A Meta-Analysis of Country-Level Studies on Environmental Change and Migration

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Abstract: The impact of climate change on migration has gained both academic and public interest in recent years. Here we employ a meta-analysis approach to synthesize the evidence from 30 country-level studies which estimate the effect of slow and rapid-onset events on migration worldwide. Most studies find that environmental hazards affect migration, although with contextual variation. Migration is primarily internal or to low- and middle-income countries. The strongest relationship is found in studies with a large share of non-OECD countries, particularly from Latin America and the Caribbean and Sub-Saharan Africa, and in studies of middle-income and agriculturally dependent countries. Income and conflict moderate and partly explain the relationship between environmental change and migration. Combining our estimates for differential migration responses with the observed environmental change in these countries during the past decades illustrates how the meta-analytic results can provide useful insights for the identification of potential hotspots of environmental migration.

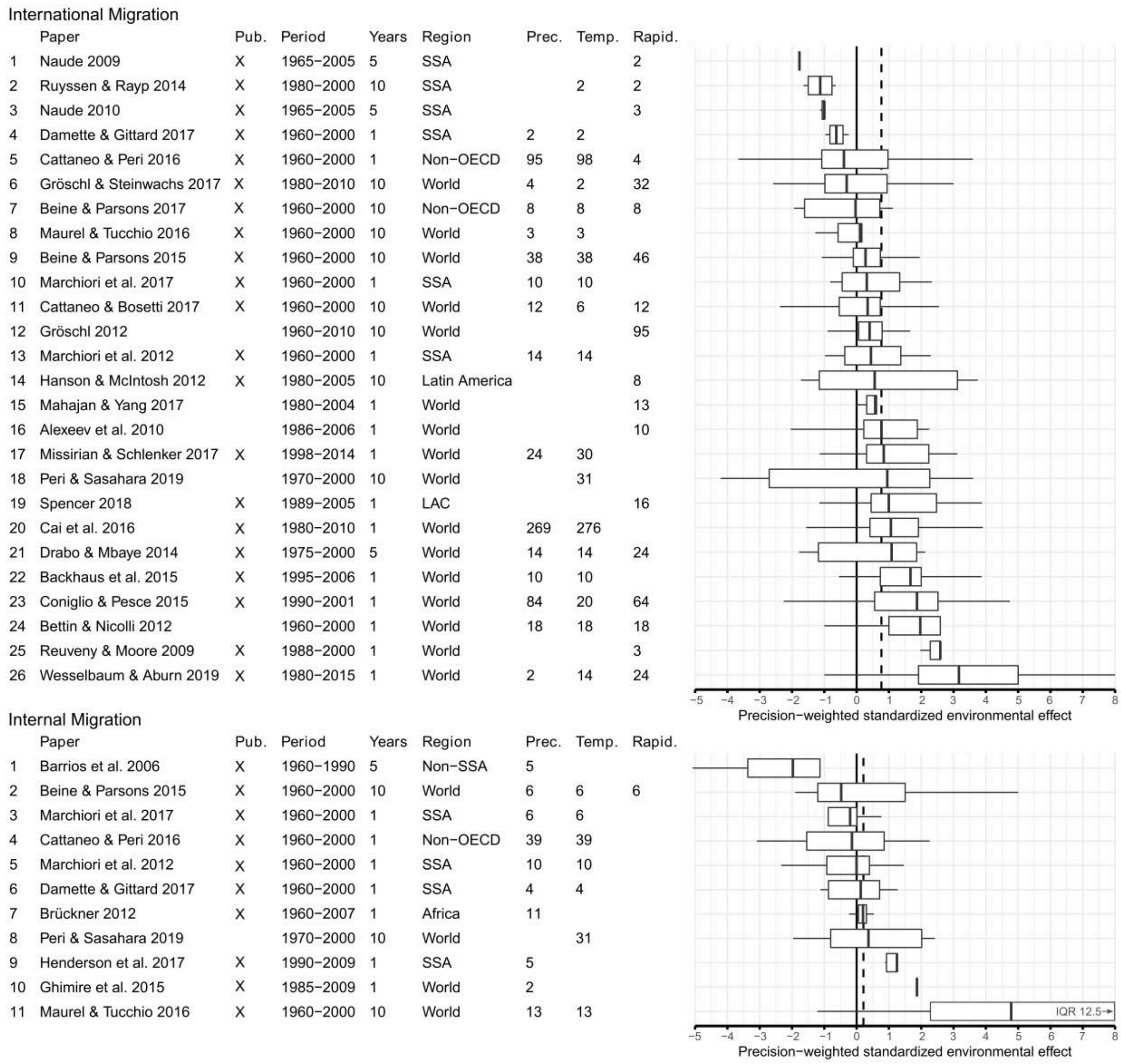
The potential effect of climate change on worldwide migration is highly present in the public debate. Recent mass migration episodes such as the Syrian refugee crisis in 2015 and the ‘migrant caravan’ from Central America to the United States in 2018 have been partly attributed to severe droughts experienced in these countries [1–3]. Possible relationships between changing environmental conditions and subsequent migration have also been observed in other parts of the world (Extended Data Figure 1). The extent to which environmental factors fuel economic and sociopolitical crises and influence migration has led to controversial discussions in the literature [4]. If the claim that adverse climatic conditions drive migration is true, it can be expected that an increase in average global temperature of 2°C or more would result in significantly higher migration flows in the future[5–8].

In the past decade, the number of empirical studies focusing on climate and other environmental drivers of migration has increased notably. Yet, there is little consensus concerning the direction and the extent to which these factors influence migration. Environmental change has been found to contribute to increased human migration in some studies, whereas no effect or a decline in migration has been reported in others [9–14]. The empirical results differ depending on the environmental factors considered, the data and scale of the analysis, the methodology employed, and the geographical contexts covered. Even within the same studies, estimates of the size and direction of environmental migration flows vary considerably. The heterogeneity of the existing evidence hampers policy efforts to address the challenges related to potential increases in global migration flows due to future environmental change.

Here we use a meta-analysis approach to synthesize the results of 30 scientific papers published between 2006 and 2019, which quantitatively analyze the influence of different environmental factors on migration (Figure 1) [15-44]. We focus on macro studies which estimate the effects on migration using longitudinal country-level data and exploiting variations both across countries and over time. The considered studies focus on a broad range of environmental drivers, such as changing temperatures, rainfall anomalies, or heavy storms. Typically, they estimate separate regression models considering the impacts of different environmental factors and other migration drivers, using different modelling techniques, country samples, and specifications.

From the 30 selected studies (n) and their models, we extracted a total of 1803 effect estimates (k) of the relationship between individual environmental factors and migration (Supplementary Figure S1). Each model estimate represents a separate observation in our analysis. To achieve comparability, we standardize the estimates using distributional information for each of the environmental and migration variables considered. The standardized effects show the estimated change in migration in standard deviations corresponding to a one standard deviation change in the respective environmental factor. In our meta-analysis, we take an explorative approach aiming at unveiling patterns in the environment-migration relationships estimated by the pool of existing studies and analyzing drivers of heterogeneity in the empirical findings.

