data incompleteness while the surveillance system was under development. All records on individuals with missing data for the month of at least one of their entries or exits from the cohort were excluded.

Our outcomes of interest were the out-migration events undertaken for reasons that are likely to be sensitive to inter-annual crop yield variation, namely, for work, crop cultivation, and pasture outside of the Nouna HDSS area. Episodes of observation that ended with out-migration for reasons that are unrelated to inter-annual crop yield variations – namely marriage, divorce, studies, to form a household, funeral – where included in the time at risk (the denominator) but censored upon out-migration – either for the period of absence from the cohort for the subjects who subsequently returned into the cohort, or permanently for those who did not return. Observations that ended with out-migration for reasons whose sensitivity to interannual crop yield variation was unclear – namely health reasons, returning to parents to give birth, returning to parents for reasons other than giving birth, and following family or someone else, unknown reasons, and reasons recorded as "other" – were excluded from the main analysis to avoid outcome misclassification. The classification of yield sensitive *vs* non-yield sensitive reasons for migration reflects the degree to which migration reasons are influenced by agricultural productivity and economic conditions tied to crop yields. Yield-sensitive reasons directly respond to economic pressures from agricultural performance, while non-yield sensitive reasons are driven by social and cultural factors. In Nouna HDSS, out-migration was recorded for all absences from Nouna HDSS area for longer than 2 months.

Exposure

We obtained data on crop yields (kg/ha) and harvest amounts (kg) in Kossi Province during 1994–2016 from the Annual Agricultural Survey of Burkina Faso, undertaken by the Agricultural Statistics Service of Burkina Faso using crop cut estimation method representative at the province level (16). We used our previously published method to calculate the FCPI (16). The Food Crop Productivity Index (FCPI) measures the yield of key food crops (millet, sorghum, maize, fonio, and rice) in Nouna district, Burkina Faso, relative to their 1992–2012 average, expressed as a percentage. An FCPI of 100% reflects average yields, with lower values indicating deficits. Derived from crop yield data sourced from Burkina Faso's Agricultural Statistics Service, FCPI variability is strongly linked to weather conditions. A prior weather-to-crop model (14) showed that 72% of FCPI fluctuations are explained by weather factors like temperature and precipitation. Thus, FCPI serves as an indirect measure of climate variability's impact on agricultural productivity.

We used two exposure time frames:

1. FCPI of the single harvest preceding each observation episode: to examine the direct effect of the most recent yield in the single preceding harvest on out-migration,
2. Cumulative FCPI over the last three agricultural years preceding each observation episode: to examine the cumulative effect of past harvests on out-migration, which is likely to be mediated through changes in disposable assets and other adaptive capacities that happen in response to low and high yield levels. Past (unpublished) research suggests that in this setting both practices are common: increased asset

acquisition in the years of high yield (as means of wealth accumulation) and asset sales in the years of low yields (asset liquidation). To allow accounting for both practices, we calculated the cumulative FCPI values as the period mean value of FCPI over the last three harvests preceding each observation episode.

Co-variates

Nouna HDSS data included information on three levels:

- Individual demographic and socioeconomic characteristics: age, family relationship within the household, sex, ethnicity, religion, literacy, occupational status, including primary and secondary occupation
- Household information: assets and housing characteristics, and
- Village level: rural *vs* semirural, presence of a school, market, a health care facility, drilled water well, and quality of road connection.

While some of these data were used directly as co-variates, others were used to generate more complex co-variates:

1. **Occupational relevance to agriculture:** we developed a new categorical variable to indicate the relevance of individuals' occupation to agriculture. For this variable we defined the following categories:

a) Employed in crop cultivation either as a primary or secondary occupation or both;

b) Employed in the wider agricultural and food sector, which includes as either the primary or secondary occupation or both the following occupation types: beekeeper, fisherman, shepherd, breeder, butcher, beer maker, gardener;

c) Employed in sectors unrelated to agriculture, which includes as either the primary or secondary occupation or both the following occupation types: artist, trades person, black-smith, guard, builder, potter, religious service, mechanic, dry cleaner, weaver, well digger, tailor, official, shoemaker, hairdresser, driver, missionary;

d) Unoccupied, which includes those outside of the working population (children, students, housewives, disabled, elderly) and the unemployed (those without employment but are seeking employment);

e) Unknown, which is assigned to subjects whose occupational status or occupation type was not known (e.g., missing data entries).

2. **Household wealth index:** we used the household wealth index developed by Schoeps et al. (43) which represents housing conditions (e.g., water source in the dry and rainy seasons, dwelling type, type of toilet and sanitation, type of roof and walls, energy source for cooking, source of lighting) and asset ownership (e.g., agricultural assets, means of transportation, and ownership of household items such as a radio, television, refrigerator, or modern stove) based on the data for 2009 (43). Because the wealth index data were available only for 2009, we assigned the index value from 2009 to all years through which the household could be traced in our data set over the course of the analysis period from 1994 to 2016. We re-coded the continuous wealth index values into a categorical variable with two levels reflecting values above and below median wealth index. We reclassified any missing data on individual and socioeconomic characteristics into a separate, i.e., third category labelled "unknown."

