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Drought and aridity influence internal migration worldwide

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While the effects of climatic changes on migration have received widespread public and scientific attention, comparative evidence for their influence on internal migration worldwide remains scarce. Here we use census-based data from 72 countries (1960–2016) to analyse 107,840 migration flows between subnational regions. We find that increased drought and aridity have a significant impact on internal migration, particularly in the hyper-arid and arid areas of Southern Europe, South Asia, Africa and the Middle East and South America. Migration patterns are shaped by the wealth, agricultural dependency and urbanization of both origin and destination areas with migration responses being stronger in rural and predominantly agricultural areas. While overall climatic effects on migration are stronger in richer countries, we observe higher out-migration from poorer towards wealthier regions within countries. Furthermore, age and education groups respond differently to climatic stress, highlighting distinct mobility patterns of population subgroups across different geographic contexts.

Owing to rising temperatures and changing precipitation patterns, many parts of the world are experiencing protracted drought and aridification trends[1–3] with important implications for food and water security, agricultural productivity and human health. When other adaptation options fail, households may choose or be forced to migrate from an affected area[4,5]. While in the public discourse, climatic factors are often portrayed as a cause of major international migration flows, numerous empirical studies and meta-analyses have demonstrated a stronger impact on short-distance, internal migration within countries as opposed to cross-border migration[6–10]. Local economic, sociopolitical and demographic conditions are essential in shaping climate-related (im)mobility patterns and outcomes[11–14].

However, because of data limitations, limited comparative evidence exists on the impacts of climatic factors on internal migration worldwide and the moderating role of contextual influences. Most evidence on migration within countries to date relies on country-specific case studies[15–17] and, in the case of cross-national analyses, proxy measures of internal migration, such as cross-country urbanization trends or population density estimates[18–20]. The World Bank's recent Groundswell Report, for example, uses a scenario-based approach which approximates the number of internal migrants in the future. It predicts that under a pessimistic scenario, 216 million people globally may move within their countries' borders as a result of climate change by 2050 (ref. 21).

Here we examine the impact of drought and aridity on global internal migration flows using a census-based migration dataset. The migration data are derived from census microdata provided by the Integrated Public Use Microdata Series (IPUMS) International for the period 1960–2016 (ref. 22). Using data from 201 censuses and 72 countries, we created a unique longitudinal database at the subnational regional level (1,410 first-level administrative regions). Internal migration is estimated on the basis of information on the census takers' current and previous region of residence 1 or 5 years before the census date. This allows us to calculate 107,840 bilateral migration flows between each pair of regions in each country over time[23–25] (Extended Data Figs. 1–3).

To comprehensively model drought and aridity impacts, we use a range of composite indicators derived from different data sources[26,27].

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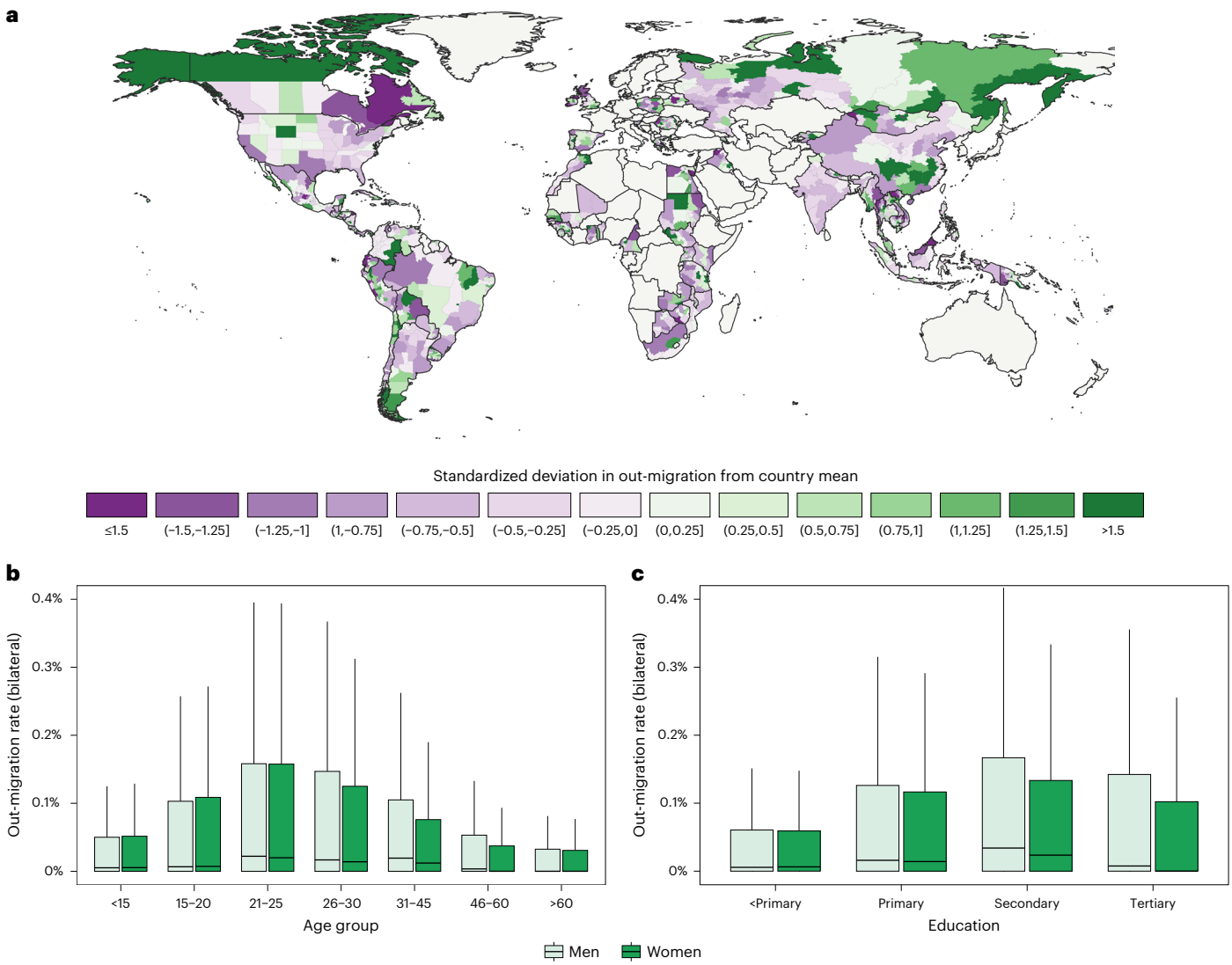

Fig. 1 | Patterns in internal migration worldwide. a, The standardized deviation of the regional out-migration rates from the country-specific mean for the last available census. The standardization ensures the comparability of the information across different country contexts and administrative settings. Regions with an above-average out-migration rate are shown in green and regions with a below-average out-migration rate are shown in purple. Countries coloured in grey are those not available in our database. **b**,**c**, Differences in regional out-migration rates by age and sex ($n = 107{,}840$) (**b**) and by education and sex ($n = 107{,}840$) (**c**). The boxplots show the median, interquartile ranges (IQR) and 1.5× IQR of the distributions across subnational regions.

We use the UNEP aridity index (AI), the Palmer drought severity index (PDSI) and the standardized precipitation evapotranspiration index measured over a 3 month (SPEI03) and 12 month time window (SPEI12). Whereas the first two measures are well-suited to capture long-term aridification processes, the SPEI can also reflect shorter-term extreme events. Gravity-type fixed-effects models are used to estimate migration impacts across regions over time[28]. Our work complements previous studies analysing internal migration using IPUMS census data[25,29–33] by providing large-scale longitudinal evidence on climate-induced internal migration across all world regions.

Internal migration worldwide

Patterns of internal migration differ substantially across countries. Considering areas with disproportionately high and low levels of annual out-migration relative to the country mean (Fig. 1a), we observe high- and low-mobility clusters which are shaped by country-specific topographic and socio-economic characteristics. For instance, in China, the central regions are characterized by higher out-migration, whereas lower levels of out-migration and higher immigration are observed in eastern coastal regions where major economic activities concentrate. In Russia, on the other hand, out-migration is higher in the eastern parts of the country and lower in the more urbanized western parts. In the United States, Canada and Brazil, out-migration is highest in the central parts of the countries and in Argentina in the South.

Most internal migration is over short distances and between neighbouring regions (Supplementary Table 4, model 6) with the bilateral out-migration rate being 0.15 percentage points [90% confidence interval (CI 90): 0.13,0.17] higher between adjacent as opposed to non-adjacent regions. Regions at the periphery of a country with an international land border have an on-average 0.04 percentage points [CI 90: 0.03,0.05] higher out-migration rate as opposed to regions without a border, suggesting a tendency for internal migrants to move towards the countries' centres.

Using census-based information on urban population shares in origin and destination regions, we find considerably higher migration to urban as opposed to rural areas, highlighting the importance of rural–urban moves for internal migration. Likewise higher out-migration is observed towards regions with a higher (gross domestic product) GDP

Table 1 | Baseline models estimating impacts of drought and aridity on out-migration rate

	Outcome: annual out-migration rate			
	(1)	(2)	(3)	(4)
AI (origin)	0.0930*** (0.0215)			
AI (destination)	−0.0723*** (0.0190)			
PDSI (origin)		0.0444*** (0.0171)		
PDSI (destination)		−0.0191 (0.0168)		
SPEI03 (origin)			0.0636*** (0.0211)	
SPEI03 (destination)			−0.0298 (0.0199)	
SPEI12 (origin)				0.0843*** (0.0193)
SPEI12 (destination)				−0.0655*** (0.0188)
Time window of 5 yr	−1.315*** (0.0418)	−1.307*** (0.0418)	−1.309*** (0.0422)	−1.312*** (0.0418)
World region×decade FE	Yes	Yes	Yes	Yes
Origin and destination FE	Yes	Yes	Yes	Yes
Observations	107,840	107,445	107,840	107,840
Pseudo R^2	0.26263	0.26255	0.26255	0.26259
BIC	457,105.20	454,364.30	457,105.40	457,105.30

PPML fixed effects, gravity models. Poisson regression coefficients with cluster robust standard errors in parentheses. Clustering of standard errors at the origin–destination pair level. *P* values were derived based on two-sided *t*-tests and no adjustments were made for multiple comparisons. Input variables: AI, PDSI and SPEI. All drought and aridity variables were rescaled so that larger values indicate more severe drought or greater dryness. The outcome variable is the annual internal out-migration rate. The variable time window of 5 years indicates that the census used a 5 year instead of a 1 year time window to capture migration. All models control for world region–decade and origin–destination pair fixed effects (FE). The pseudo R^2 and Bayesian information criterion (BIC) evaluate the performance and goodness of fit of the models.
$^{*}P \leq 0.1$, $^{**}P \leq 0.05$, $^{***}P \leq 0.01$.

per capita and a lower agricultural employment share. At the country level, regions in countries with higher income inequality exhibit higher out-migration rates on average. In additional analyses (Supplementary Table 5), we explore whether increases in internal migration are systematically related to increases in international migration[19,30] over time but do not find evidence for a strong relationship.