The focus on country-level studies allowed us to retrieve and recalculate the distributional information required for standardization, a process which is not feasible for idiosyncratic micro-level studies. The standardization enables us to effectively compare the size of different effects across models despite differences in measurement and scaling of the key variables. The estimation methodology used in the country-level studies is broadly similar, allowing for a direct comparison of the results. By extracting further information on study characteristics, modeling techniques, the particular contexts considered, and the sample composition used, we explore the sources of heterogeneity in the effect sizes across estimates, as well as potential mechanisms explaining the differences in the study results.



International Migration

	Paper	Pub.	Period	Years	Region	Prec.	Temp.	Rapid.
1	Naude 2009	X	1965−2005	5	SSA			2
2	Ruyssen & Rayp 2014	X	1980−2000	10	SSA		2	2
3	Naude 2010	X	1965−2005	5	SSA			3
4	Damette & Gittard 2017	X	1960−2000	1	SSA	2	2	
5	Cattaneo & Peri 2016	X	1960−2000	1	Non−OECD	95	98	4
6	Gröschl & Steinwachs 2017	X	1980−2010	10	World	4	2	32
7	Beine & Parsons 2017	X	1960−2000	10	Non−OECD	8	8	8
8	Maurel & Tucchio 2016	X	1960−2000	10	World	3	3	
9	Beine & Parsons 2015	X	1960−2000	10	World	38	38	46
10	Marchiori et al. 2017	X	1960−2000	1	SSA	10	10	
11	Cattaneo & Bosetti 2017	X	1960−2000	10	World	12	6	12
12	Gröschl 2012		1960−2010	10	World			95
13	Marchiori et al. 2012	X	1960−2000	1	SSA	14	14	
14	Hanson & McIntosh 2012	X	1980−2005	10	Latin America			8
15	Mahajan & Yang 2017		1980−2004	1	World			13
16	Alexeev et al. 2010		1986−2006	1	World			10
17	Missirian & Schlenker 2017	X	1998−2014	1	World	24	30	
18	Peri & Sasahara 2019		1970−2000	10	World		31	
19	Spencer 2018	X	1989−2005	1	LAC			16
20	Cai et al. 2016	X	1980−2010	1	World	269	276	
21	Drabo & Mbaye 2014	X	1975−2000	5	World	14	14	24
22	Backhaus et al. 2015	X	1995−2006	1	World	10	10	
23	Coniglio & Pesce 2015	X	1990−2001	1	World	84	20	64
24	Bettin & Nicolli 2012		1960−2000	1	World	18	18	18
25	Reuveny & Moore 2009	X	1988−2000	1	World			3
26	Wesselbaum & Aburn 2019	X	1980−2015	1	World	2	14	24

Internal Migration

	Paper	Pub.	Period	Years	Region	Prec.	Temp.	Rapid.
1	Barrios et al. 2006	X	1960−1990	5	Non−SSA	5		
2	Beine & Parsons 2015	X	1960−2000	10	World	6	6	6
3	Marchiori et al. 2017	X	1960−2000	1	SSA	6	6	
4	Cattaneo & Peri 2016	X	1960−2000	1	Non−OECD	39	39	
5	Marchiori et al. 2012	X	1960−2000	1	SSA	10	10	
6	Damette & Gittard 2017	X	1960−2000	1	SSA	4	4	
7	Brückner 2012	X	1960−2007	1	Africa	11		
8	Peri & Sasahara 2019		1970−2000	10	World		31	
9	Henderson et al. 2017	X	1990−2009	1	SSA	5		
10	Ghimire et al. 2015	X	1985−2009	1	World	2		
11	Maurel & Tucchio 2016	X	1960−2000	10	World	13	13	

Figure 1 - Primary quantitative country-level studies testing for a relationship between environmental factors and international and internal migration. "Pub." indicates whether the paper was published in a scientific journal listed in SciRef. "Period" refers to the starting and end years of the panel data used in each study. "Years." captures the most common average period, for which the environmental indicators were measured in the studies. Region shows the geographical focus of the study. The final columns indicate the environmental factors considered with the figures showing the number of model estimates (cases k) for each factor. Boxplots with median, interquartile ranges (IQR), and whiskers (either maximum value or max 1.5xIQR) of the precision-weighted standardized environmental effects on the right. Effects are weighted using the inverse of the estimated variance. SSA, sub-Saharan Africa; OECD, Organization for Economic Co-Operation and Development; LAC, Latin America and the Caribbean; Prec., precipitation; Temp, temperature; Rapid, rapid-onset disaster events.

Overview of Country-Level Studies

Most of the individual estimates consider migration responses to gradual environmental changes (k=1413, 78.4%), such as changes in the level or variability of temperature (39.1%) or precipitation (39.3%). Rapid-onset events, such as heavy storms, floods, or landslides, are analyzed in 390 of the considered cases (21.6%). Conceptualization and measurement of environmental events and hazards vary considerably across studies and models, ranging from changes in absolute levels, to anomalies, or coefficients of variation/variability.

To facilitate the interpretation, the environmental measures used by the original studies are categorized into rapid-onset disasters, temperature and precipitation level change measures, and temperature and precipitation variability and anomaly measures (Supplementary Table S1 and Table S2). In the original models, variability and anomaly measures take only positive values and reflect, in contrast to level variables, changes and spikes in the distribution of environmental factors such as precipitation and temperature.

Overall, 27 of the 30 considered studies come to the conclusion that environmental factors are a relevant migration driver. The majority of the estimates focus on international migration (k=1587, 88.0%), with relatively few estimates for internal migration flows, which are mainly captured using urbanization rates as a proxy (k=216, 12.0%). Bilateral migration flows are the most commonly analyzed data. Other studies use more unique data sources focusing on other types of migration such as asylum applications [33] and displacement data [21].

Environmental hazards and events are just one of many factors influencing the decision to migrate[45]. The recent literature has emphasized the role of different macro-level conditions including economic, cultural and sociopolitical factors which can reinforce migratory responses to environmental shocks or suppress them [46]. Agricultural dependence and income are often considered as moderators of the environment-migration relationship, based on the notion that there is a trade-off between the incentives to move and the resources needed to do so. Environmental conditions can either directly influence migration decisions, e.g. by posing an immediate threat to health and well-being or indirectly by affecting other migration drivers such as economic and sociopolitical conditions [47]. The manifold pathways through which environmental changes together with other factors affect migration suggests a strong context-dependency of the relationship.