3. **Village infrastructural development level:** we used principal component analysis to construct a village infrastructural development index from data on characteristics of Nouna HDSS villages (presence of health-care facilities, drilled water wells, markets, and the quality of road connections) from a geographic information system database of the Centre de Recherche en Santé de Nouna, which we recoded into quartiles.

4. **Order of migration:** using data on the dates of out-migration events, we developed a variable that reflects the observed order of every out-migration event for every individual over the course of our observation period.

5. **Permanent *vs* temporary out-migration:** using data on in-migration events and their dates, we determined and classified every out-migration event to indicate if it was permanent (defined as out-migration events that were not followed by in-migration, i.e., return, over the course of our observation period) or temporary.

6. **Duration of out-migration:** we calculated the duration of all temporary migration episodes and classified temporary out-migration as short term (absence of <1 year) or long term (absence of ≥1 year).

Analyses

We treated out-migration as a recurrent outcome, for which subjects become "at risk" of out-migration from birth but came under observation from September 1st 1994 – the start of the first annual crop harvest under observation.

We examined associations of the preceding and cumulative FCPI with out-migration using tabulations, cumulative hazard plots, and Prentice-Williams-Peterson regression models based on total time since entry under study with age used as the analysis time.

For cumulative hazard plots, each exposure index was transformed into a binary indicator above *vs* below the period average FCPI. For the Prentice-Williams-Peterson models, we used continuous exposure indices.

Prentice-Williams-Peterson models were selected, as they allow taking account of the correlated nature of event recurrence within subjects, as subjects who have out-migrated before are more likely to out-migrate again in the future (44). We assessed whether any number of the smallest risk sets with the highest ranks of the observed order of out-migration events (e.g., combining data in the risk set of the 4th and 5th rank or risk sets of the 3rd, 4th and 5th rank) into one risk set benefits the model fit by comparing the model Akaike Information Criterion (AIC). Results of the model assessment are available in Supplement 1.

The hazard ratios (HRs) are reported in relation to the change in exposure from the 90th percentile of exposure to the 10th percentile.

Treatment of confounders. All Prentice-Williams-Peterson models were adjusted for potential confounders, which we determined a priori (45–47) but also assessed in terms of their contribution to the model fit by comparing AIC: linear time trend (i.e., year fitted as a linear term to control for any long- term, continuous changes in rates of out-migration and crop yields), all time invariant sociodemographic characteristics of the subjects, their households, and their villages: ethnicity, religion, literacy, and village infrastructural development index, rural *vs* semirural residence, and market presence in the village.

Treatment of effect modification. To examine whether and how an individual's previous experience of migration influences the association, we tested for effect modification of the association by the order of out-migration event for every individual and stratified the analyses by the observed rank order. To examine whether and how the association varied with individual sex, household wealth, and with the relevance of occupation to agriculture, we tested for effect modification of the association by each of these variables. We first assessed two-way interaction terms of these variables with FCPI in separate models, and then gradually added the interaction terms together in one model, assessing the change in the model AIC with each addition. We tested for effect modification in all models by assessing significance of every interaction term using the Wald test for the respective parameter. We also assessed the relevance of three-way and four-way interaction terms of these variables using the same methods (Wald test for the interaction parameter and change in the model AIC). We present hazard ratios for every combination of values of all the variables for which we found evidence of effect modification.

Sensitivity analyses

(i) We performed sensitivity analyses where we included all out-migration events regardless of the reported reason of out-migration. (ii) To examine whether expansion of the Nouna HDSS population through the addition of new villages in the years 2000 and 2004 could have biased our analyses, we performed sensitivity analyses by restricting the data set to only those villages that had been part of the HDSS since its inception. (iii) As full migration history of subjects who entered under observation later than from birth was unknown, we conducted a sensitivity analysis on a subset of only those subjects who entered under observation upon birth (i.e., those born after the 1 September 1994, ages of 22 or younger). Results of the sensitivity analyses are reported for the migrants’ first out-migration for yield-sensitive reasons in the Supplement 3 and Supplementary Tables S6-S8.

Statistical analyses were performed using Stata 17 (StataCorp LLC, College Station, Texas). This study received ethical approval from the Ethics Committee of the Medical Faculty of Heidelberg University, Germany, and the Comité Institutionnel d’Éthique du Centre de Recherche en Santé de Nouna, Burkina Faso. The approval reference number is 2022-11-240. Written informed consent was obtained from all participating households enrolled in the longitudinal cohort. All participants were adults over the age of 18; no children were involved in the study.