The IPUMS census data enable us to further discern the internal migration patterns of distinct population subgroups, considering factors such as age, sex and educational attainment. In line with the existing migration literature[34,35], we find distinct migration patterns by age (Fig. 1b) and education (Fig. 1c). Mobility is highest among individuals aged 21–30 years as well as among the more educated, in particular those with secondary education. Better labour market prospects and increased mobility among young adults are probable explanations for this finding. Across various age and education groups, the mobility is found to be slightly higher for men compared to women[36].

Drought and aridity drive migration between regions

To test for the impacts of drought and aridity, we combine the subnational bilateral migration data with information on climatic conditions in the regions of origin 10 years before the census date. The drought and aridity measures were rescaled to facilitate interpretation with positive values reflecting increased dryness (Table 1). All longitudinal models control for region of origin and destination pair fixed effects and world region-specific time trends to provide causal estimates of migration impacts over time.

We find significant and sizeable effects of drought and aridity on migration. A 1 s.d. increase in the AI (model 1) is estimated to lead to a 9.3% [CI 90: 5.8,12.8] change in the annual out-migration rate in the affected region. Similar effect sizes are found for the PDSI (model 2), SPEI03 (model 3) and SPEI12 (model 4), which are estimated to lead to an increase in migration of 4.4% [CI 90: 1.6,7.3], 6.4% [CI 90: 2.9,9.8] and 8.4% [CI 90: 5.2,11.6], respectively, pointing to a high consistency in the effects of dryness on human mobility.

In our models, we also tested for the impacts of changes in the climatic conditions in the prospective destinations considering all possible origin–destination pair combinations. We consistently find that increased dryness in a region leads to reduced migration towards this region. Compared to the impacts of climatic changes in the origin, the effects are weaker and significant only in two of the four models, suggesting that changes in the conditions in the origin regions may be more relevant in influencing migration decisions.

Using distributed lag models[37], we uncover differential impacts over time, suggesting relevant temporal dynamics in the relationships (Supplementary Table 6). For origin areas, we observe protracted and delayed effects on internal migration with effects being strongest for changes in drought and aridity occurring in the period 6–15 years before the census. For changes in the climatic conditions in destination areas, on the other hand, we see more immediate effects in the short run.

We furthermore find evidence for nonlinear migration impacts with increasing environmental stress levels in line with threshold and tipping point theories of migration[38–40] (Supplementary Table 8). The more severe the changes in aridity in an area, the more substantial the migration response observed. When faced with significant pressure, households may eventually reach a point where relocation becomes the only viable option, as coping and adapting in situ may no longer be feasible[41–43].

In additional analyses, we performed several robustness and falsification tests to check for the sensitivity of our results (Supplementary Tables 17–38). All findings remain fully robust to variations in the model specification (including accounting for spatial dependencies, multilateral resistance[28,44] and international migration), weighting and standardization approaches, time windows considered and the conceptualization of the migration and climate measures (see also section on 'Robustness checks' in Methods). We also vary the estimation of the standard errors (Supplementary Tables 39 and 40), accounting for two-way clustering, which yields consistently significant findings in most models.

Effects differ by world region and ecological zones

Using a series of interaction models, we test for differences in migration impacts for different world regions (Fig. 2a), revealing significant

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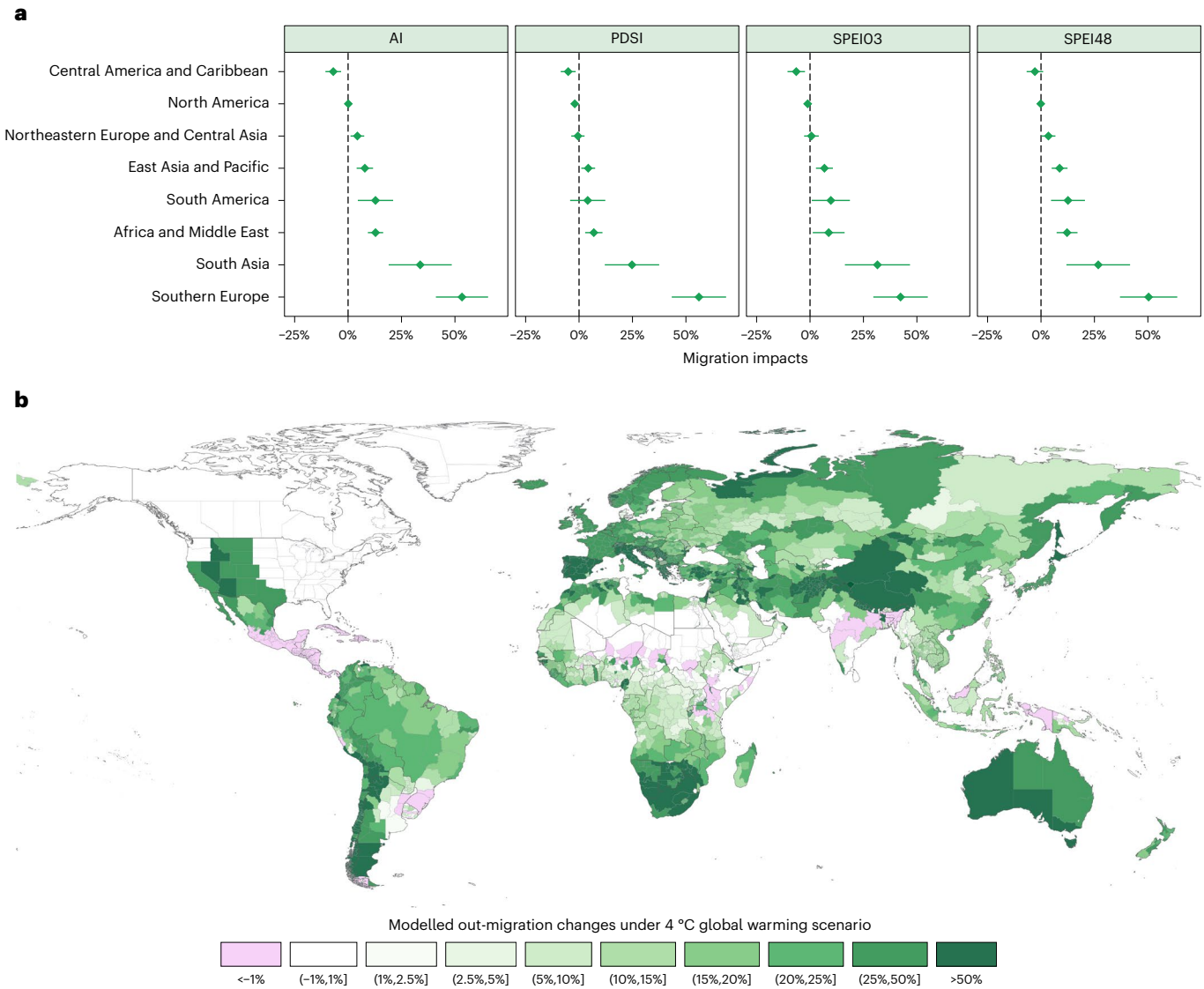

Fig. 2 | Differences in migration impacts of drought and aridity across world regions. a, Differences in migration impacts by the geographical location of the subnational regions distinguishing effects across world regions (n = 107,840). The x axis shows the marginal effects and CI 90 (error bars) of a 1 s.d. increase in aridity levels on out-migration rates. The underlying full models are displayed in Supplementary Table 9. **b**, Modelled migration changes under a 4 °C global warming scenario based on projected changes in dryness in the regions until the end of the century[45]. For the prediction, extended models (Supplementary Table 10) were used to estimate differential migration responses by world region and baseline aridity level (reference period 2001–2020) distinguishing between hyper-arid/arid, semi-arid, subhumid and humid regions. The derived predicted marginal effects were combined with the projected changes in the AI in the regions to explore potential impacts on internal migration.

geographical heterogeneity in migration responses. A change in the AI by 1 s.d. is estimated to have increased out-migration towards other regions by 53.3% [CI 90: 41.0,65.6] in Southern Europe, by 33.8% [CI 90: 18.9,48.6] in South Asia, by 12.8% [CI 90: 9.2,16.4] in Africa and the Middle East and by 12.8% [CI 90: 4.5,21.1] in South America.

Positive but weaker effects are observed for countries in East Asia and the Pacific and Northeastern Europe and Central Asia, where changes in the AI are estimated to have led to a 7.9% [CI 90: 4.0,11.7] and 4.4% [CI 90: 1.1,7.6] increase in internal migration, respectively. No consistent significant impacts are observed in North America. For Central America and the Caribbean, negative effects are estimated for all indicators, suggesting that wetter periods potentially due to more extreme storms were related to higher out-migration from affected areas. Please note that these results depend on the subsets of countries and census waves available in our sample and should not be interpreted as a fully representative picture of the situation in the regions today.

In further analyses (Supplementary Table 10), we find heterogeneity in the magnitude of the effects across baseline levels of dryness in the origin region (reference period 2001–2020). The strongest migration responses are found in hyper-arid and arid regions, which are characterized by high levels of dryness, high temperatures and limited rainfall. Future increases in aridity may exacerbate desertification and land degradation in these areas, leading to lower crop productivity and placing additional pressure on the livelihoods of already vulnerable local populations[41,43].

We use the results of these extended models for explorative predictions combining the estimated differential migration responses by world region and baseline aridity levels with projections of future changes in the AI at 4 °C global warming by the end of the century[45]. The results (Fig. 2b) suggest large regional differences in the relevance of drought and aridity for human mobility with migration patterns in drylands expected to be particularly affected.