The Direction and Magnitude of Environmental Effects

The mean of the standardized effects across all cases (k=1803), corresponding to individual estimated coefficients, is positive and significantly different from zero. On average, a one standard deviation change in the environmental conditions leads to an increase in migration by 0.021 standard deviations (95CIs: 0.0176; 0.0235, random effects model, PM estimator, $Tau^2=0.002$, $I^2= 70.0\%$, H=1.83,)[48]. To account for differences in the precision of the original estimations in our synthesis, the standardized effects obtained from each study are precision-weighted in our analysis. We use the inverse of the estimated effect variance to down-weight the influence of highly uncertain estimates [49,50].

As the interquartile ranges of the estimated effects show (Figure 1, Supplementary Figure S2), the strength and direction of the relationship between environmental factors and migration vary both within and between studies (Extended Data Figure 2). Despite heterogeneity in the findings, a sizeable share of the considered estimates (23.1%, alpha = 0.05, t-value ≥ 1.96) indicate a significant positive effect, suggesting that in many of the cases considered, environmental changes and shocks have led to an increase in migration. At the same time, 5.5% of the estimates are significantly negative, implying that environmental hazards can also constrain migration in certain contexts [51].

Migration Responses by Type of Environmental Hazards

Further exploring the underlying heterogeneity of the findings, Table 1 shows the results of meta-regression models with study-specific intercepts, where the standardized environmental effects (k=1803) are regressed on characteristics of the models estimated by the studies, such as the types of environmental factors considered, the measurement of migration, as well as characteristics of the model specification and composition of the samples (Supplementary Table S3). The estimates refer to changes in the standardized effects to a one-unit change in the considered explanatory factor. All standard errors of the meta-regression estimates are clustered at the study level. The results are robust to different specification changes (Supplementary Tables S4-S10), including restricting the sample to cases which control for spatial and time period fixed effects (Supplementary Table S4 and S5), using mixed effects meta-regression models (Supplementary Table S6), and adding further controls (Supplementary Table S7).

The strength of the migration response largely depends on the type of environmental change or hazard considered. While changes in the level of precipitation tend to have only a small impact on migration, changes in the variability and anomalies of rainfall usually show a significantly positive impact of a similar size to that of rapid onset events (Figure 2). In line with other studies[52], the observed standardized effects on migration are found to be strongest for temperature level changes. On average, one standard deviation change in temperature levels leads to a stronger increase in migration by 0.018 standard deviations relative to a comparable change in precipitation levels (Table 1, Model 1).

Table 1 – Meta-regression models with precision weighting and study-specific intercepts

	Outcome Standardized environmental effect				
	Model 1	Model 2	Model 3	Model 4	Model 5
Environmental drivers *(ref: prec. level change)*					
Precipitation variability/anomalies	0.017^{**}	0.016^{*}	0.016^{**}	0.016^{**}	0.015^{*}
	(0.008)	(0.008)	(0.007)	(0.007)	(0.008)
Rapid-Onset event	0.015^{*}	0.015^{*}	0.015^{*}	0.015^{*}	0.014^{*}
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
Temperature level change	0.018^{**}	0.017^{**}	0.018^{**}	0.018^{**}	0.017^{**}
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
Temperature variability/anomalies	0.016^{*}	0.014^{*}	0.014^{*}	0.014^{*}	0.013^{*}
	(0.008)	(0.008)	(0.007)	(0.007)	(0.008)
Further environmental controls					
Environment-migration lag in years		-0.001	-0.0004	-0.0004	-0.001
		(0.001)	(0.0005)	(0.001)	(0.001)
Measurement timeframe > 1 year		-0.016^{***}	-0.016^{***}	-0.017^{***}	-0.010^{***}
		(0.0004)	(0.0003)	(0.0003)	(0.002)
Other environmental factors controlled for in original model		-0.002^{**}	-0.003^{***}	-0.003^{***}	-0.003^{***}
		(0.001)	(0.0005)	(0.0005)	(0.001)
Migration destination (*ref: international, worldwide*)					
Internal migration			0.006^{**}	0.006^{**}	0.006^{**}
			(0.002)	(0.002)	(0.003)
International, destination only low/middle-income countries			0.069^{**}	0.068^{**}	0.063^{**}
			(0.030)	(0.029)	(0.027)
International, destination only high-income countries			0.005	0.005^{*}	0.003
			(0.003)	(0.003)	(0.003)
International, destination ambiguous			-0.008^{***}	-0.007^{**}	-0.010^{***}
			(0.003)	(0.003)	(0.003)
Sample composition					
% non-OECD countries in sample				0.006^{**}	
				(0.002)	
% low-income-countries in sample					-0.074^{***}
					(0.021)
% lower middle-income-countries in sample					0.014^{**}
					(0.006)
% upper middle-income-countries in sample					0.044^{***}
					(0.008)
% agriculturally dependent countries in sample					0.104^{***}
					(0.022)
% conflict countries in sample					-0.022^{***}
					(0.003)
# of case observations (k)	1,803	1,803	1,803	1,803	1,803
# of studies (n)	30	30	30	30	30
R-squared	0.272	0.284	0.305	0.309	0.340
Adj. R squared	0.255	0.267	0.287	0.291	0.321

Notes: Meta-regression coefficients with cluster robust standard errors in parentheses. Clustering of standard errors on study level (n=30). The dependent variable is the weighted standardized coefficient derived from the original models (k=1803). All models are based on equation (3) in the Methods section. They control for study-specific intercepts (fixed effects). Additional omitted controls capturing whether the estimate was derived from an interaction term, whether the original model controls for spatial fixed effects and time fixed effects, and the sum of all control variables included in the model. See Supplementary Section E for further model specifications and estimations. P-values: * 0.1 ** 0.05 *** 0.01