Supplement 2: Technical results

Model selection and specification results

When fitting Prentice-Williams-Peterson regression models, there was no improvement in model fit with the removal of the smallest risk sets that corresponded to the highest ranks of the observed order of out-migration events. Therefore, we based our models on all five distinct risk sets corresponding to the five orders of the observed out-migration events. The model fit improved with the addition of all the following adjustments for confounding: linear time trend, sex, wealth, relevance of occupation to agriculture, ethnicity, religion, literacy, and village infrastructural development index. No improvements were found with the addition of variables indicating rural *vs* semirural residence and market presence in the village. Therefore, these two variables were excluded from the model adjustments.

Wald tests were significant for the two-way interaction of the preceding single and cumulative FCPI with sex ($p<0.001$), wealth index ($p<0.001$), relevance of occupation to agriculture ($p<0.001$), and order of out-migration events ($p<0.001$), when these terms were fitted into the fully adjusted models separately. They remained significant when combined into one model (single preceding FCPI: $p<0.001$ for wealth and relevance of occupation to agriculture, $p=0.017$ for the order of out-migration, $p=0.011$ for sex; cumulative FCPI: $p<0.001$ for sex, relevance of occupation to agriculture, and rank of out-migration, $p=0.212$ for wealth). Addition of each of these interaction terms improved the model fit. Most three-way or four-way interaction terms were not significant (preceding FCPI: p- values for three-way interaction ranged from 0.041—0.542, for four-way interaction $p=0.703$ – only one model with four-way interaction terms compiled; cumulative FCPI: p-values for three-way interaction ranged from 0.087—0.859 and 0.566—0.774, models with four-way interactions did not compile). Two configurations of three-way terms were significant, according to the Wald test – preceding FCPI: $p<0.001$ and $p=0.041$; cumulative FCPI: $p=0.034$, $p<0.001$. However, inclusion of these terms did not add to the model fit, according to the AIC. Therefore, we excluded all three-way and four-way interaction terms.

Supplement 2: Tables containing extended results

Table S1. Full version of Table 3: Association of migrants' *first* out-migration, undertaken for yield-sensitive reasons, with FCPI in the single preceding harvest and with cumulative FCPI over the preceding three harvests by sex, wealth index, and relevance of occupation to agriculture (n = 168,089 people), Nouna Health and Demographic Surveillance System, Burkina Faso, 1993-2016

Characteristics			HR of Δ90p–10p in single preceding FCPI	95% CI	HR of Δ90p–10p in cumulative FCPI	95% CI
Sex	Relevance of occupation to agriculture	Wealth level				
Men	Farmers	Low	1.54	1.41, 1.69	1.41	1.23, 1.62
		High	1.40	1.27, 1.54	1.40	1.22, 1.61
		Unknown	1.93	1.73, 2.14	2.57	2.19, 3.02
	Wider agricultural/food sector	Low	1.32	0.94, 1.87	1.62	0.91, 2.87
		High	1.20	0.85, 1.69	1.61	0.91, 2.86
		Unknown	1.65	1.17, 2.34	2.94	1.64, 5.29
	Non-agricultural occupation	Low	0.84	0.69, 1.03	0.71	0.55, 0.92
		High	0.76	0.63, 0.92	0.71	0.56, 0.89
		Unknown	1.05	0.85, 1.29	1.29	0.99, 1.70
	Unoccupied	Low	1.60	1.41, 1.81	1.33	1.10, 1.61
		High	1.44	1.29, 1.62	1.32	1.11, 1.57
		Unknown	1.99	1.76, 2.26	2.42	1.99, 2.94
	Unknown	Low	0.62	0.55, 0.69	0.38	0.32, 0.44
		High	0.56	0.50, 0.62	0.38	0.32, 0.44
		Unknown	0.77	0.69, 0.86	0.69	0.59, 0.81
Women	Farmers	Low	1.37	1.20, 1.55	0.96	0.80, 1.16
		High	1.24	1.08, 1.41	0.96	0.79, 1.15
		Unknown	1.70	1.49, 1.94	1.75	1.44, 2.13
	Wider agricultural/food sector	Low	1.17	0.83, 1.65	1.10	0.62, 1.96
		High	1.06	0.75, 1.50	1.10	0.62, 1.95
		Unknown	1.46	1.25, 1.60	2.01	1.12, 3.60
	Non-agricultural occupation	Low	0.74	0.61, 0.91	0.48	0.37, 0.63
		High	0.67	0.56, 0.81	0.48	0.38, 0.61
		Unknown	0.92	0.75, 1.13	0.88	0.67, 1.15
	Unoccupied	Low	1.41	1.25, 1.60	0.90	0.75, 1.09
		High	1.28	1.14, 1.43	0.90	0.77, 1.06
		Unknown	1.76	1.56, 1.98	1.65	1.38, 1.97
	Unknown	Low	0.55	0.49, 0.61	0.26	0.22, 0.30
		High	0.49	0.44, 0.55	0.26	0.22, 0.30
		Unknown	0.68	0.61, 0.76	0.47	0.40, 0.55

Abbreviations: Δ90p–10p, decrease from 90th to 10th centile; CI, confidence interval; FCPI, food crop productivity index; HR, hazard ratio.