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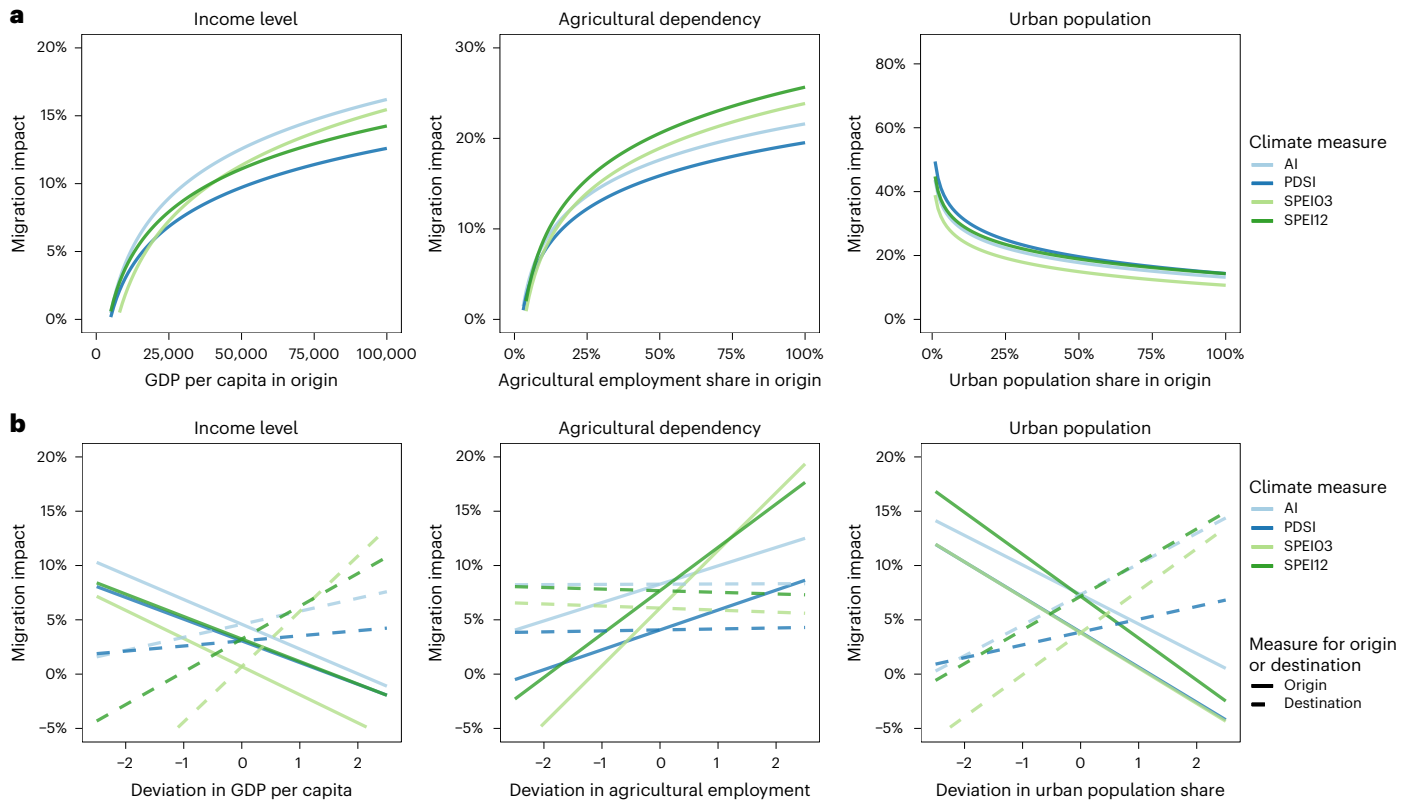

Fig. 3 | The role of regional background characteristics in shaping migration responses to drought and aridity. a, The role of regional characteristics in influencing migration responses to drought and aridity. The *y* axis shows the marginal effects of a 1 s.d. change in the climate indicators on the out-migration rate. The figures rely on model estimates considering interactions between the climate indicators and the GDP per capita (measured in purchasing power parity; $n = 77{,}226$), the agricultural employment share ($n = 68{,}134$) and the urban population share ($n = 50{,}340$) in the regions of origin (Supplementary Tables 11–13). Increasing (decreasing) functions indicate increasing (decreasing) migration impacts with higher levels of the interaction variable. All models estimating interactions with agricultural employment and urban population share also control for interactions with GDP per capita to rule out confounding wealth effects. **b**, The results of interaction models which interact the climate indicators with regional deviations in GDP per capita ($n = 77{,}202$), agricultural employment ($n = 97{,}813$) and urban population share ($n = 70{,}829$) from the country-specific mean (Supplementary Tables 14–16). Considering standardized deviations as opposed to the overall level values of the variables allows testing for differences in migration responses by within-country differences in wealth, agricultural dependency and urban population. Solid lines show the results where interaction variables refer to deviations in origin areas. Dashed lines show the results for deviations in prospective destination areas.

Migration impacts are moderated by contextual factors

The substantial regional differences suggest that local socio-economic and political conditions play an important role in moderating climatic impacts on migration. By examining interactions between the four aridity and drought indicators and the GDP per capita, agricultural employment and urban population share in origin and destination regions (Fig. 3), we find significant variations in migration responses based on the socio-economic characteristics of these regions and disparities between them.

Considering first differences across all countries and regions in the sample (Fig. 3a), we find stronger migration responses in overall wealthier areas with a higher agricultural employment and lower urban population share. The findings suggest that migration constraints may hamper mobility in poorer countries. These constraints may be exacerbated in the face of environmental stress, potentially leading to involuntary immobility[46–51].

The strong effects in rural and agriculturally dependent areas suggest that these areas are particularly vulnerable to drought and aridity because of their impacts on agricultural production and livelihoods. Especially in low-income countries, agriculture represents an important economic sector and provider of local food supplies[52,53]. Differential necessities to migrate in response to environmental stress can hence moderate the effects[10]. These results also hold when using country- instead of region-level background characteristics (Supplementary Fig. 10).

When considering differences within countries (Fig. 3b), we find migration flows from less to more urbanized regions to be more impacted by increased drought and aridity. Additionally, our findings indicate that regions with a higher share of agricultural employment compared to the country average experience more out-migration (solid lines). However, no clear patterns are visible in terms of destination areas (dashed lines). The relative share of agricultural employment in destination areas does not appear to be a decisive factor in determining the migration destination choice of individuals affected by drought and aridity.

Although migration responses were overall stronger in richer countries, indicating that a certain level of wealth is necessary to enable mobility, the within-country analysis reveals a more nuanced pattern. Here we find that regions with comparatively lower income in a country experience a higher rate of out-migration. A 1 s.d. increase in within-country GDP, on the other hand, is associated with a 2.3% [CI 90, −3.5; −1.1] reduction in the migration impact of a 1 s.d. increase in the AI. This suggests that while we see overall higher levels of mobility in wealthier countries, it is often the poorer regions within those countries where populations respond more strongly when exposed to

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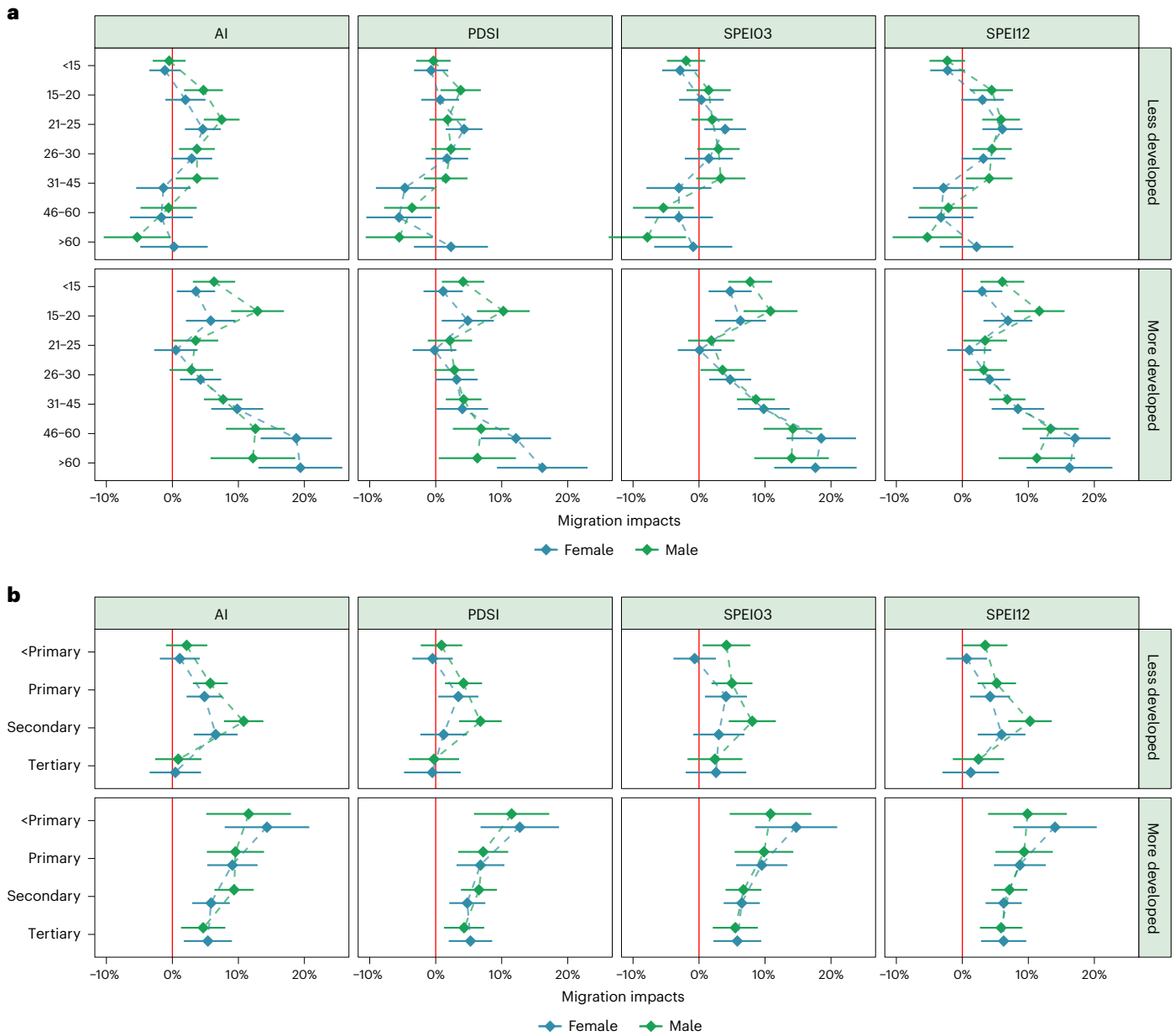

Fig. 4 | Migration impacts by different population subgroups in more and less developed countries. a, Estimated differences in migration responses for men (green dots and whiskers) and women (blue dots and whiskers) in different age groups (*y* axis) for populations in more ($n = 36{,}348$) and less developed countries ($n = 69{,}113$). **b**, Differences in migration responses for men and women by International Standard Classification of Education (ISCED) levels (*y* axis) in more ($n = 35{,}973$) and less developed countries ($n = 67{,}215$). The *x* axis shows the marginal effects and CI 90 (error bars) of a 1 s.d. increase in drought and aridity measured with the four climate indicators. The classification into more and less developed countries is based on data from the UN World Population Prospects[69].

increased drought and aridity. Furthermore, we find migration towards relatively wealthier destination areas to increase more strongly if an origin region is affected.

Migration responses differ for different population groups

As a final step, we examine which population groups are most likely to migrate in response to increased drought and aridity. For this, we categorize the census participants into different subgroups and estimate group-specific migration flows (Fig. 4). We classify migration flows by sex, age groups (0–14, 15–20, 21–25, 26–30, 31–45, 46–60 and >60 years) and education levels (less than primary, primary, secondary or tertiary). In the analysis, we further distinguish between less developed (top of Fig. 4a,b) and more developed (bottom of Fig. 4a,b) countries, two groups that reveal significant differences in age and education-specific migration responses.