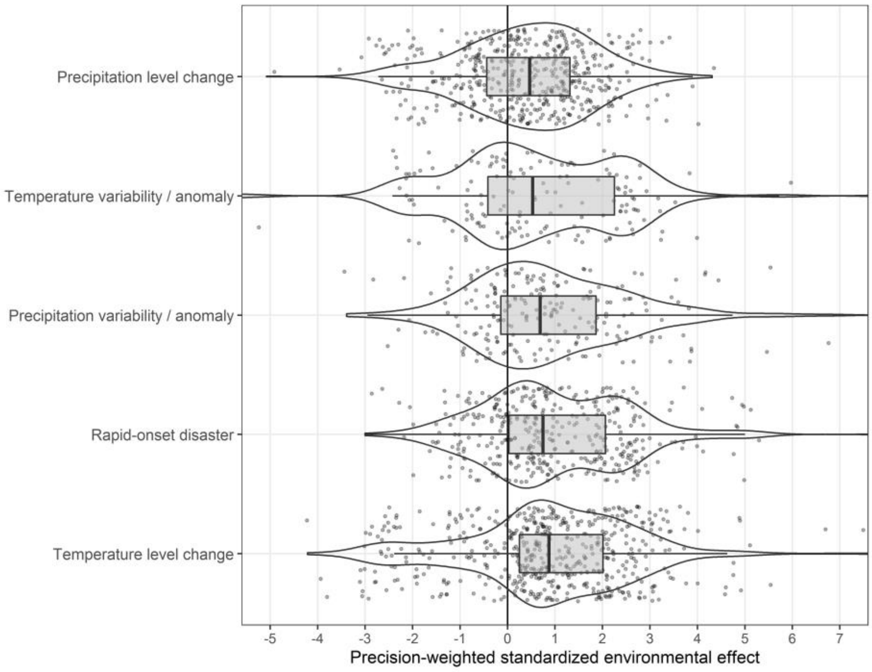


Figure 2 – Distribution of the precision-weighted standardized effects by type of environmental hazard. Effects are weighted using the inverse of the estimated variance. The violin plots show the kernel density distribution of the effects of the environmental hazards on migration. The boxplots show the median and the interquartile ranges. We distinguish between effects of precipitation and temperature level changes and effects estimated for changes in precipitation and temperature variability or anomalies. Additionally, we consider the effects of rapid-onset disasters, such as storms, floods, and other related hazards.

One reason for why we observe less strong effects of precipitation level changes may be because increased precipitation levels can have both positive (e.g. after a drought) and negative impacts (e.g. in the case of excess rainfall and flooding) over time depending on the context, which might lead to a weakening of the average estimated effect. This is less of an issue for other types of environmental hazards for which increases in the original variables (e.g. in the rainfall variability or temperature levels) are more clearly linked with negative impacts.

The estimated effect sizes depend on further features of the models related to the measurement of the environmental factors (Model 2). We find that a broader timeframe in the measurement of the environmental and migration variables (five or ten years compared to one) leads to smaller effect estimates. The strength of the effect also depends on whether the original models simultaneously control for other environmental factors [53,54]. If other factors are controlled for, the effect estimates change, suggesting important interactions between different types of environmental hazards, which can re-inforce each other in influencing migration (Supplementary Table S11). We also find that not only do environmental conditions play a role as a push factor, they can also possibly serve as a pull factor, thus influencing the choice of migration destination (Supplementary Table S12).

Differences by Migration Destination

When comparing the effect size by destination, we find larger environmental effects for internal migration than for estimates considering global migration flows (Table 1, Model 3). The differences however are not that large, possibly due to the limited measurement of internal migration in the original country-level studies. The few studies that consider internal migration in our sample usually approximate it using data on urbanization, which overlooks certain forms of internal migration such as rural-to-rural, urban-to-rural, urban-to-urban and other irregular forms of migration and displacement. Despite this limitation of our meta-sample, the internal migration effect is found to be robust across all of our meta-regressions.

When the studies consider international migration, the effects are largest for models assessing migration to low or middle-income country destination. The environmental effects are 0.069 standard deviations larger for those models compared to models estimating worldwide migration. Taken together, the results of our meta-regressions showing the importance of internal migration and migration to low or middle-income country destinations mirror the findings in the empirical literature, which reports that environmental migration is often short-distance, regional, and temporary[9,11].

Country Contexts as a Moderator of the Relationship

Previous research has emphasized the role of context in explaining differences in environmental migration patterns [14,55]. The last two models in Table 1 take compositional characteristics of the samples of coefficient estimates into account in order to assess the role of contextual factors as determinants of the environment-migration link. The original studies use different country samples to estimate environmental effects on migration in different contexts. For example, some country samples focus on low-income countries, while others concentrate on certain world regions such as Latin America and the Caribbean (LAC) or Sub Saharan Africa (SSA).

In total, the effect estimates (k=1803) from the original studies are based on 121 samples consisting of different combinations of countries. For each sample, we calculate the share of non-OECD countries; low, lower-middle, and upper-middle-income countries; agriculturally dependent countries; and countries that have undergone persistent conflicts (see Extended Data Figure 3 for the distribution of the compositional share measures). This allows us to test whether the estimated effect sizes (k) differ depending on the sample composition used in the original models and thus explore the extent to which contexts influence migration responses to environmental changes.

Model 4 shows that models with samples consisting only of non-OECD countries report on average a larger environmental effect compared to samples consisting only of OECD countries. Further distinguishing the compositional shares for different world regions (Supplementary Table S13), we find the strongest positive environmental effects in the study samples focusing on the LAC and SSA region, and weaker, but positive effects in the samples focusing on the Middle East and North Africa (MENA) and Asia.

Model 5 includes further sample composition measures reflecting the economic and sociopolitical context measured as income level, agricultural dependence and conflict. Fig. 3 illustrates the sample composition effects identified in our meta-regression model for different groups of cases. Considering the different dimensions simultaneously, we find weaker environmental effects on average in the samples with a larger share of low-income countries.

If a study sample consists exclusively of low-income countries, the effects are on average 0.074 standard deviations smaller compared to a sample without any low-income countries, suggesting that liquidity constraints prevent migration in low-income contexts after an environmental shock (Fig. 3, panel A). The lack of economic resources enabling migration might be amplified under environmental stress, potentially resulting in 'trapped populations' [23,29,41]. Moreover, we find that studies with a larger number of lower-middle- and particularly upper-middle-income countries report larger environmental effects, suggesting a non-linearity in the migration response to environmental hazards across different income strata[33,40]. This is in line with the migration hump theory, which predicts an inverted U-shaped relationship between socio-economic development and migration[56].

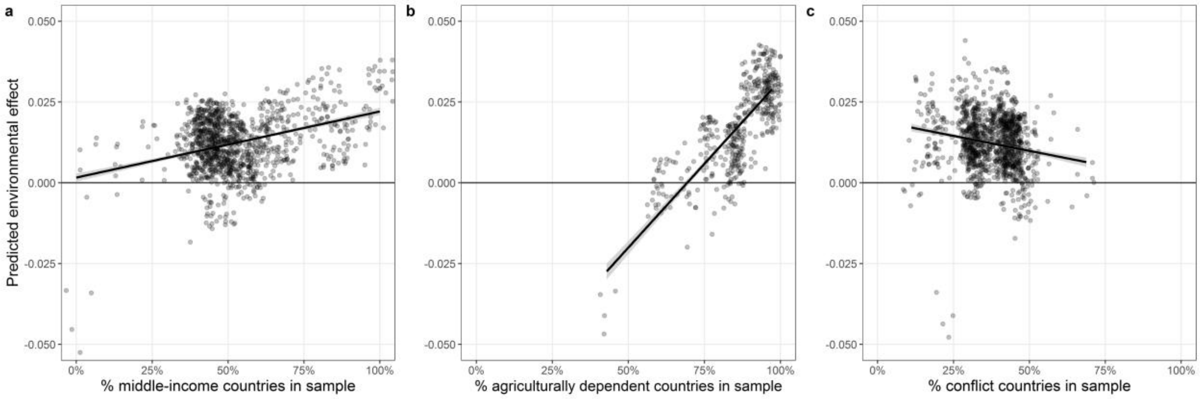


Figure 3 – Predicted environmental effects on migration by country sample compositions. A) Predicted effects by the share of middle-income-countries in the sample (only samples with < 50% agriculturally dependent and conflict countries); B) share of agriculturally dependent countries (only samples with >80% low-income countries), and C) share of countries which experienced a conflict for at least 5 years between 1960 and 2000 (only samples < 50% agriculturally dependent countries). Predictions are based on a simplified version of our main Model 5 (Supplementary Table S15). Shaded areas (in grey) show 95% confidence intervals. All relationships are shown for selected sub-samples, e.g. samples with a high share of low-income countries (Panel B), to highlight patterns in the data and to avoid confounding effects counterbalancing the depicted patterns.