Table S2. Association of migrants' *second* out-migration, undertaken for yield-sensitive reasons, with FCPI in the single preceding harvest and with cumulative FCPI over the preceding three harvests by sex, wealth index, and relevance of occupation to agriculture (n = 168,089 people), Nouna Health and Demographic Surveillance System, Burkina Faso, 1993-2016

Characteristics			HR of Δ90p–10p in single preceding FCPI	95% CI	HR of Δ90p–10p in cumulative FCPI	95% CI
Sex	Relevance of occupation to agriculture	Wealth level				
Men	Farmers	Low	1.93	1.67, 2.25	1.88	1.53, 2.30
		High	1.75	1.49, 2.05	1.87	1.51, 2.31
		Unknown	2.41	2.04, 2.85	3.42	2.70, 4.32
	Wider agricultural/food sector	Low	1.66	1.16, 2.38	2.15	1.18, 3.90
		High	1.50	1.04, 2.17	2.14	1.17, 3.89
		Unknown	2.07	1.43, 3.00	3.91	2.12, 7.21
	Non-agricultural occupation	Low	1.05	0.83, 1.33	0.94	0.70, 1.28
		High	0.95	0.76, 1.19	0.94	0.70, 1.25
		Unknown	1.31	1.03, 1.67	1.72	1.25, 2.37
	Unoccupied	Low	2.00	1.69, 2.38	1.76	1.38, 2.25
		High	1.81	1.53, 2.14	1.76	1.39, 2.22
		Unknown	2.49	2.08, 2.98	3.21	2.48, 4.16
	Unknown	Low	0.77	0.67, 0.89	0.50	0.42, 0.61
		High	0.70	0.60, 0.81	0.50	0.41, 0.61
		Unknown	0.96	0.83, 1.12	0.91	0.74, 1.12
Women	Farmers	Low	1.71	1.42, 2.05	1.28	0.99, 1.65
		High	1.55	1.28, 1.87	1.27	0.98, 1.65
		Unknown	2.13	1.75, 2.58	2.33	1.78, 3.06
	Wider agricultural/food sector	Low	1.83	1.25, 2.66	1.46	0.80, 2.67
		High	1.60	1.34, 1.91	1.46	0.80, 2.67
		Unknown	1.83	1.25, 2.66	2.67	1.44, 4.93
	Non-agricultural occupation	Low	0.93	0.73, 1.18	0.64	0.47, 0.88
		High	0.84	0.67, 1.06	0.64	0.47, 0.87
		Unknown	1.16	0.90, 1.48	1.17	0.84, 1.63
	Unoccupied	Low	1.77	1.48, 2.12	1.20	0.94, 1.54
		High	1.60	1.34, 1.91	1.20	0.94, 1.52
		Unknown	2.20	1.83, 2.64	2.19	1.69, 2.84
	Unknown	Low	0.68	0.58, 0.80	0.34	0.28, 0.42
		High	0.62	0.53, 0.72	0.34	0.28, 0.42
		Unknown	0.85	0.72, 1.00	0.62	0.50, 0.78

Abbreviations: Δ90p–10p, decrease from 90th to 10th centile; CI, confidence interval; FCPI, food crop productivity index; HR, hazard ratio.

Table S3. Association of migrants' *third* out-migration, undertaken for yield-sensitive reasons, with FCPI in the single preceding harvest and with cumulative FCPI over the preceding three harvests by sex, wealth index, and relevance of occupation to agriculture (n = 168,089 people), Nouna Health and Demographic Surveillance System, Burkina Faso, 1993-2016