Focusing on differences by age and sex (Fig. 4a), we consistently find more pronounced migration responses in more developed compared to less developed contexts. While we find a hump-shaped distribution in less developed countries, with the middle age groups showing the strongest migration response to drought and aridity, it is the older age groups in more developed countries who are most likely to change their mobility. Whereas the pattern in lower-income contexts suggests a higher out-migration of the working-age population, we see an opposite effect in higher-income contexts, where older population groups are more mobile. This could be due to a generally higher mobility among older groups or retirement migration, where individuals move to areas with a more pleasant climate[54]. Across the

age groups, we do not find consistent evidence for gender differences in migration.

Also, for education (Fig. 4b), differences in patterns are visible between less and more developed countries in the sample. Our results indicate a positive education gradient in less developed countries where the mobility of population groups with secondary education is particularly affected by drought and aridity. This difference may be due to migration constraints among the lower-educated or reflect differential migration prospects for lower- and higher-educated individuals[35,55]. We see weaker or no effects for those with tertiary education suggesting that these groups may be less affected by the environmental stressors considered. For more developed countries, while overall migration responses are more uniform across education groups, out-migration rates appear to be higher among groups with a primary level of education, although the very low number of individuals in this group results in large error bars.

Discussion and conclusion

Analysing census-based migration data, our study shows significant and sizeable impacts of drought and aridity on internal migration worldwide. The effects are particularly pronounced in agriculturally dependent, rural regions, especially in drylands in Southern Europe, South Asia, Africa and the Middle East and South America. Economic factors are important in moderating the relationships. Across countries, migration is found to be higher in wealthier areas where constraints to mobility may be lower. Within countries, migration responses to drought and aridity are typically stronger in regions that are relatively poorer compared to their country's average. While mobility is higher among the better-educated working-age population in developing countries, we observe stronger impacts on the mobility for older age groups across all education strata in wealthier countries. These findings highlight the importance of differing mobility patterns among distinct population groups in diverse contexts.

Our study adds to the growing body of literature emphasizing the important role of climatic factors in shaping (im)mobility outcomes[5,7–10]. The relationships are not simple but are characterized by nonlinearities[38,40,56] and a high context dependency[14,57–59] leading to differences in migration patterns[60]. Aside from spatial heterogeneity, our results reveal large differences in migration responses for different subgroups of the population, consistent with findings from the extensive micro-level literature on the subject[16,61,62]. Both demographic and socio-economic characteristics can influence a person's ability and willingness to migrate, as well as the exposure and vulnerability to hazards[63,64]. Taking a holistic perspective which accounts for both subnational spatial and social differences is key to comprehensively understanding the multifaceted links between climatic factors and human (im)mobility.

Despite improvements in migration data and modelling, the limited availability and comparability of internal migration data pose considerable challenges to reflect mobility within countries accurately[65,66]. Our longitudinal migration dataset extracted from census microdata can address some of these issues[22]. Through extensive data harmonization and cleaning efforts, this dataset offers comparable information on internal migration across 72 countries, facilitating a systematic examination of geographic disparities in migration patterns. While the data provide a comprehensive picture of global internal migration, they have limitations. In particular, certain forms of climate-related mobility, including short-distance, temporal migration and international migration, are omitted from the analysis (see section on 'Limitations' in Methods).

As climate change continues to unfold, projections suggest an increase in the frequency and severity of drought and arid conditions in various regions across the globe[45,67]. Populations living in areas experiencing chronic water scarcity and agricultural challenges will probably face heightened pressures to seek alternative livelihoods and better living conditions elsewhere[68]. Those who need to migrate but do not have the resources to do so would need support to facilitate migration and better means to protect themselves and their communities. Likewise, given the vital role of the rural-to-urban migration corridor, it is important to provide adequate facilities, infrastructure and social and health services in destination regions for a growing urban population. Policies that support livelihood diversification and social safety nets can assist in reducing forced migration and displacement, promote resilience in affected communities and protect mobile and immobile populations.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-024-02165-1.

References

1. Burrell, A. L., Evans, J. P. & de Kauwe, M. G. Anthropogenic climate change has driven over 5 million km^2 of drylands towards desertification. *Nat. Commun.* **11**, 3853 (2020).
2. *World Atlas of Desertification—Rethinking Land Degradation and Sustainable Land Management* (European Commission Publications Office, 2018).
3. IPCC *Climate Change 2022: Impacts, Adaptation and Vulnerability* (eds Pörtner, H. et al.) (Cambridge Univ. Press, 2022).
4. McLeman, R. & Smit, B. Migration as an adaptation to climate change. *Clim. Change* **76**, 31–53 (2006).
5. Hunter, L. M., Luna, J. K. & Norton, R. M. Environmental dimensions of migration. *Annu. Rev. Socio.* **41**, 377–397 (2015).
6. Borderon, M. et al. Migration influenced by environmental change in Africa: a systematic review of empirical evidence. *Demogr. Res* **41**, 491–544 (2019).
7. Šedová, B., Čizmaziová, L. & Cook, A. *A Meta-Analysis of Climate Migration Literature* (CEPA, 2021).
8. Beine, M. & Jeusette, L. *A Meta-Analysis of the Literature on Climate Change and Migration* (IZA, 2019).
9. Cattaneo, C. et al. Human migration in the era of climate change. *Rev. Environ. Econ. Policy* **13**, 189–206 (2019).
10. Hoffmann, R., Dimitrova, A., Muttarak, R., Crespo Cuaresma, J. & Peisker, J. A meta-analysis of country level studies on environmental change and migration. *Nat. Clim. Change* **10**, 904–912 (2020).
11. Cai, R., Feng, S., Oppenheimer, M. & Pytlikova, M. Climate variability and international migration: the importance of the agricultural linkage. *J. Environ. Econ. Manag.* **79**, 135–151 (2016).
12. Beine, M. & Parsons, C. Climatic factors as determinants of international migration. *Scand. J. Econ.* **117**, 723–767 (2015).
13. Cattaneo, C. & Peri, G. The migration response to increasing temperatures. *J. Dev. Econ.* **122**, 127–146 (2016).
14. Black, R. et al. The effect of environmental change on human migration. *Glob. Environ. Change* **21**, 3–11 (2011).
15. Bohra-Mishra, P., Oppenheimer, M., Cai, R., Feng, S. & Licker, R. Climate variability and migration in the Philippines. *Popul. Environ.* **38**, 286–308 (2017).
16. Gray, C. & Mueller, V. Drought and population mobility in rural Ethiopia. *World Dev.* **40**, 134–145 (2012).
17. Mueller, V., Gray, C. & Kosec, K. Heat stress increases long-term human migration in rural Pakistan. *Nat. Clim. Change* **4**, 182–185 (2014).
18. Henderson, J. V., Storeygard, A. & Deichmann, U. Has climate change driven urbanization in Africa? *J. Dev. Econ.* **124**, 60–82 (2017).