Controlling for differences in the samples' income levels, we find that studies using samples with a higher share of agriculturally dependent countries report larger environmental effects on average (Fig. 3, panel B). Environmental change can have major implications for agricultural production [57–60] and agriculture tends to be a particularly important economic sector in low-income countries, where livelihoods of a large segment of the population depend on agricultural output. This suggests that the necessity to migrate due to livelihood disruptions is also a strong driver of the observed differences in the environmental effects on migration.

Finally, we find a weak negative effect of the compositional share of countries that have experienced a persistent conflict (Fig. 3, panel C). This suggests that adverse sociopolitical conditions can interact with the impact of environmental shocks and consequently affect the migration response [1–3]. Overall, the findings from our meta-regressions show the important role the economic and sociopolitical context plays in shaping the relationship between environmental factors and migration.

The Role of the Income and Conflict Mechanisms

In a series of additional meta-regressions, we consider the absolute size of the standardized effect to assess whether the absolute strength of the relationships changes depending on the model specification (Supplementary Table S14). In particular, we explore the role of income and conflict as two potential mechanisms explaining environmental effects on migration [61,62]. If these actually represent mechanisms, controlling for them in a migration model would lead to a reduction in the size of the environmental effects. Indeed, we find that those studies, which remove the potentially mediating effects of income and conflict on migration, report on average smaller environmental effects by 0.012 and 0.026 standard deviations, respectively. This suggests that both income and conflict could represent mechanisms explaining environmental effects on human mobility.

Economic and sociopolitical factors can affect the relationship between climate change and migration in different ways [45,55]. Climate change and the resulting environmental depletion can disrupt livelihoods and lead to the onset and spread of conflicts in certain contexts, especially where governance is weak [50,61–63], leading to forced displacement and migration. At the same time, existing conflicts can fuel the impact of adverse environmental conditions on migration. Using an indirect estimation approach, we provide additional support for the role of income changes and conflict in explaining the environment migration relationship. Although environmental factors are unlikely to be the primary driver of political instability and the causal relationships between the different factors are highly complex and context-dependent, their role as a trigger of migration through income shocks and conflict is supported by our analysis[9].

Predicting Hotspots of Environmental Migration

We use estimates of the environment-migration link based on our main meta-regression model (Table 1, Model 5) to identify potential hotspots of environmental migration worldwide. For this exercise, a country-level data set with 221 countries is constructed based on: the actual exposure to environmental change of countries from 1960 to 2000, measured in standard deviations of the world distribution; and countries' economic and sociopolitical characteristics in the year 2000. For the latter, we include the same variables used in the construction of the compositional share measures in the models: income level, agricultural dependence, and conflict (Supplementary Section G).

We combine our estimates for differential migration responses by contexts with the observed environmental change in the countries during the past decades. As a first step, we translate our meta-regression estimates for the effect of different compositional shares to predicted differences in the migration response for different types of countries, e.g. low vs. high-income countries. As a second step, we combine the estimated differential migration responses with a measure of environmental hazards exposure (i.e. precipitation anomalies, temperature anomalies, and population exposed to natural disasters) in each country. We then predict the country-specific environmental impact on migration by multiplying the observed environmental change with the estimated migration response (Figure 4).

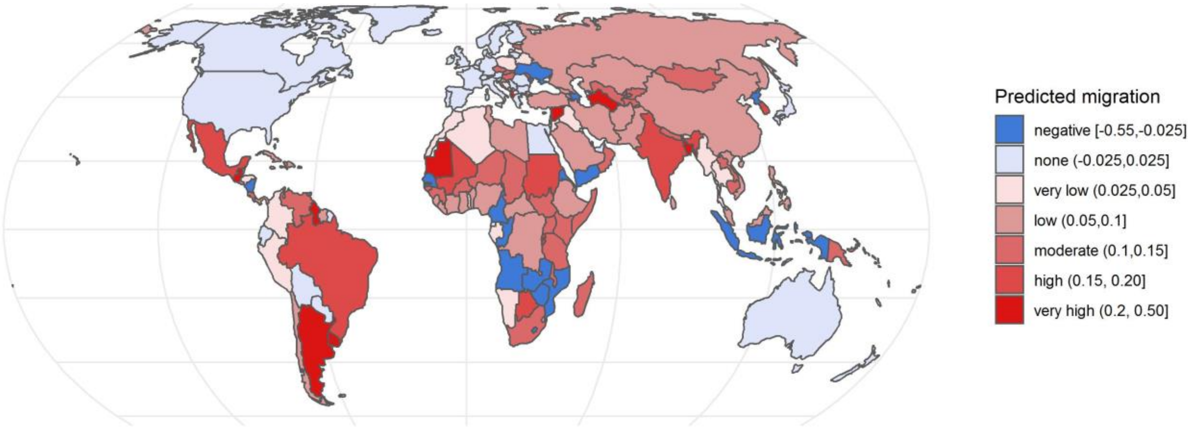


Figure 4 – Predicted environmental migration worldwide measured in predicted standard deviation changes in migration. Predictions are based on a simplified version of model 5 (Supplementary Table S15), which estimates different migration responses by context. The differential migration responses are combined with information on countries' exposure to environmental change from 1960-2000. The derived estimates are integrated in a country level data set and used to project the predictions in the map. The map uses an equal area projection. The term 'negative' refers to a predicted reduction in migration due to environmental change [-0.55,-0.025] 'none' refers to cases with neither a sizeable positive nor negative environmental impact on migration (-0.025, 0.025]. Positive impacts on migration are subdivided in, 'very low' (0.025, 0.05],'low' (0.05, 0.10],'moderate' (0.10, 0.15],'high' (0.15, 0.20], and 'very high' (0.20, 0.50]

We predict higher levels of environmental migration for countries in Latin America and the Caribbean, for selected countries in Sub-Saharan Africa, particularly in the Sahel region and East Africa, as well as in Western, South and parts of Southeast Asia. The increased predicted levels are mainly due to an increased exposure to multiple environmental hazards in these areas as well as a sufficiently high level of income to finance migration, coupled with a high level of agricultural dependence increasing the populations' vulnerability to environmental change.