Characteristics			HR of Δ90p–10p in single preceding FCPI	95% CI	HR of Δ90p–10p in cumulative FCPI	95% CI
Sex	Relevance of occupation to agriculture	Wealth level				
Men	Farmers	Low	2.17	1.39, 3.38	1.56	0.89, 2.74
		High	1.96	1.26, 3.06	1.55	0.88, 2.74
		Unknown	2.70	1.72, 4.23	2.84	1.59, 5.05
	Wider agricultural/food sector	Low	1.86	1.07, 3.23	1.78	0.81, 3.95
		High	1.68	0.97, 2.92	1.78	0.80, 3.94
		Unknown	2.32	1.33, 4.05	3.25	1.45, 7.29
	Non-agricultural occupation	Low	1.18	0.73, 1.90	0.78	0.43, 1.44
		High	1.07	0.66, 1.71	0.78	0.43, 1.42
		Unknown	1.47	0.91, 2.37	1.43	0.77, 2.65
	Unoccupied	Low	2.24	1.43, 3.53	1.47	0.82, 2.61
		High	2.03	1.30, 3.18	1.46	0.82, 2.60
		Unknown	2.79	1.78, 4.40	2.67	1.48, 4.80
	Unknown	Low	0.87	0.56, 1.35	0.42	0.24, 0.73
		High	0.78	0.50, 1.22	0.42	0.24, 0.73
		Unknown	1.08	0.69, 1.68	0.76	0.43, 1.34
Women	Farmers	Low	1.91	1.21, 3.03	1.06	0.59, 1.92
		High	1.73	1.09, 2.75	1.06	0.58, 1.92
		Unknown	2.38	1.50, 3.78	1.93	1.06, 3.52
	Wider agricultural/food sector	Low	1.64	0.94, 2.87	1.22	0.54, 2.72
		High	1.49	0.85, 2.60	1.21	0.54, 2.71
		Unknown	2.05	1.17, 3.59	2.21	0.98, 5.00
	Non-agricultural occupation	Low	1.04	0.64, 1.69	0.53	0.29, 0.99
		High	0.94	0.58, 1.52	0.53	0.29, 0.98
		Unknown	1.30	0.80, 2.11	0.97	0.52, 1.83
	Unoccupied	Low	1.98	1.25, 3.13	1.00	0.55, 1.80
		High	1.79	1.14, 2.83	0.99	0.55, 1.79
		Unknown	2.47	1.56, 3.90	1.82	1.01, 3.29
	Unknown	Low	0.76	0.49, 1.20	0.28	0.16, 0.51
		High	0.69	0.44, 1.09	0.28	0.16, 0.50
		Unknown	0.95	0.61, 1.50	0.52	0.29, 0.92

Abbreviations: Δ90p–10p, decrease from 90th to 10th centile; CI, confidence interval; FCPI, food crop productivity index; HR, hazard ratio.

Table S4. Association of migrants' *fourth* out-migration, undertaken for yield-sensitive reasons, with FCPI in the single preceding harvest and with cumulative FCPI over the preceding three harvests by sex, wealth index, and relevance of occupation to agriculture (n = 168,089 people), Nouna Health and Demographic Surveillance System, Burkina Faso, 1993-2016

Characteristics			HR of Δ90p–10p in single preceding FCPI	95% CI	HR of Δ90p–10p in cumulative FCPI	95% CI
Sex	Relevance of occupation to agriculture	Wealth level				
Men	Farmers	Low	1.27	0.34, 4.83	0.49	0.04, 6.26
		High	1.15	0.30, 4.38	0.49	0.04, 6.24
		Unknown	1.59	0.42, 6.06	0.90	0.07, 11.49
	Wider agricultural/food sector	Low	1.09	0.28, 4.32	0.56	0.04, 7.63
		High	0.99	0.25, 3.92	0.56	0.04, 7.60
		Unknown	1.36	0.35, 5.02	1.03	0.08, 14.02
	Non-agricultural occupation	Low	0.69	0.18, 2.66	0.25	0.02, 3.19
		High	0.63	0.16, 2.41	0.25	0.02, 3.17
		Unknown	0.86	0.22, 3.33	0.45	0.03, 5.85
	Unoccupied	Low	1.32	0.35, 5.02	0.46	0.04, 5.90
		High	1.19	0.31, 4.55	0.46	0.04, 5.90
		Unknown	1.64	0.43, 6.29	0.84	0.07, 10.87
	Unknown	Low	0.51	0.13, 1.93	0.13	0.01, 1.67
		High	0.46	0.12, 1.75	0.13	0.01, 1.67
		Unknown	0.63	0.17, 2.42	0.24	0.01, 3.08
Women	Farmers	Low	1.13	0.30, 4.28	0.34	0.03, 4.28
		High	1.02	0.27, 3.88	0.33	0.03, 4.27
		Unknown	1.40	0.37, 5.36	0.61	0.05, 7.86
	Wider agricultural/food sector	Low	0.97	0.24, 3.82	0.38	0.03, 5.21
		High	0.87	0.22, 3.47	0.38	0.03, 5.19
		Unknown	1.20	0.30, 4.79	0.70	0.05, 9.57
	Non-agricultural occupation	Low	0.61	0.16, 2.35	0.17	0.13, 2.18
		High	0.55	0.14, 2.13	0.17	0.01, 2.16
		Unknown	0.76	0.20, 2.94	0.31	0.24, 3.99
	Unoccupied	Low	1.17	0.31, 4.44	0.32	0.02, 4.04
		High	1.05	0.28, 4.02	0.31	0.02, 4.02
		Unknown	1.45	0.38, 5.56	0.58	0.04, 7.41
	Unknown	Low	0.45	0.12, 1.71	0.09	0.01, 1.15
		High	0.41	0.11, 1.55	0.09	0.01, 1.14
		Unknown	0.56	0.15, 2.14	0.16	0.01, 2.10

Abbreviations: Δ90p–10p, decrease from 90th to 10th centile; CI, confidence interval; FCPI, food crop productivity index; HR, hazard ratio.