19. Marchiori, L., Maystadt, J. F. & Schumacher, I. Is environmentally-induced income variability a driver of migration? *Migr. Dev.* **6**, 33–59 (2017).
20. Niva, V. et al. Global migration is driven by the complex interplay between environmental and social factors. *Environ. Res. Lett.* **16**, 114019 (2021).
21. Clement, V. et al. *Groundswell Part 2: Acting on Internal Climate Migration* (World Bank, 2021).
22. *Integrated Public Use Microdata Series International Version 7.2* (IPUMS, 2020); https://international.ipums.org/international-action/variables/group
23. Abel, G. J., Muttarak, R. & Stephany, F. *Climatic Shocks and Internal Migration: Evidence from 442 Million Personal Records in 64 Countries* (World Bank Group, 2022).
24. Abel, G. J. & Sander, N. Quantifying global international migration flows. *Science* **343**, 1520–1522 (2014).
25. Garcia, A. J., Pindolia, D. K., Lopiano, K. K. & Tatem, A. J. Modeling internal migration flows in sub-Saharan Africa using census microdata. *Migr. Stud.* **3**, 89–110 (2015).
26. Beguería, S., Vicente-Serrano, S. M. & Angulo-Martínez, M. A multiscalar global drought dataset: the SPEIbase: a new gridded product for the analysis of drought variability and impacts. *Bull. Am. Meteorol. Soc.* **91**, 1351–1356 (2010).
27. Harris, I., Osborn, T. J., Jones, P. & Lister, D. Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Sci. Data* **7**, 109 (2020).
28. Beine, M., Bertoli, S. & Fernández-Huertas Moraga, J. A practitioners' guide to gravity models of international migration. *World Econ.* **39**, 496–512 (2016).
29. Bell, M. et al. Internal migration and development: comparing migration intensities around the world. *Popul. Dev. Rev.* **41**, 33–58 (2015).
30. Cirillo, M., Cattaneo, A., Miller, M. & Sadiddin, A. Establishing the link between internal and international migration: evidence from Sub-Saharan Africa. *World Dev.* **157**, 105943 (2022).
31. Lerch, M. International migration and city growth in the Global South: an analysis of IPUMS data for seven countries, 1992–2013. *Popul. Dev. Rev.* **46**, 557–582 (2020).
32. Thiede, B., Gray, C. & Mueller, V. Climate variability and inter-provincial migration in South America, 1970–2011. *Glob. Environ. Change* **41**, 228–240 (2016).
33. Thiede, B. C., Robinson, A. & Gray, C. Climatic variability and internal migration in Asia: evidence from big microdata. *Popul. Dev. Rev.* **50**, 513–540 (2024).
34. Manning, P. & Trimmer, T. *Migration in World History* (Routledge, 2020).
35. Levy, M. B. & Wadycki, W. J. Education and the decision to migrate: an econometric analysis of migration in Venezuela. *Econometrica* **42**, 377–388 (1974).
36. Abel, G. J. & Cohen, J. E. Bilateral international migration flow estimates updated and refined by sex. *Sci. Data* **9**, 173 (2022).
37. Gasparrini, A., Armstrong, B. & Kenward, M. G. Distributed lag non-linear models. *Stat. Med.* **29**, 2224–2234 (2010).
38. McLeman, R. Thresholds in climate migration. *Popul. Environ.* **39**, 319–338 (2018).
39. Meze-Hausken, E. On the (im-)possibilities of defining human climate thresholds. *Clim. Change* **89**, 299–324 (2008).
40. Nawrotzki, R. J., DeWaard, J., Bakhtsiyarava, M. & Ha, J. T. Climate shocks and rural–urban migration in Mexico: exploring nonlinearities and thresholds. *Clim. Change* **140**, 243–258 (2017).
41. Dow, K., Berkhout, F. & Preston, B. L. Limits to adaptation to climate change: a risk approach. *Curr. Opin. Environ. Sustain.* **5**, 384–391 (2013).
42. Hoffmann, R., Wiederkehr, C., Dimitrova, A. & Hermans, K. Agricultural livelihoods, adaptation, and environmental migration in sub-Saharan drylands: a meta-analytical review. *Environ. Res. Lett.* **17**, 083003 (2022).
43. Warner, K. et al. *Evidence from the Frontlines of Climate Change: Loss and Damage to Communities Despite Coping and Adaptation* (The Loss and Damage Collaboration, 2012).
44. Bertoli, S. & Fernández-Huertas Moraga, J. Multilateral resistance to migration. *J. Dev. Econ.* **102**, 79–100 (2013).
45. Wang, X., Jiang, D. & Lang, X. Future changes in Aridity Index at two and four degrees of global warming above preindustrial levels. *Int. J. Climatol.* **41**, 278–294 (2021).
46. Zickgraf, C. in *Routledge Handbook of Environmental Displacement and Migration* (eds McLeman, R. & Gemenne, F.) 71–84 (Routledge, 2018).
47. Mallick, B. & Schanze, J. Trapped or voluntary? Non-migration despite climate risks. *Sustainability* **12**, 4718 (2020).
48. Nawrotzki, R. J. & DeWaard, J. Putting trapped populations into place: climate change and inter-district migration flows in Zambia. *Reg. Environ. Change* **18**, 533–546 (2018).
49. Cundill, G. et al. Toward a climate mobilities research agenda: intersectionality, immobility, and policy responses. *Glob. Environ. Change* **69**, 102315 (2021).
50. Benveniste, H., Oppenheimer, M. & Fleurbaey, M. Climate change increases resource-constrained international immobility. *Nat. Clim. Change* **12**, 634–641 (2022).
51. Farbotko, C., Dun, O., Thornton, F., McNamara, K. E. & McMichael, C. Relocation planning must address voluntary immobility. *Nat. Clim. Change* **10**, 702–704 (2020).
52. Mendelsohn, R. The impact of climate change on agriculture in developing countries. *J. Nat. Resour. Policy Res.* **1**, 5–19 (2008).
53. Schlenker, W. & Lobell, D. B. Robust negative impacts of climate change on African agriculture. *Environ. Res. Lett.* **5**, 014010 (2010).
54. Savaş, E. B., Spaan, J., Henkens, K., Kalmijn, M. & Dalen van, H. P. Migrating to a new country in late life: a review of the literature on international retirement migration. *Demogr. Res.* **48**, 233–270 (2023).
55. *Global Education Monitoring Report* Ch. 3 (UNESCO, 2019).
56. Pasini, A. & Amendola, S. Linear and nonlinear influences of climatic changes on migration flows: a case study for the 'Mediterranean bridge'. *Environ. Res. Commun.* **1**, 011005 (2019).
57. Upadhyay, H. et al. Conceptualizing and contextualizing research and policy for links between climate change and migration. *Int. J. Clim. Change Strateg. Manag.* **7**, 394–417 (2015).
58. McLeman, R. A. & Hunter, L. M. Migration in the context of vulnerability and adaptation to climate change: insights from analogues. *WIREs Clim. Change* **1**, 450–461 (2010).
59. Hoffmann, R. Contextualizing climate change impacts on human mobility in African drylands. *Earths Future* **10**, e2021EF002591 (2022).
60. Muttarak, R. Demographic perspectives in research on global environmental change. *Popul. Stud.* **75**, 77–104 (2021).
61. Hermans, K. & Garbe, L. Droughts, livelihoods, and human migration in northern Ethiopia. *Reg. Environ. Change* **19**, 1101–1111 (2019).
62. Blocher, J. M., Hoffmann, R. & Weisz, H. The effects of environmental and non-environmental shocks on livelihoods and migration in Tanzania. *Popul. Environ.* **46**, 7 (2024).
63. de Haas, H. A theory of migration: the aspirations–capabilities framework. *Comp. Migr. Stud.* **9**, 8 (2021).
64. de Sherbinin, A. et al. Migration theory in climate mobility research. *Front. Clim.* **4**, 78 (2022).
65. Vinke, K. & Hoffmann, R. Data for a difficult subject: climate change and human migration. *Migr. Policy Pract. J.* **X**, 16–22 (2020).

66. Hoffmann, R., Šedová, B. & Vinke, K. Improving the evidence base on climate migration: methodological insights from two meta-analyses. *Glob. Environ. Change* **71**, 102367 (2021).
67. Huang, J., Yu, H., Guan, X., Wang, G. & Guo, R. Accelerated dryland expansion under climate change. *Nat. Clim. Change* **6**, 166–171 (2016).
68. Rigaud, K. K. et al. *Groundswell—Preparing for Internal Climate Migration* (World Bank, 2018).
69. 2022 Revision of World Population Prospects. *UN* https://population.un.org/wpp/ (2022).

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Methods

Data

Information on migration and socio-economic conditions were derived from harmonized census microdata samples from the IPUMS international database[22]. Each set of census microdata contains a small random sample (0.4–10%) of unidentified private households and associated persons based on a full census conducted by the national statistical agency in each country. Countries used in the study were selected on the basis of the availability of information on migration. In addition, we retrieved additional variables from the censuses on census takers' age, sex, education and occupational profile.

The data were drawn from 201 different censuses covering the period 1960–2016 (Extended Data Fig. 2). While for some countries, data are available for up to eight censuses (for example, Mexico from 1960 to 2015), most countries have fewer observations over time, resulting in an unbalanced time series. In our estimation, we control for this by including decadal fixed effects in our estimation to rule out any confounding influences of the timing of the censuses.

The census data were combined with gridded time-series data from the Climatic Research Unit (CRU) of the University of East Anglia (CRU TS, v.4.07). The CRU TS dataset uses a 0.5° latitude by 0.5° longitude grid covering all land areas of the world, excluding Antarctica[27]. The data provide monthly information from 1901 until 2022 on various climate indicators, including temperature, precipitation and potential evapotranspiration (PET). The measures are based on interpolations (angular-distance weighting) of climate anomalies from an extensive network of weather stations worldwide.

In addition, information on drought conditions were retrieved from the SPEI database (SPEIbase v.2.8:1), which spans the period between January 1901 to December 2020[26]. The SPEI calculations use the CRU monthly precipitation and PET data using the FAO-56 Penman–Monteith estimation for PET. Like the CRU data, the SPEI database operates at a spatial resolution of 0.5° and a monthly time resolution. It provides information on a range of SPEI timescales spanning 1–48 months.

Finally, data were retrieved from the gridded global datasets for GDP and human development index spanning the period 1990–2015 (ref. 70). The database provides details about economic prosperity and human development with a resolution of 5 arcmin, using various subnational sources. Consistency across time and space is ensured by calibrating the gridded estimates with reported national values, thereby maintaining representativeness at the national level.

Information from the gridded data products was extracted to the subnational regional level using harmonized first-level administrative regions shapefiles provided by IPUMS. The subnational units were harmonized so that their boundaries remain geographically stable over time. To account for changes in administrative boundaries, affected geographic units were merged to form larger and temporally stable units comprising two or more states, provinces and similar entities. While most boundary changes involve the division of larger units into smaller ones, there are also instances where state or province boundaries have shifted. All variables in IPUMS align with the corresponding harmonized first-level geography codes, including variables referring to migration, allowing us to estimate migration flows between harmonized regions of origin and destination.

Estimating global internal migration flows

The migration measure used in our analysis is based on the census question about the census taker's previous subnational region of residence 1 or 5 years before the census and their current place of residence. For both questions, information on the first-level administrative region is provided in the data. This enables us to calculate from the microdata the total flows of migrants between subnational regions of origin and destination in each country:

$$F_{ijt} = \sum_{p=1}^{P} A_{pijt} \times \omega_p \quad (1)$$

where the total flow of internal migrants F_{ijt} between regions i and j in the time period t before a census is the sum of all census takers A_{pijt} living in region j who lived in region i previously. Before summing up the observations, we use sampling weights ω_p provided by IPUMS international to derive representative information on the number of migrants. The weights account for how many observations in the total population each individual p in the census sample represents. We follow the same approach to derive information on migration flows for population subgroups by sex, age and education.

The harmonized first-level administrative region pairs represent the units of analysis in our study. In total, we derived information on 107,840 bilateral migration flows covering a sample of 1,410 subnational regions. Our data contain information on 72 countries (Extended Data Fig. 1): 2 countries from North America, 12 from Central America and the Caribbean, 11 from South America, 3 from Southern Europe, 9 from Northeastern Europe and Central Asia, 22 from Africa and the Middle East, 2 from South Asia and 11 from East Asia and the Pacific.

The question on the previous place of residence is asked differently in the censuses considering a different temporal resolution, either (1) 1 year ago, (2) 5 years ago or (3) length of stay in the current location. For the last, where the continuous temporal period of stay is available, we reduced the information to a binary measure indicating whether or not the respondent has migrated in the past 1 year as a benchmark value. In total, 47.4% of all internal migration flows captured in our analysis refer to migration within the past year and 52.6% to migration within the past 5 years.

On the basis of the information on the current and previous regions of residence, we calculate bilateral migration flows F_{ijt} between region i and region j and vice versa in the past 1 or 5 years (Extended Data Fig. 3). From the bilateral migration flows F_{ijt}, we derive an estimate of the annual migration rate M_{ijt} by dividing the flow measure by the total population P_{it} of region i at time t and by (2) the time interval I_{it} of 1 or 5 years considered for the migration measurement in the respective census:

$$M_{ijt} = \frac{F_{ijt}}{P_{it} \times I_{it}} \quad (2)$$

The constructed annual internal migration rate is typically lower for censuses that capture migration over a 5 year instead of a 1 year period. This is because circular migration patterns within that time frame are not recorded. To account for this, we control for the migration measurement time window used in each census to correct our estimates for changes in the time window that may have occurred in the same country over time. Since the time window usually does not change between censuses, the differences should not largely affect our estimation which is based on changes in migration patterns within regions over time.

In further analyses (Supplementary Table 7), we also explicitly tested for differences in drought and aridity impacts on migration conditional on the time window used in the respective census. As expected, we find more pronounced impacts of drought and aridity if censuses used a shorter time window of 1 year compared to a broader time window of 5 years. Since the latter measure may miss some return migration, some of the people migrating because of drought and aridity might have returned to their origin location at the time of the census. This finding also speaks for the potential relevance of circular mobility in the context of changing environmental conditions.

The harmonized census data allow for a comprehensive analysis of the relationships between climatic changes and inter-regional migration across different geographical contexts. Although IPUMS also provides information on international migration, it does not specify the specific subnational origin regions of cross-border migrants. As this makes it more difficult to determine whether an international migrant was exposed to an environmental impact or not, we focus our analysis entirely on internal mobility.

Drought and aridity indicators

On the basis of the derived climate data, we prepare four key composite indicators to measure the level of aridity and drought in the subnational regions. All aridity indicators are similarly scaled, with smaller values indicating dryer conditions and larger values indicating more humid conditions. For our analysis, the indicators were rescaled so that larger values indicate greater dryness.