Relatively low levels of environmental migration are predicted for high-income countries, especially in Europe and North America. In some low-income countries in Sub-Saharan Africa and Southeast Asia, environmental migration is predicted to be low or constrained, mainly due to their lower income combined with relatively smaller agricultural sectors. While the mapping exercise serves mainly as an illustration of our main models and does not represent actually observed migration patterns, it illustrates how the results from the meta-analysis can provide useful insights for the identification of potential hotspots of environmental migration.

Conclusions

Despite an increasing number of studies, the environmental-migration nexus and its underlying mechanisms remain poorly understood. Different theories offer explanations as to why and how environmental change influences migration decisions. Aside from disrupting livelihoods, especially of agricultural households which largely depend on environmental conditions for their income generation [57,59,64], environmental change can influence migration through several other channels. Urbanization and internal migration due to environmental stress can result in increased pressures on the labor market and trigger outmigration [24,32,43]. Conflicts play an important role, not only as a moderator, but also as a potential mediator of environmental effects [21,26,50,61,62]. Environmental conditions also have immediate effects on health and productivity[65,66], which may further contribute to increasing human mobility [67–70].

The relationship between environmental factors and migration is not deterministic and unique across countries and over time, as the heterogeneity of the findings for different economic and sociopolitical contexts suggests. Environmental conditions alone are rarely the only driver, but one of many that influence migration. Different forms of hazards have differential impacts on livelihoods and consequently can both amplify or suppress migration [45,71]. Gaining a more systematic understanding of the underlying causes of this heterogeneity should be a primary focus of future empirical research. As shown in our analysis, economic resources play an important role in moderating the environment-migration nexus. Better understanding of the causes and consequences of immobility and non-migration under environmental stress appears particularly important in this regard [72,73].

In many cases, what constitutes an environmental hazard is not clear ex ante, without taking the actual local conditions and potential inter-dependencies into account [12]. Exposure to environmental changes may have very different implications in different areas, depending, for example, on local agricultural conditions [57,60,74], adaptation options [75] and possibilities for income diversification [76–78]. At the same time, environmental factors are not independent, but may be correlated with one another (both across time and space) [53,54,79]. Likewise, environmental effects may be non-linear and only affect migration after reaching a tipping point after which the pressures become too strong for the system to resist or adapt [59,62]. These thresholds are highly context-specific with risk perceptions and adaptation options varying across individuals, households and communities [75]. With few exceptions [33,40], the majority of studies considered in our analysis report linear models, which reflect local linear approximations of more complex non-linear relationships [50].

In the same spirit, there is a need to better understand and conceptualize migration as an adaptation strategy to environmental hazards as well as to define what constitutes successful migration and adaptation for whom [80]. A stronger focus on agency would help identify cultural and psychosocial factors underlying migration decisions beyond the macro-level variables considered in this study [81–83]. Migration is only one of many potential responses to environmental stress and has to be analyzed against the background of other adaptation strategies, which can complement or substitute migration [84-85]. Policy interventions need to explicitly distinguish between involuntary migration as a reaction to typically rapid-onset events and voluntary migration as a proactive adaptation response to diversify livelihood strategies.

Progress in the availability of data and modeling techniques have improved our understanding on the role of environmental drivers for human mobility [10,54]. International migration data are now available for a wide range of countries. At the same time, there has been an increasing number of micro-level studies that explore how environmental drivers affect mobility patterns in selected local areas. Despite these advancements, disaggregated and detailed high frequency and long-term data on migration remain unavailable or incomplete, especially for many low-income countries. There is a need for an integrated perspective which allows for the systematic analysis and comparison of findings from different studies. Our meta-analysis contributes to this aim, as it provides a synthesis of methods and measurements used and offers critical reflections which can serve as a guidance for future studies examining the environment-migration link.

Our findings have important implications for future migration scenarios and policy. Supranational bodies and international organizations emphasize the need for reducing vulnerabilities and building up capacities that allow households to better cope with and adapt to environmental stress. Adaptation may be possible, but will have high costs and requires a concerted strategy to address the multiple dimensions of vulnerability [67,86–88]. Given the expected adverse consequences of climate change in many regions of the world, environmental migration may become more prevalent in the future for certain countries while vulnerable subgroups in the population may not be able to afford to migrate if needed to. Knowledge of the direction and the size of future migration flows accounting for the influences of the geographic, economic and sociopolitical context is thus central for global migration projections and the policy assessment of the consequences of climate change. The relevance of understanding the role of environmental effects is particularly high for such policy initiatives aimed at cross-border displacement and migration as the UNFCCC Task Force on Displacement, the Platform on Disaster Displacement, and the Global Compact for Migration. The results presented in this study can inform evidence-based policies in different fields and raise awareness among governments and policy makers about the implications of changing environmental conditions for migration.

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Methods

Meta-analytic methods

Meta-analytical methods systematically synthesize the evidence from quantitative studies and allow for a unified and comprehensive interpretation of existing findings while controlling for between-study heterogeneities [89–91]. In an extensive and systematic search of the literature (Supplementary Section A), we identify quantitative studies which statistically analyze the relationship between environmental factors and migration. We focus solely on macro-level studies using panel country-level datasets to ensure that estimates are comparable and that, to the extent that unobserved heterogeneity can be accounted for, causal relations can be inferred. Our approach considers standardized changes in migration on a continuous scale as the main outcome and thus complements existing synthesis studies that consider only the statistical significance and direction of the effects. The latter type of methods faces different challenges in the interpretation of results, which we overcome by standardizing and directly comparing the effect sizes[92,93].

Typically, in the studies considered in our meta-analysis, migration is explained using general linear models of the form:

$$M_{ct} = \alpha + E_{ct}\beta + C_{ct}\gamma + \theta_c + \tau_t + \epsilon_{ct} \tag{1}$$

with the outcome variable M_{ct} representing migration in country *c* at time *t* (usually measured in decadal intervals). Most studies consider net migration rates (or a transformation of this measure) as the main outcome. E_{ct} is a vector containing the environmental factor(s) of interest such as the variability of precipitation, the temperature level or the occurrence of a rapid-onset disaster. C_{ct} is a vector of control variables including information on economic and sociopolitical conditions, θ_c and τ_t represent unobserved country and time period specific characteristics (fixed effects), and ϵ_{ct} is the random error term. A slight variation of the above model are specifications which consider simultaneously characteristics of the origin (push factors) and destination country (pull factors) as determinants of bilateral migration flows (gravity-type models)[94].