Table S5. Association of migrants' *fifth* out-migration, undertaken for yield-sensitive reasons, with FCPI in the single preceding harvest and with cumulative FCPI over the preceding three harvests by sex, wealth index, and relevance of occupation to agriculture (n = 168,089 people), Nouna Health and Demographic Surveillance System, Burkina Faso, 1993-2016

C			HR of Δ90p–10p in single preceding FCPI	95% CI	HR of Δ90p–10p in cumulative FCPI	95% CI
Sex	Relevance of occupation to agriculture	Wealth level				
Men	Farmers	Low	0.94	<0.01, 1974	<0.01	<0.01, <0.01
		High	0.85	<0.01, 1786	<0.01	<0.01, <0.01
		Unknown	1.17	<0.01, 2458	<0.01	<0.01, <0.01
	Wider agricultural/food sector	Low	0.81	<0.01, 1738	<0.01	<0.01, <0.01
		High	0.73	<0.01, 1572	<0.01	<0.01, <0.01
		Unknown	1.00	<0.01,2165	<0.01	<0.01, <0.01
	Non-agricultural occupation	Low	0.51	<0.01, 1076	<0.01	<0.01, <0.01
		High	0.46	<0.01, 973	<0.01	<0.01, <0.01
		Unknown	0.64	<0.01, 1340	<0.01	<0.01, <0.01
	Unoccupied	Low	0.97	<0.01, 2046	<0.01	<0.01, <0.01
		High	0.88	<0.01, 1850	<0.01	<0.01, <0.01
		Unknown	1.21	<0.01, 2548	<0.01	<0.01, <0.01
	Unknown	Low	0.38	<0.01, 789	<0.01	<0.01, <0.01
		High	0.34	<0.01, 714	<0.01	<0.01, <0.01
		Unknown	0.47	<0.01, 982	<0.01	<0.01, <0.01
Women	Farmers	Low	0.83	<0.01, 1743	<0.01	<0.01, <0.01
		High	0.75	<0.01, 1577	<0.01	<0.01, <0.01
		Unknow	1.03	<0.01,	<0.01	<0.01,

		n		2171		<0.01
	Wider agricultural/food sector	Low	0.71	<0.01, 1534	<0.01	<0.01, <0.01
		High	0.64	<0.01, 1388	<0.01	<0.01, <0.01
		Unknown	0.89	<0.01, 1911	<0.01	<0.01, <0.01
	Non-agricultural occupation	Low	0.45	<0.01,950	<0.01	<0.01, <0.01
		High	0.41	<0.01, 859	<0.01	<0.01, <0.01
		Unknown	0.56	<0.01, 1183	<0.01	<0.01, <0.01
	Unoccupied	Low	0.86	<0.01, 1806	<0.01	<0.01, <0.01
		High	0.78	<0.01, 1634	<0.01	<0.01, <0.01
		Unknown	1.07	<0.01, 2249	<0.01	<0.01, <0.01
	Unknown	Low	0.33	<0.01, 697	<0.01	<0.01, <0.01
		High	0.30	<0.01, 630	<0.01	<0.01, <0.01
		Unknown	0.41	<0.01, 868	<0.01	<0.01, <0.01

Abbreviations: Δ90p–10p, decrease from 90th to 10th centile; CI, confidence interval; FCPI, food crop productivity index; HR, hazard ratio.

Supplement 3: Sensitivity analyses

Results of the first sensitivity analysis, where we used out-migration events undertaken for all reasons (as opposed to only for yield-sensitive reasons, i.e., work, cultivation, and pasture elsewhere, that were examined in the main analyses), are presented in the Supplementary Table S5. The central estimates of the hazard ratios associated with the 90th to 10th centile decrease in FCPI were generally lower in this sensitivity analysis than in the main analyses for farmers, those occupied in the wider agricultural/food sector, and among the unoccupied at the lower wealth level, but higher among the same occupational groups of the higher wealth level. We did not find evidence for statistical significance of the association for those employed in non-agricultural sector in relation to the FCPI in the single preceding harvest but we did find evidence for the association in relation to the cumulative FCPI, notably at the higher wealth levels.

Results of the second sensitivity analysis on whether expansion of the Nouna HDSS population through the addition of new villages in the years 2000 and 2004 could have introduced bias are presented in the Supplementary Table S6. The associations in this sensitivity analysis remained significant for most of categories as in the main analysis, suggesting that bias due to the expansion of the HDSS is unlikely. Exceptions were associations with both exposures for female farmers of higher wealth level and associations with cumulative FCPI for female farmers and the unoccupied. These associations were not significant in the sensitivity analysis, possibly due to the loss of statistical power to detect these weaker associations (as the sensitivity analysis was restricted to a notably smaller sample size). Therefore, these differences may not necessarily indicate bias.

Results of the sensitivity analysis (iii) on a subset of only those subjects who entered under observation upon birth are presented in the Supplementary Table S7. The associations remained statistically significant and similar to the results of the main analyses for male farmers but were no longer significant for the male unoccupied. In this sensitivity analysis, the associations became statistically significant in several groups where there was no statistical significance in the main analysis, e.g., in females employed in the wider agricultural sector and non-agricultural occupations and in males employed in non-agricultural occupations – at low wealth levels for preceding FCPI and at high wealth levels for cumulative FCPI.