(1) The AI measures dryness as the ratio between the yearly precipitation and PET in an area. Lower values of the AI represent higher dryness, with areas with an AI <0.05 being classified as hyper-arid, <0.20 as arid, <0.5 as semi-arid, <0.65 as dry sub-humid and >0.65 as humid. The AI is particularly suitable to reflect longer-term changes in aridity and persistent drought conditions.

(2) As a second measure of dryness, we consider the PDSI, which is based on temperature and precipitation data to assess relative dryness. This standardized index typically ranges from −10 (dry) to +10 (wet), although more extreme values are possible. Like the AI, the PDSI is used to quantify long-term drought and aridity by considering PET through temperature data and a water balance model. However, it has limitations in detecting droughts on timescales shorter than 12 months. It also lacks multi-timescale features found in other indices like SPEI, making it difficult to correlate it with specific water resources such as runoff, snowpack and reservoir storage. In our analysis, we use the self-calibrating version of the PDSI, which helps to address comparability issues across different regions.

(3) For the final two climate indicators, our analyses use the SPEI. The SPEI measures the water balance in a region on the basis of both the local precipitation and PET. The SPEI measure is particularly useful for detecting drought events over a short or medium time period. The SPEI is centred around the value of zero, with positive values indicating higher humidity and negative values dryer conditions. Areas with an SPEI below −1.5 are considered severely dry and areas with a value below −2.0 extremely dry. Here we use two SPEI-based variables, one which considers the water balance accumulated over a rolling 3 month period and one over a longer 12 month period, allowing us to capture water imbalances and drought conditions over shorter periods to complement the other climate indicators.

Standardization and rescaling of climate indicators

For our analysis, the climate indicators were aggregated to reflect the average level of drought and aridity in the period 10 years before the census date. This time window represents a common gap between censuses in a country and covers a sufficiently broad period of time to capture the adverse impacts of drought and aridity on livelihoods and well-being, which may only unfold over longer time horizons. To allow for comparisons across the different measures, all indicators were standardized. For this, we use the information on the distributions of measures across different geographical scales.

For the main models, all indicators were standardized at the subnational regional level. For this, the long-run regional mean of the drought and aridity variables $\bar{C}_i$ in a region i was subtracted from the observed values C_{it} and divided by the long-run standard deviation $\sigma(C)_i$ of the variable. The resulting standardized anomaly measures $C_{\text{stan},it}$ show the standardized deviation in drought conditions and aridity in a region from the long-run normal conditions in a reference period:

$$C_{\text{stan},it} = \frac{C_{it} - \bar{C}_i}{\sigma_{C_i}} \tag{3}$$

Here we consider as reference the period from 1901 to 2021 for the calculation of the long-run mean and standard deviation. All results are robust to using shorter reference periods (1960–2021) and to using a rolling reference period window (50 years before each census date) to account for adaptation effects. For additional robustness tests, we used the unstandardized climate indicators and indicators using the country-wide distribution or the global distribution of the variables as the basis for the standardization (Supplementary Tables 34–36).

The original versions of the drought and aridity variables considered are scaled so that negative values indicate dryer conditions and positive values more humid conditions. To facilitate the interpretation of the results, we rescaled the variables so that positive values indicate greater dryness and negative values more humid conditions. Accordingly, positive model coefficients refer to a positive effect of drought and greater aridity on migration and negative coefficients to a negative effect, making the interpretation more intuitive for readers. The findings show the effect on migration of a 1 s.d. increase in dryness for the respective indicators.

Statistical modelling

The impacts of climatic changes and hazards on migration are estimated using a series of gravity-type fixed-effects panel models, which regress the bilateral out-migration rate between regions of origin i and destination j on the different aridity and drought indicators $C_{\text{stan},it}$ (refs. 12,28). Our models are estimated parsimoniously to avoid over-controlling issues[71]. All models control for the respective time interval (5 years versus 1 year) used for measuring migration flows between the region of origin and destination. The full model can be written as:

$$\ln(M_{ijt}) = \beta C_{\text{stan},it} + \gamma C_{\text{stan},jt} + \delta I_{it} + \alpha_{ij} + \theta_{rt} + \varepsilon_{ij,t} \tag{4}$$

where M_{ijt} is the annual out-migration rate from a region i to a region j at time t. $C_{\text{stan},it}$ refers to the vector of climate indicators in the origin region and $C_{\text{stan},jt}$ to indicators measuring the condition in the different destination areas[12]. I_{it} captures the migration time interval (1 year versus 5 years) considered in the census. Unobserved spatial heterogeneity is controlled for via the use of region of origin and destination pair fixed effects (α_{ij}). These account for relatively stable characteristics of region pairs over time, including cultural differences, political systems and climatic zones, which could otherwise confound the analysis.

To account for confounding influences of temporal trends, we furthermore control for world region r specific time trends through the use of time-fixed effects (θ_{rt}). The time-fixed effects are estimated using decadal period dummies, which we interact with world region dummies to capture differing time trends in each macro-region in our data. The results are fully robust when controlling for time-fixed effects in the form of 5 year time steps and estimating country-specific trends (Supplementary Tables 32 and 33). $\varepsilon_{ij,t}$ is the random error term capturing the remaining unexplained variation in the data. To estimate robust standard errors, all standard errors were clustered at the origin–destination pair level.

Equation (4) is estimated using the Poisson-pseudo maximum likelihood (PPML) estimator, which accounts for the right-skewness and zero inflation of the migration outcome[12,72,73]. The estimator also allows for unbiased estimates if any of the covariates of equation (4) are correlated with higher moments of the error term, which can be a problem

in log-linear models[28] (Supplementary Table 21). The estimation is implemented in R using the fixest package[74]. As we control for origin and destination pair fixed effects, the models build on variation within region pairs over time. Since changes in environmental conditions over time are plausibly exogenous conditional on geographic location and time trends, our models allow estimating the causal impacts of changes in drought and aridity on internal migration.

We use interaction models to explore differential climatic impacts by ecological and socio-economic characteristics of regions of origin and destination. A particular advantage of our census-based data is that they do not only allow to estimate the extent of the migration flows but also to explore who was migrating based on the migrants' characteristics and where they moved to, based on information about the destination regions. For this, we further distinguish migration flows by underlying demographic characteristics of the census takers, distinguishing between the migration of people with different educational backgrounds (no education, primary, secondary or tertiary) and age groups (0–14, 15–20, 21–25, 26–30, 31–45, 46–60 and >60 years) by sex (male, female). Owing to the small size of specific demographic groups in some regions, the estimation of accurate migration flows is more challenging. To account for this, outliers with a migration rate >10% were removed from the subgroup analysis (<1% of observations).

Predictions

On the basis of the empirical findings, we provide explorative predictions of potential migration changes under a 4 °C global warming scenario. For this prediction exercise, we combine (1) the results from statistical models estimating differential migration responses to changes in the AI by world regions and baseline levels of aridity (Supplementary Table 10) with (2) data on projected changes in the AI until the end of the century (Supplementary Fig. 9).

To define the baseline aridity level, we consider the mean AI in the origin regions in the reference period 2001–2021. On the basis of this average, we classify regions into hyper-arid/arid (AI < 0.2), semi-arid (0.2 ≤ AI < 0.50), subhumid (0.50 ≤ AI < 0.65) and humid regions (AI ≥ 0.65) and estimate whether changes in drought and aridity over time are more impactful in regions characterized by an overall dryer climate. On the basis of the significant estimates, we derive predicted marginal effects for each world region and aridity level.

We combine these effects with gridded projection data on expected changes in the AI by the end of the century provided by ref. 45. The projections are based on outputs from 21 coupled model intercomparison project phase 5 models under the representative concentration pathway 8.5 scenario. They project changes in the AI at 2 and 4 °C levels of global warming. According to the projections, more substantial increases in aridity are expected in the northern high latitudes. An expansion of drylands is expected in both semi-arid and arid regions.

Robustness checks

We perform various robustness and falsification tests varying different elements of our baseline model to test for the consistency and sensitivity of our results. These additional results are shown and described in detail in Supplementary Section E. Our findings are robust to controlling for (1) spatial interdependencies in the form of spatial models, which additionally account for drought and aridity conditions in neighbouring subnational regions (Supplementary Table 17); (2) multilateral resistance[28,44] which arises from confounding influences that changes in the attractiveness of alternative destinations exert on the bilateral migration rate (Supplementary Table 18); (3) international migration using data on decadal international migration stocks derived from the World Bank global bilateral migration database (Supplementary Table 19); and (4) lead values of the drought and aridity indicators for the period 10 years after the census (Supplementary Table 20). This latter falsification test (4) shows no indication that future conditions predict past mobility suggesting that our findings are not merely the outcome of confounding time trends. Our findings are furthermore insensitive to (5) the use of log-linear models with total migration flows as alternative outcome (Supplementary Table 21) or linear models with net migration as outcome (Supplementary Table 22); (6) weighting by population size, the size of the subnational regions and the number of subnational regions (Supplementary Tables 23–25); (7) varying the time window (1, 1–5, 6–10 and 11–20 years before census) over which the climate indicators are measured (Supplementary Tables 26–29); (8) varying the way the fixed effects are estimated and time trends are captured (Supplementary Tables 30–33); and (9) varying the standardization and measurement of the climate indicators (Supplementary Tables 34–37). Finally, (10) we study the impacts of precipitation and temperature anomalies in the 10 years before the census date on migration patterns (Supplementary Table 38) revealing results that are highly consistent with our findings using the composite drought indicators: negative precipitation and positive temperature anomalies drive out-migration from origin areas, whereas they reduce immigration to destination areas.

Limitations

The migration data and empirical strategy used come with certain limitations which are important for the interpretation of the results reported in this study. While the harmonized census migration data provide a unique dataset to comprehensively analyse internal migration worldwide, the derived information is available only at a coarse temporal and spatial scale.

Given that censuses are collected only every decade for most countries, shorter-term changes in mobility are difficult to capture. Also, most censuses use a broad time window of 5 years when asking census takers about their previous place of residence. While this enables us to capture mobility over longer time horizons, we may miss migration over shorter periods and circular forms of mobility. At the time of the census, some people may have already migrated back to their origin regions or moved on to another region in the country. Also, more seasonal forms of mobility are not captured in our migration measures.

Although we can use migration data to estimate the movement of people between regions, we cannot capture mobility at a more granular level within subnational regions. As most climate-related mobility occurs within shorter distances, our models will probably produce conservative estimates of drought and aridity impacts on migration. Also, due to differences in the size of administrative units across countries, short-distance mobility may be better reflected in some areas than others. While this would not affect our model estimates, which are entirely based on within regional changes over time, it can be relevant for the external validity of our findings for different world regions.