Our analysis concentrates on the coefficient vector β, which captures the effect of the changing environmental factor(s) on the migration outcome M_{ct}. The studies exploit variation over time in a longitudinal perspective to derive a credible causal interpretation of the findings. Spatial and temporal autocorrelation, as well as time trends, may however play a role both in the migration drivers and in their responses, and many of the models used in the literature account for these factors. 95.7% of the cases control for time period dummies (time fixed effects) in their models to account for time trends that are common across all countries. Furthermore, the majority of the models considered in our analysis (92.1%) control for location-specific intercepts (spatial fixed effects), e.g. in the form of country dummies, ruling out the possibility that the estimated effects are driven by different average levels in migration and environmental conditions between the cross-sectional units in the dataset. In the supplementary materials, we re-estimated our main meta-regressions excluding studies that do not control for spatial fixed effects (Supplementary Table S4) and time fixed effects (Supplementary Table S5). All results remain fully robust to this sample variation, suggesting that unobserved heterogeneity is not a source of bias in our analysis. In addition, all our meta-regression models control for whether the original studies included spatial and time fixed effects to account for differences in their estimation approach and inferential framework (relying on between-country variation versus within-country variation as a source of information for the estimation).

Standardizing the Coefficients

The studies considered usually estimate the effect of more than one environmental variable in order to compare the influence of different environmental factors on migration. Generally, the estimates are also carried out for different sub-samples of countries. We pool all estimates, considering parameters β_{im} obtained from a particular model (indexed by i) in a given study (indexed by m). In total, we obtain information on 1803 separable effect estimates. These coefficient estimates cannot be directly compared, since the outcome and environmental variables used in each model (even within the same paper) are mostly defined and measured differently.

To harmonize the estimated coefficients, we used summary statistics on the distribution of the environmental and migration variables considered, which we either retrieved from summary statistics tables in the original studies, by contacting the authors, or from our own calculation based on the original data sources. In particular, we obtained the information on standard deviations of the key variables ($\sigma_{M,im}, \sigma_{E,im}$), which allowed us to ex-post transform the estimated linear coefficients into (beta) standardized effect sizes. The calculated standardized coefficients measure a standard deviation change in the migration outcome with one standard deviation change in the environmental factor:

$$\beta_{stan,\,im} = \beta_{im}\frac{\sigma_{E,\,im}}{\sigma_{M,\,im}}. \tag{2}$$

Since the estimated coefficients rely on different sample sizes and specifications, and have different sampling variability, the precision of the estimates differs across the studies. To account for differences in precision in our synthesis, the study coefficients are weighted using the inverse of the estimated variance to down-weight the influence of highly uncertain estimates [49,50,90]. For few cases (k=20, 2 studies), information on the distribution of the estimated coefficients (standard errors, t-statistics) was missing or incomplete. In this case, we imputed the standard errors to allow for the inclusion of these cases in our analysis (more detailed information on the standardization and pooling of the estimated coefficients is provided in Supplementary Section B). For a few outlier cases (k=2, n=2 studies), the estimated standardized effects were very large ($\beta_{stan,\,im} > 10$). As these cases were usually also estimated with lower precision, the weighting effectively reduced their influence on our estimation so we can include them in our meta-sample. All our results remain robust when excluding the imputed and outlier cases from the analysis.

Specification of the Meta-Regressions

Apart from analyzing the overall distribution of the standardized effect sizes using precision-weighted random effects meta-regression models (PM estimator) [48], we assess how the particular characteristics of the studies explain the observed differences in the strength and direction of the relationships estimated. For this, the estimates of the standardized effects ($\beta_{stan,im}$) are regressed on different covariates D_{im} related to characteristics of the original studies,

$$\beta_{stan,im} = \mu_m + D_{im}\delta + u_{im} \,. \qquad (3)$$

Using this specification (Table 1, Model 1-5), we assess whether the size of the standardized effects depends on the characteristics of the environmental factors considered in the study (e.g. level change and variability/anomalies of precipitation and temperature, rapid-onset events), type of migration (internal vs. international migration with different destinations), and the composition of the sample used (share of countries by region and other characteristics). Further evidence on the role of environmental interactions, the impact of environmental change in destination regions, and the influence of further characteristics (e.g. estimation method, publication status) is presented in extended models in Supplementary Section F.

In addition, we also estimate meta-regressions considering the absolute size of the standardized coefficients in order to test whether specification choices influence the strength of the effects (Supplementary Table S14). Unless otherwise stated, all models are estimated including study-specific intercepts (fixed effects). They thus exploit the variability observed within the results of a given original study. Such a specification allows us to control for systematic differences between the studies which are not captured by the covariates and implies an underlying assumption that, after controlling for their particular characteristics, the studies may not share a common true effect.

Exploring Mechanisms

We explore the role of different potential mechanisms underlying the relationship between environmental change and migration by exploiting differences in the structure of the model specifications and the inclusion of potential mediating factors as controls. If a particular factor is indeed a mediating channel, controlling for it should reduce the environmental effect on migration compared to a model which does not control for the mediator. Accounting for the effect of the mediator, the remaining environmental effect on migration should only capture the direct effect on migration, net of the indirect effect running through the mediator (Supplementary Figure S3).

In the original studies, the inclusion of mediating variables, which may themselves be affected by the environment, can potentially bias the estimates of interest, since the mediator absorbs part of the total environmental effect on migration [50,62]. In our analysis, we make use of this so-called ‘bad control’ problem by assessing whether the size of the standardized environmental effect estimates differs depending on whether or not a potential mediator was included in the original specification [95]. We consider income and conflict as potential mediators, since they have been frequently cited as important mechanisms in the environmental-migration literature [45,59–61,96–98] and are commonly used as control variables in the model specifications. 50.5% of the considered study cases control for some income proxy, and 32.4% control for some type of conflict measured at the same time as or after the environmental event.

Accounting for Sample Composition

Most of the quantitative country-level studies assess the relationship between environmental factors and migration for different country samples in order to address heterogeneity in the effect size and to highlight the role of context in shaping migration responses to environmental shocks [51]. For example, some studies split their analytical sample into agriculturally dependent and non-dependent countries [32,43] or low, middle and high-income countries [19]. Other studies employ interactions between environmental variables and country context covariates to obtain separate environmental effect estimates by country characteristics. We treat the main and interaction effects, which are calculated by interacting the environmental variable with a country classifier (e.g. agriculturally dependent), as a separate coefficient estimate to obtain more comparable data on effect heterogeneities (see Supplementary Section B).

In total, the studies considered and their models rely on 121 different country subsamples. We derive information about the country composition in each of these samples in order to test whether the estimates of the environmental effects are sensitive to the subset of countries included in the sample. Using the classification of the World Development Indicators dataset [99], the countries in each sample are assigned to world regions (Europe and North America; Asia; Sub-Saharan Africa; Latin America and the Caribbean, Middle East and North Africa), income level classifications (low-income; lower-middle-income; upper-middle-income; and high-income) and are categorized as being an OECD member country or not and as being agriculturally dependent or not. We classify the countries where agricultural share to GDP is larger than 20% as an agricultural dependent country, which comprises about a fourth of all countries considered. We acknowledge that quantifying agricultural dependency is complex and our measure, which is based on a simple macroeconomic indicator, hence serves only as one of many possible proxies.