Table S6. Sensitivity analysis 1: Association of migrants' first out-migration, undertaken for *all* reasons, with FCPI in the single preceding harvest and with cumulative FCPI over the preceding three harvests by sex, wealth index, and relevance of occupation to agriculture (n = 196,320 people), Nouna Health and Demographic Surveillance System, Burkina Faso, 1993-2016

Characteristics			HR of Δ90p–10p in single preceding FCPI	95% CI	HR of Δ90p–10p in cumulative FCPI	95% CI
Sex	Relevance of occupation to agriculture	Wealth level				
Men	Farmers	Low	1.35	1.27, 1.44	1.38	1.26, 1.52
		High	1.40	1.32, 1.48	1.55	1.43, 1.68
		Unknown	1.57	1.48, 1.67	2.09	1.91, 2.28
	Wider agricultural/food sector	Low	1.23	1.03, 1.46	1.57	1.22, 2.03
		High	1.27	1.07, 1.51	1.76	1.37, 2.27
		Unknown	1.43	1.20, 1.70	2.37	1.84, 3.06
	Non-agricultural occupation	Low	1.07	0.95, 1.20	1.18	1.01, 1.38
		High	1.10	0.99, 1.22	1.32	1.15, 1.52
		Unknown	1.24	1.11, 1.39	1.78	1.53, 2.07
	Unoccupied	Low	1.40	1.32, 1.49	1.68	1.54, 1.86
		High	1.45	1.38, 1.52	1.89	1.76, 2.02
		Unknown	1.63	1.55, 1.72	2.54	2.34, 2.75
	Unknown	Low	0.72	0.67, 0.76	0.49	0.45, 0.53
		High	0.74	0.70, 0.78	0.55	0.51, 0.59
		Unknown	0.83	0.79, 0.88	0.73	0.68, 0.79
Women	Farmers	Low	1.28	1.19, 1.38	1.21	1.09, 1.35
		High	1.33	1.24, 1.42	1.36	1.23, 1.50
		Unknown	1.49	1.39, 1.60	1.83	1.65, 2.03
	Wider agricultural/food sector	Low	1.17	0.98, 1.39	1.38	1.07, 1.78
		High	1.21	1.02, 1.44	1.54	1.20, 1.99
		Unknown	1.36	1.14, 1.62	2.08	1.61, 2.69
	Non-agricultural occupation	Low	1.01	0.90, 1.14	1.03	0.88, 1.21
		High	1.05	0.94, 1.17	1.16	1.00, 1.34
		Unknown	1.18	1.06, 1.32	1.56	1.34, 1.81
	Unoccupied	Low	1.33	1.26, 1.40	1.48	1.37, 1.59
		High	1.38	1.32, 1.44	1.65	1.56, 1.75
		Unknown	1.55	1.48, 1.62	2.22	2.08, 2.38
	Unknown	Low	0.68	0.64, 0.72	0.43	0.39, 0.46
		High	0.70	0.67, 0.74	0.48	0.45, 0.51
		Unknown	0.79	0.75, 0.83	0.64	0.60, 0.69

Abbreviations: Δ90p–10p, decrease from 90th to 10th centile; CI, confidence interval; FCPI, food crop productivity index; HR, hazard ratio.

Table S7. Sensitivity analysis 2: Association of migrants' first out-migration, undertaken for yield-sensitive reasons, with FCPI in the single preceding harvest and with cumulative FCPI over the preceding three harvests by sex, wealth index, and relevance of occupation to agriculture among only those *villages that were originally part* of the Nouna Health and Demographic Surveillance System since 1993 (n = 94,381 people), Burkina Faso, 1993-2016