While the migration data considered in this study comprehensively map internal migration flows, international migration is not captured. Although IPUMS census data can provide information on international migration, it only includes the previous country of residence of the census taker without specifying the subnational regions of origin within that country from where the international migrant moved. As our models rely on regional changes in climatic conditions, an estimation of drought and aridity impacts on international migration was therefore not possible. With this, we may miss a relevant part of climate-related mobility, especially in contexts where cross-border migration is common.

Despite these potential blind spots, not accounting for international migration in our longitudinal models would not confound our estimates (Supplementary Fig. 11) and the main conclusions derived from our analysis remain valid: internal migration within countries is affected by drought and aridity with contextual factors and characteristics of populations shaping mobility responses. As most climate-related migration is internal, we believe these findings add an important comparative perspective on the climate–mobility nexus, complementing existing studies considering international migration flows[11–13,19].

While our analysis highlights the significant impact of drought and aridity, it is important to note that the data are historical, dating back to the 1960s for some countries. Consequently, the findings may not directly reflect the current situation experienced in specific regions and are more representative of countries for which we have more observations over time. For instance, our estimates for Central America (Fig. 2) suggest increased migration during periods of higher humidity, probably due to past events of excessive rainfall and severe storms[75]. However, today the region is facing increasing challenges associated with drought and aridity, which place substantial pressure on local communities and influence migration patterns[76]. Therefore, although our results overall demonstrate the critical role of drought and aridity in shaping internal migration, the estimated regional differences and their implications for current migration should be interpreted with caution. Moreover, the historical data may only provide limited information about the implications for future migration, especially in regions experiencing unprecedented levels of dryness and continued aridification.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The replication data used to generate and visualize the results reported in this study are available in a Harvard Dataverse repository[77]. The data analysis was carried out in R.

Code availability

The code used to generate and visualize the results reported in this study and the details of the R packages used in the data analysis are available in a Harvard Dataverse repository[77].

References

70. Kummu, M., Taka, M. & Guillaume, J. H. A. Gridded global datasets for gross domestic product and human development index over 1990–2015. *Sci. Data* **5**, 180004 (2018).
71. Hsiang, S. Climate econometrics. *Annu. Rev. Resour. Econ.* **8**, 43–75 (2016).
72. Santos Silva, J. M. C. & Tenreyro, S. The log of gravity. *Rev. Econ. Stat.* **88**, 641–658 (2006).
73. Gröschl, J. & Steinwachs, T. Do natural hazards cause international migration? *CESifo Econ. Stud.* **63**, 445–480 (2017).
74. Bergé, L. R. *Efficient Estimation of Maximum Likelihood Models with Multiple Fixed-Effects: The R Package FENmlm* (RePEc, 2018); https://econpapers.repec.org/RePEc:luc:wpaper:18-13
75. Spencer, N. & Urquhart, M.-A. Hurricane strikes and migration: evidence from storms in Central America and the Caribbean. *Weather Clim. Soc.* **10**, 569–577 (2018).
76. Baez, J., Caruso, G., Mueller, V. & Niu, C. Heat exposure and youth migration in Central America and the Caribbean. *Am. Econ. Rev.* **107**, 446–450 (2017).
77. Hoffmann, R., Abel, G., Muttarak, R., Malpede, M. & Percoco, M. Replication data and code for: 'Drought and aridity influence internal migration worldwide'. *Harvard Dataverse* https://doi.org/10.7910/DVN/QVLBGN (2024).

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Author contributions

R.H., G.A., M.M., R.M. and M.P. contributed to the conceptualization of the paper, as well as the development of its methodology and research design. G.A., R.H. and M.M. were responsible for data preparation and management. R.H. conducted the analysis and prepared the display items. R.H. also drafted the original version of the paper. All authors participated in the revision and editing process. R.H. administered and managed the project.

Competing interests

The authors declare no competing interests.

Additional information

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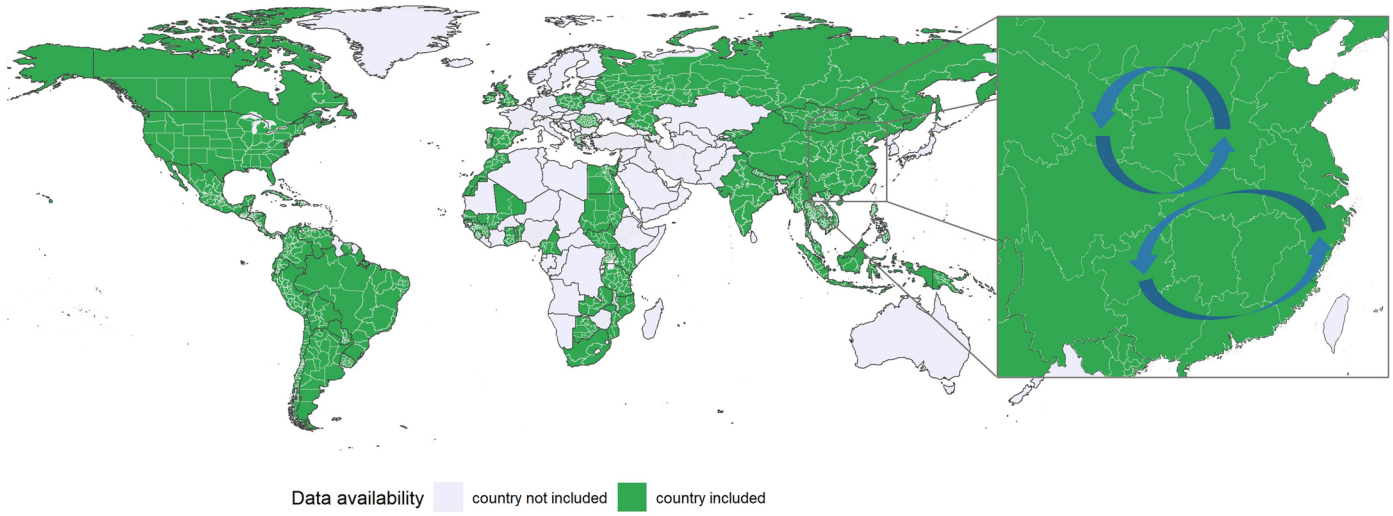

Extended Data Fig. 1 | Countries and subnational regions included in the census migration database. The map shows the boundaries of the subnational regions, which form the basis of the migration flow estimation. The inlay to the right shows exemplary migration flows between four regions in China.

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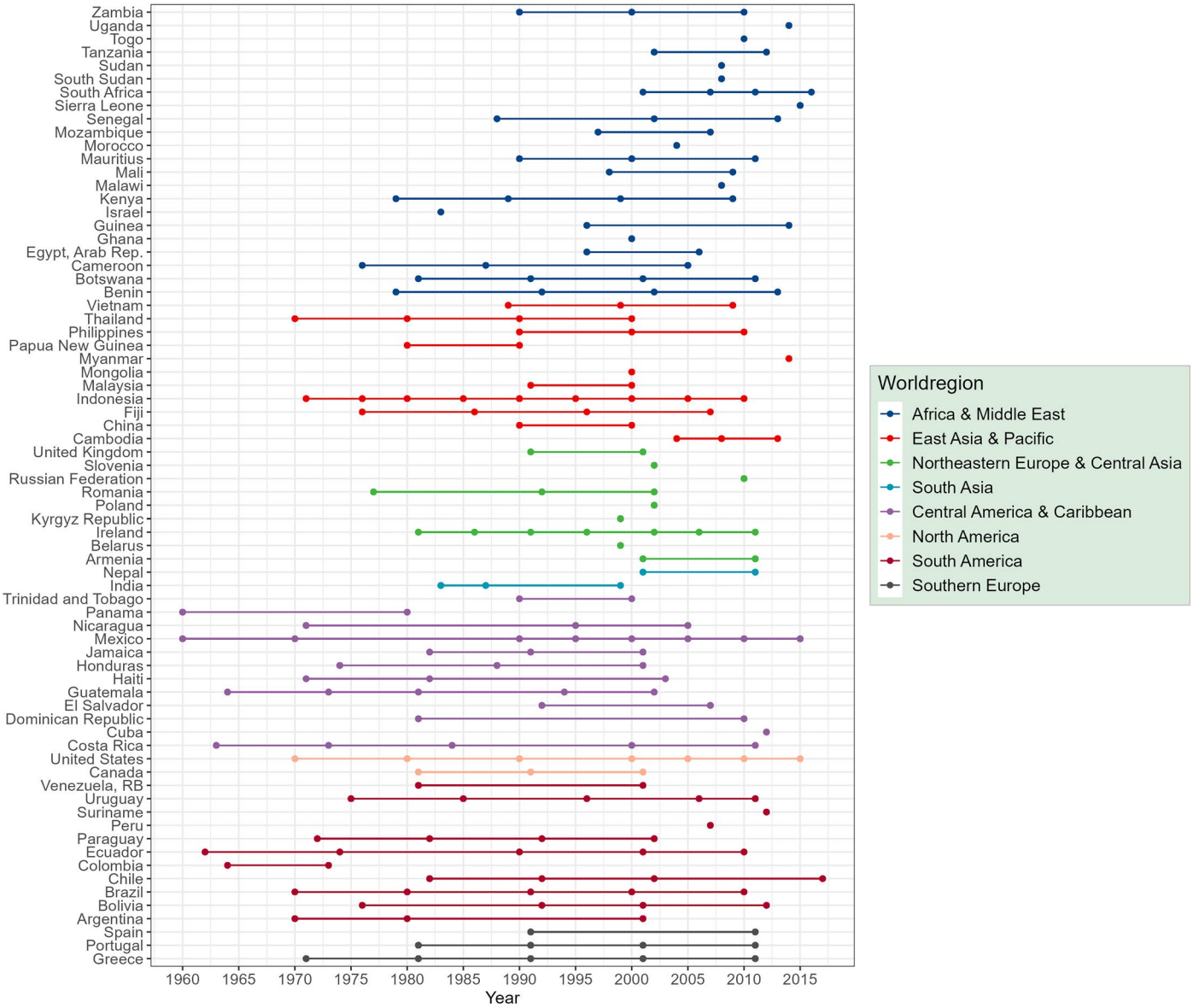

Extended Data Fig. 2 | Timing of censuses across countries and world regions covered in the migration dataset. Data are available for countries in North America, Central America and the Caribbean, South America, Africa and the Middle East, South Asia, Est Asia and Pacific, Northeastern Europe and Central Asia, and Southern Europe. The unbalanced longitudinal data contain information for 72 countries from 1960 to 2016.