For the country classification, the year 2000 is used as period of reference. In addition, we determine whether countries experience an episode of conflict between 1960 and 2000, which are the mode start and end year of the panels employed in the considered empirical literature. Conflict data are obtained from the Major Episodes of Political Violence (MEPV) database provided by the Center for Systemic Peace [100]. A conflict is defined as a recurring violent event (at least 5 years in the specified period) with fatalities in the country. We use alternative conflict definitions as well as data from the Uppsala Conflict Database (UCDP) [101,102] to assess the robustness of our results (Supplementary Table S10).

Based on the distribution of countries in the samples, we calculate the share of countries belonging to different classifications for each study case in our sample (Extended Data, Figure 3, Panel A). Given differences in country/regional focus of each publication, the share of countries in each sample differs substantially (Extended Data, Figure 3, Panel B). This allows us to test for the effects of contextual factors in moderating environmental migration. Importantly, the compositional measures are objectively comparable across studies based on our classifications and hence do not rely on any information or operationalization used in the studies.

Mapping Hotspots of Environmental Migration

We use the estimates from our meta-regressions to graphically identify hotspots of environmental migration worldwide. For this exercise, we construct a country-level data set with 221 countries containing information on country-level exposure to environmental change between 1960 and 2000, as well as the economic and sociopolitical characteristics (i.e. income status, agricultural dependence, and conflict) used to construct the compositional shares for the main models in Table 1 (Model 5). In this part of our analysis, we combine our estimates for differential migration responses with the observed environmental change in a country in the past decades.

As a first step, based on a simplified version of our main model (Supplementary Table S15), we obtain the expected migration response for each country in the dataset. The estimated migration response, which is a function of the country's characteristics (e.g. low-income, agriculturally dependent, no-conflict), can be interpreted as an expected change in migration in standard deviations for a one standard deviation change in the country's environmental conditions. As a second step, we construct a measure reflecting the environmental change in each of the 221 countries for the period 1960-2000. The measure is based on three commonly used indicators to capture environmental hazards: anomalies in precipitation, anomalies in temperature, and the share of the population affected by disasters. The first two indicators are based on the data from the Climatic Research Unit (CRU) at the University of East Anglia (time series TS3.26) [103], the third one is based on the Emergency Events Database (EM-DAT) data[104]. In order to mirror the approach used for the standardization of the coefficients, the final measure is expressed in standard deviations of the world distribution.

Multiplying the observed environmental change measure with the estimated migration response, we predict the level of environmental migration for each country in our sample. This allows us to identify countries or regions in which environmental change may have led to a stronger migration response. The derived estimates are only predictions which serve as illustration of our model results. They do not reflect the actually observed environmentally-induced migration or projections of migration outcomes in the future (more detailed information on the construction of the country data and the procedures are provided in Supplementary Section G).

Publication Bias

We account for publication bias in our analysis in different ways [50,62]. First, in the literature screening and selection phase, we rigorously search for both academic and grey literature and include the findings from non-published studies, thus eliminating potential editorial selection biases. Five of the studies included (16.6%) were unpublished at the time of our analysis. Furthermore, our main meta-regressions control for study-specific intercepts to rule out any systematic differences between published and unpublished work. We explicitly test for publication effects in additional estimations (Supplementary Section H), showing that our key findings are not sensitive to including further variables related to the publication process in our meta-regression models.

Limitations of the Meta-Analytical Approach

While the goal of our meta-analysis is to provide a comprehensive overview and synthesis of the literature, it comes with certain limitations, which are important for how our results should be interpreted. The main purpose of our analysis is explorative aiming to provide a synthesis of the country-level literature on environmental drivers of migration. Our results reveal interesting patterns and relationships, but do not allow for deterministic causal conclusions.

First, to ensure that estimates from individual studies are sufficiently comparable and can be standardized, we restrict our analysis to macro-level studies, which use country-level data. This necessary design choice comes at the cost of a loss in precision and contextualization of the effects analyzed. The greater level of aggregation, on the other hand, allows us to investigate how different contexts influence the environment-migration relationship [22].

Second, the scope of our analysis depends on the focus of the original studies. Due to data limitations, for instance, we cannot distinguish between the differential impact of environmental shocks of different intensity and thus assess potentially non-linear environmental effects on migration. The data used in the studies considered rely mostly on official country-level migration statistics, which exclude irregular forms of migration and consequently may underestimate the actual migration flows. In addition, while official migration data is provided at a country-level, environmental impacts, like conflict, can affect populations across borders potentially leading to a spatial mismatch between the considered environmental and migration measures.

At the same time, given that macro-level cross-national data on internal migration were not available until recently[105], a comprehensive assessment of the environmental impact on internal migration across countries is challenging. Most existing studies rely on urbanization as a proxy for internal migration, which is likely to underestimate the intensity of environmental migration because the urbanization indicator does not capture all possible forms of internal migration and displacement. To gain a complete picture, data collected at a more granular level of geographical aggregation, which allows for the inclusion of destinations of short and temporary migration moves, would be necessary. Recent efforts to collect internal migration data for more than 130 countries based on various sources including population censuses, population registers and administrative collections would now facilitate cross-country analysis of environmentally-induced internal migration[105,106].

Third, our results do not provide direct implications regarding the vulnerability of the affected households. Depending on adaptation options, households may not be able to use migration as a coping strategy to changing environmental conditions. A further exploration of the topic of immobility, although very important, is not possible in the context of the present analysis. While we consider important macro drivers of heterogeneity, we are unable to explore patterns and differential responses on smaller scale, such as differences by gender [107]. Despite these limitations, our findings systematize the knowledge contained in the macro literature on environmental migration and help to gain an informed understanding of the existing evidence on the underlying mechanisms and processes shaping migration responses to environmental change in different contexts.

Data Availability

The meta-data and country-level data generated during and/or analyzed during the current study are available in the Harvard Dataverse repository[109], https://dataverse.harvard.edu/dataverse/Meta-Analysis_EnvironmentalMigration.

Code Availability

The data analysis was carried out in R[108]. The complete codes used to generate and visualize the results reported in this study are available in the Harvard Dataverse repository[109], https://dataverse.harvard.edu/dataverse/Meta-Analysis_EnvironmentalMigration. All used packages are acknowledged and cited in the source code file.

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Conflicts of Interest

The authors declare no conflict of interest.

Authors' Contribution

R.H. and R.M. conceived the project and designed research; A.D., R.H. and R.M. collected and reviewed the literature; J.C.C. helped with statistical techniques and procedures; A.D., R.H. and J.P. collected, compiled and analysed data; J.C.C., A.D., R.H., R.M. and J.P. interpreted the results and wrote the manuscript.

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