Characteristics			HR of Δ90p–10p in preceding FCPI	95% CI	HR of Δ90p–10p in cumulative FCPI	95% CI
Sex	Relevance of occupation to agriculture	Wealth level				
Men	Farmers	Low	1.69	1.51, 1.89	1.66	1.40, 1.96
		High	1.48	1.30, 1.69	1.46	1.21, 1.76
		Unknown	2.07	1.81, 2.36	2.80	2.28, 3.45
	Wider agricultural/food sector	Low	1.66	1.07, 2.56	2.20	0.99, 4.88
		High	1.45	0.94, 2.26	1.94	0.87, 4.32
		Unknown	2.02	1.29, 3.16	3.73	1.65, 8.41
	Non-agricultural occupation	Low	0.50	0.35, 0.72	0.35	0.22, 0.57
		High	0.44	0.30, 0.63	0.31	0.19, 0.50
		Unknown	0.61	0.42, 0.89	0.59	0.36, 0.98
	Unoccupied	Low	2.18	1.86, 2.56	1.86	1.45, 2.39
		High	1.91	1.62, 2.26	1.64	1.27, 2.12
		Unknown	2.66	2.24, 3.17	3.16	2.40, 4.16
	Unknown	Low	0.71	0.62, 0.82	0.45	0.37, 0.54
		High	0.63	0.54, 0.73	0.40	0.32, 0.49
		Unknown	0.87	0.75, 1.01	0.76	0.61, 0.94
Women	Farmers	Low	1.23	1.04, 1.44	0.97	0.76, 1.24
		High	1.08	0.90, 1.28	0.86	0.67, 1.10
		Unknown	1.50	1.26, 1.78	1.65	1.27, 2.13
	Wider agricultural/food sector	Low	1.20	0.78, 1.86	1.29	0.58, 2.87
		High	1.05	0.68, 1.64	1.14	0.51, 2.54
		Unknown	1.47	0.94, 2.30	2.19	0.97, 4.93
	Non-agricultural occupation	Low	0.36	0.25, 0.52	0.21	0.13, 0.33
		High	0.32	0.22, 0.46	0.18	0.11, 0.29
		Unknown	0.44	0.30, 0.64	0.35	0.21, 0.57
	Unoccupied	Low	1.58	1.36, 1.83	1.09	0.88, 1.36
		High	1.39	1.19, 1.61	0.96	0.77, 1.20
		Unknown	1.93	1.65, 2.25	1.85	1.46, 2.35
	Unknown	Low	0.52	0.45, 0.59	0.26	0.22, 0.32
		High	0.45	0.39, 0.53	0.23	0.19, 0.29
		Unknown	0.63	0.55, 0.73	0.45	0.36, 0.55

Abbreviations: Δ90p–10p, decrease from 90th to 10th centile; CI, confidence interval; FCPI, food crop productivity index; HR, hazard ratio.

Table S8. Sensitivity analysis 3: Association of migrants' first out-migration, undertaken for yield-sensitive reasons, with FCPI in the single preceding harvest and with cumulative FCPI over the preceding three harvests by sex, wealth index, and relevance of occupation to agriculture among those who were *born from 1 September 1993 onwards* (n = 89,273 people), Nouna Health and Demographic Surveillance System, Burkina Faso, 1993-2016

Characteristics			HR of Δ90p–10p in preceding FCPI	95% CI	HR of Δ90p–10p in cumulative FCPI	95% CI
Sex	Relevance of occupation to agriculture	Wealth level				
Men	Farmers	Low	2.05	1.53, 2.75	2.51	1.62, 3.88
		High	1.65	1.16, 2.35	2.70	1.60, 4.55
		Unknown	1.88	1.26, 2.80	3.89	2.05, 7.38
	Wider agricultural/food sector	Low	2.24	0.81, 6.19	3.64	0.48, 27.62
		High	1.80	0.64, 5.05	3.91	0.51, 29.98
		Unknown	2.05	0.72, 5.82	5.63	0.72, 44.09
	Non-agricultural occupation	Low	2.80	1.05, 7.49	4.47	0.98, 20.20
		High	2.26	0.83, 6.12	4.80	1.04, 22.19
		Unknown	2.57	0.92, 7.15	6.92	1.39, 34.45
	Unoccupied	Low	1.16	0.83, 1.62	0.72	0.41, 1.27
		High	0.93	0.66, 1.32	0.77	0.43, 1.38
		Unknown	1.06	0.70, 1.61	1.11	0.54, 2.28
	Unknown	Low	0.62	0.37, 1.04	0.13	0.05, 0.32
		High	0.50	0.30, 0.84	0.14	0.06, 0.34
		Unknown	0.57	0.33, 0.98	0.20	0.08, 0.53
Women	Farmers	Low	4.21	2.94, 6.01	7.72	4.38, 13.62
		High	3.38	2.27, 5.05	8.30	4.40, 15.65
		Unknown	3.85	2.53, 5.87	11.96	5.98, 23.91
	Wider agricultural/food sector	Low	4.58	1.62, 12.94	11.19	1.44, 86.86
		High	3.69	1.29, 10.53	12.03	1.56, 94.19
		Unknown	4.20	1.47, 12.03	17.32	2.20, 136.53
	Non-agricultural occupation	Low	5.75	2.23, 14.84	13.75	3.13, 60.45
		High	4.62	1.77, 12.08	14.78	3.32, 65.69
		Unknown	5.26	1.98, 14.01	21.28	4.52, 100.22
	Unoccupied	Low	2.38	1.89, 2.99	2.22	1.55, 3.16
		High	1.91	1.51, 2.43	2.38	1.63, 3.48
		Unknown	2.18	1.61, 2.95	3.43	2.06, 5.70
	Unknown	Low	1.28	0.78, 2.11	0.40	0.17, 0.94
		High	1.03	0.63, 1.69	0.43	0.18, 0.99
		Unknown	1.17	0.71, 1.93	0.61	0.25, 1.48

Abbreviations: Δ90p–10p, decrease from 90th to 10th centile; CI, confidence interval; FCPI, food crop productivity index; HR, hazard ratio.