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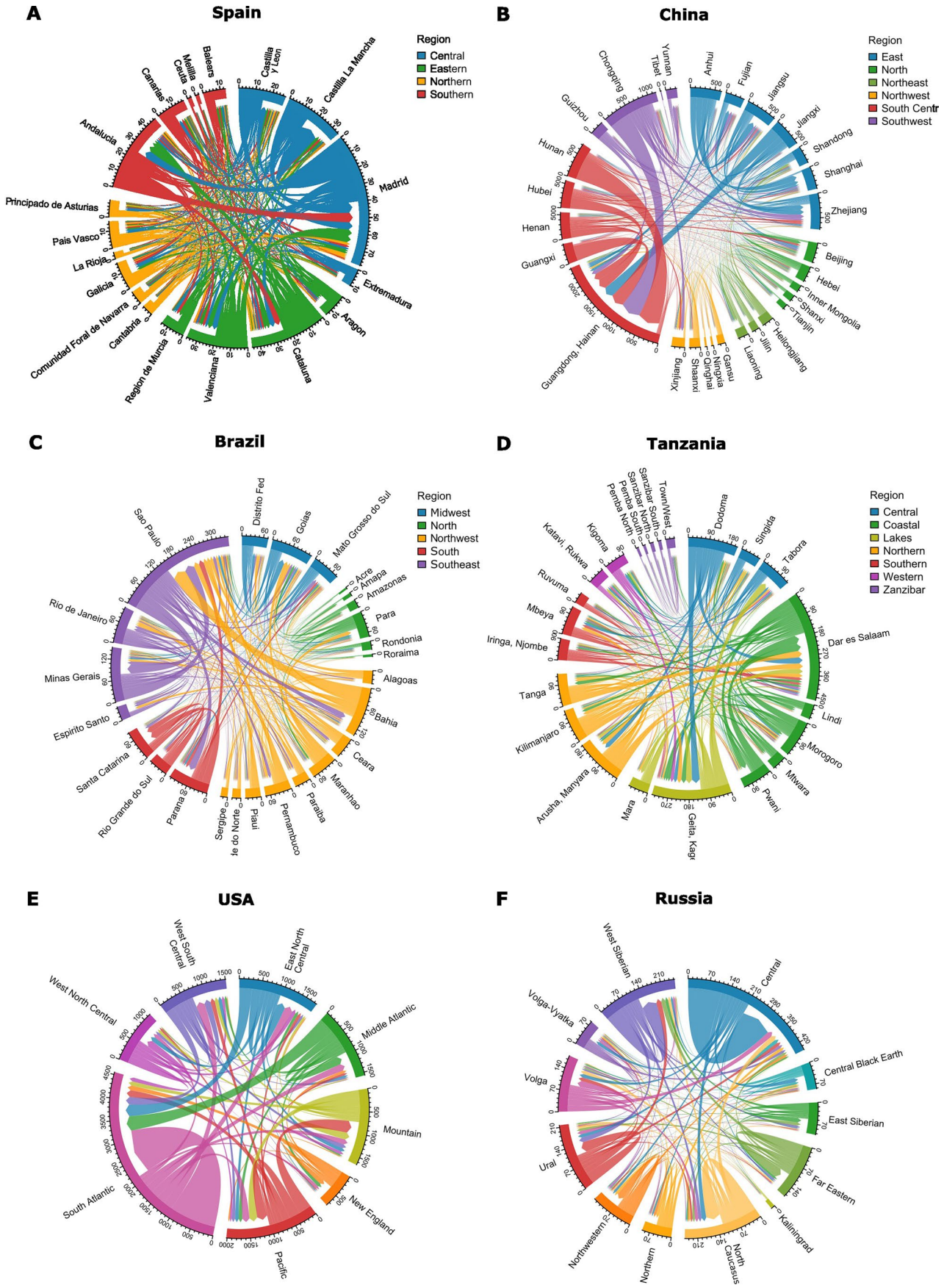

Extended Data Fig. 3 | Circular migration plots showing migration flows between subnational regions in six exemplary countries. The migration flows were estimated using the latest available census. Panels **A** Spain, **B** China, **C** Brazil, **D** Tanzania, **E** USA, **F** Russia. Subnational regions in the USA and Russia were further aggregated due to the large number of regions.

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☐	☒	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
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☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	The data analyzed in this study were compiled from different data sources, including the Integrated Public Microdata Series International (IPUMS) , the Climatic Research Unit (CRU) of the University of East Anglia CRU TS v 4.07, the SPEI Drought Database, and the Gridded global datasets for Gross Domestic Product and Human Development Index (1990–2015). All data obtained for this study were harmonized and prepared in R (open source packages used: tidyverse, RcppRoll, lubridate, countrycode, fixest, maps, ggpubr, RColorBrewer, rgdal, sf,vtable, ggcorrplot, colorspace). The data and code employed for this study are available at the Harvard Dataverse platform at https://dataverse.harvard.edu/privateurl.xhtml?token=b2cfa603-71bf-4e85-a59e-3023b7504a0e
Data analysis	All data were edited and analyzed in R (open source packages used: tidyverse, RcppRoll, lubridate, countrycode, fixest, maps, ggpubr, RColorBrewer, rgdal, sf,vtable, ggcorrplot, colorspace). The full replication code used to generate the results that are reported in this study are available at the Harvard Dataverse platform at https://dataverse.harvard.edu/privateurl.xhtml?token=b2cfa603-71bf-4e85-a59e-3023b7504a0e

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Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

The replication data and code used to generate and visualize the results reported in this study are available in the Harvard Dataverse repository: Hoffmann, Roman; Abel, Guy; Muttarak, Raya, Malpede, Maurizio, Percoco, Marco 2023, "Replication data and code for: "Drought and aridity influence internal migration worldwide", https://doi.org/10.7910/DVN/QVLBGN, Harvard Dataverse. The data analysis was carried out in R. All used packages are acknowledged and cited in the source code files.

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	The main migration data considered in our analysis were derived from IPUMS International harmonized census data for 72 countries. Based on the secondary data, we estimated bilateral migration flows between subnational regions within the countries and analyzed how changes in climatic conditions affected migration between regions. To account for differences by sex we derived separate migration flows for men and women and estimated differential impacts of drought and aridity on these. We also considered how other characteristics, such as a person's age and education, intersected with the person's sex in shaping migration responses.
Population characteristics	Each set of IPUMS census microdata contains a small random sample (0.4%-10%) of unidentified private households and associated persons based on a full census conducted by the national statistical agency in each country. The data obtained for this study is representative for the local populations at the subnational and national level. Countries used in the study were selected based on the availability of information on migration.
Recruitment	No primary data collection was carried out by the authors of this study and all data were obtained from secondary sources. The census data collection was carried out by national statistical agencies. The harmonization of the data was conducted by IPUMS International. The data employed in this study were drawn from 201 different censuses covering the period 1960-2016. While for some countries, data are available for up to 8 censuses (e.g., Mexico from 1960 to 2015), most countries have fewer observations over time, resulting in an unbalanced time series.
Ethics oversight	We have complied with all relevant ethical regulations and good scientific practices in the collection, harmonization, and analysis of the data. No primary data collection was undertaken as part of this study and all data were obtained from secondary sources. The study was carried out as part of a collaborative effort involving the International Institute for Applied Systems Analysis, the Austrian Academy of Sciences, the University of Hong Kong, the University of Bologna, the University of Verona, and Bocconi University who provided oversight and guidance to the project.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

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Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	The study uses extensive quantitative data on internal migration flows worldwide to estimate migration impacts of drought and aridity. The migration data were derived from census microdata provided by IPUMS for the period 1960-2016. Using data from 201 censuses and 72 countries, we created a unique longitudinal database at the sub-national regional level (1,410 first-level administrative regions). Internal migration is estimated based on information on the census takers' current and previous region of residence one or five years prior to the census date. To comprehensively model drought and aridity impacts, we use a range of composite indicators derived from different data sources. Gravity-type fixed effects models are employed to estimate migration impacts across regions over time. The harmonized data allow for a comprehensive analysis of the relationships between climatic change and inter-regional migration across different geographical contexts. While previous studies have analyzed internal migration using IPUMS census data, to our knowledge, this is the first large-scale longitudinal study of climate-induced internal migration that spans across all world regions.

Research sample	The data analyses were carried out at the aggregate subnational regional level considering region of origin and destination pairs within the 72 countries included in the dataset. In total, we obtained information on 1410 subnational regions (first-level administrative regions) over the period 1960-2016 allowing us to estimate 107,840 bilateral migration flows between each pair of regions in each country over time. The data were drawn from 201 different censuses. While for some countries, data are available for up to 8 censuses (e.g., Mexico from 1960 to 2015), most countries have fewer observations over time, resulting in an unbalanced time series.
Sampling strategy	The migration data were derived from harmonized census data provided by IPUMS International. Each set of IPUMS census microdata contains a small random sample (0.4%-10%) of unidentified private households and associated persons based on a full census conducted by the national statistical agency in each country. The data obtained for this study is representative for the local populations at the subnational and national level. The individual data obtained from IPUMS were aggregated to the subnational regional pair level to estimate migration flows between regions of origin and destination.
Data collection	A range of data sources were employed to study the impacts of aridity and drought on internal migration worldwide. Information on migration and socioeconomic conditions were derived from harmonized census microdata samples from the Integrated Public Use Microdata Series (IPUMS) International database. The data were drawn from 201 different censuses covering the period 1960-2016. The census data were combined with gridded time series data from the Climatic Research Unit (CRU) of the University of East Anglia (CRU TS, Version 4.07). In addition, information on drought conditions were retrieved from the SPEI database (SPEIbase v2.8: 1), which spans the period between January 1901 to December 2020. Finally, data were retrieved from the gridded global dataset for the Gross Domestic Product and Human Development Index spanning the period of 1990–2015, which provides details about economic prosperity and human development. Information from the gridded data products was extracted to the subnational regional level using harmonized first-level administrative regions shapefiles provided by IPUMS. The subnational units were harmonized so that their boundaries remain geographically stable over time.
Timing	Data collection and preparation for this study took place between January 2021 and July 2024. The data were updated consecutively whenever updates from the source datasets were made available.
Data exclusions	The complete data derived from the different sources were used in the data analysis. For the subgroup analyses presented in Figure 4, outliers with a migration rate larger than 10% (<1% of observations) were removed to obtain more stable and consistent estimates.
Non-participation	The analysis for this study was carried out at the sub-national regional level combining census-based migration data with external gridded data sources. Since the migration data are based on census data, non-participation and the systematic exclusion of population groups from the data (e.g. irregular migrants) is a relevant issue for the data collection. By using fixed effects longitudinal models, we rule out that any relatively stable differences in participation have confounded our model results. Moreover, we employ post-stratification weights provided by IPUMS to account for sample selection issues. Also with weights, the results of our models remain stable, suggesting that differences and changes in the composition of the samples are not affecting our findings. Data and selectivity issues are also transparently discussed in the paper and the limitations in the Method Section.
Randomization	Our longitudinal models control for unobserved heterogeneity as well as time trends and seasonality effects via the use of fixed effects. As the occurrence of extremes within a region over time is plausibly exogenous conditional on geographic location and time trends, our model allows us to test for the causal impacts of changes in climatic conditions and extreme events on internal migration. We performed various sensitivity tests to show that our models are robust to variations in the sample, measurement and specifications used.

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Methods

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