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Climate change and rural–urban migration in the Brazilian Northeast region

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Abstract Climate change and its potentially harmful effects on agricultural production, income, and subsistence might change the incentive and capability of the population to remain in rural areas or to migrate to urban locations. Using census micro-data in combination with high-resolution climate information, we explore the impacts of climate change on rural–urban migration in the Brazilian Northeast region. Results from a gravity model estimation reveal that the climate–migration relationship depends on the agricultural income levels of rural origin areas and the educational attainment of the rural population. Specifically, our results indicate that the intensification of climate adversities may have contributed to boosting migration from rural areas with lower socioeconomic vulnerability. In contrast, in the most deprived rural areas, harmful climate effects may have resulted in the reduction of this type of migration flow. Nevertheless, our findings suggest that education might attenuate the suppressing effects of adverse climate conditions on migration in highly vulnerable rural areas, suggesting a viable pathway to overcome mobility constraints. Our findings emphasize the complexity of climate–migration linkages and conclude that the debate on climate change and migration should no longer consider that climate change invariably results in migration, but also should investigate who is able to implement and take advantage of migration as an adaptation strategy. Policies to address issues related to climate-induced migration must focus on both facilitating migration and assisting vulnerable segments of the population who remain in place, as the less-educated rural population whose livelihoods depend on the agricultural activity.

Keywords Climate change · Rural–urban migration · Brazil · Adaptation · Vulnerability · Differential impacts

Introduction

Climate change and its potential effects are widely recognized as one of the greatest challenges to be faced in the twenty-first century (Intergovernmental Panel on Climate Change—IPCC 2014). Adverse climate conditions are viewed to have more significant

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negative effects on the agricultural sector, which is directly reliant on environmental and climatic conditions (IPCC 2014). Rural households engaged in agriculture activities in developing countries are among the most vulnerable to climate shocks since they strongly depend on the agriculture production for income generation and subsistence. Furthermore, they often lack sufficient adaptive capacity to cope with climate change impacts (IPCC 2014; Nawrotzki et al. 2015; Barbier and Hochard 2018; Tol 2018; Cattaneo et al. 2019).

Insecurity related to agricultural production within a climate change scenario is likely to make rural households to respond in ways that are not yet well understood. In the context of interactions between humans and the natural environment, migration has been identified as a potential adaptation response to adverse climate effects (Nawrotzki et al. 2015; Viswanathan and Kumar 2015; Thiede et al. 2016; Cai et al. 2016; Mastrorillo et al. 2016; Bohra-Mishra et al. 2017; Nawrotzki and Bakhtsiyarava 2017; Falco et al. 2019). Compelling evidence has suggested that because shifts in average and variability of temperature and rainfall levels lead to a decline in agricultural income, employment opportunities, or food security, the climate–migration nexus is mostly intermediated by the agricultural channel (Cai et al. 2016; Cattaneo and Peri 2016; Falco et al. 2019).

For the last decade, there has been an increasing interest in the relationship between climate change and population mobility in the scientific debate. Several studies have explored the climate effects on international and internal mobility. However, despite the rather large body of literate on the subject, no clear consensus on the adverse impact of climatic conditions has been reached yet (Falco et al. 2019). Many studies suggest that environmental stressors strongly induce migration (Thiede et al. 2016; Cai et al. 2016; Mastrorillo et al. 2016; Falco et al. 2019), while others show low or no effect of climatic shocks on migration (Mueller et al. 2014; Beine and Parsons 2015). The literature also shows opposite effects, namely situations resulting in a reduction in migration flows due to adverse climate conditions (Cattaneo and Peri 2016; Nawrotzki and Bakhtsiyarava 2017; Nawrotzki and DeWaard 2018). The mixed evidence for migration in consequence of climate change is partially attributed to data, approaches, and methodological differences among the existing studies. Additionally, interactions between climate-induced environmental changes and migration are complex and highly context-specific, mediated not only by the type and severity of climate drivers but also by the heterogeneity and vulnerability of affected societies (Coniglio and Pesce 2015; Cattaneo and Peri 2016; Nawrotzki and Bakhtsiyarava 2017; Nawrotzki and DeWaard 2018; Falco et al. 2019).

There are still significant gaps in our understanding of the complicated relationship between climate change and migration (Cattaneo et al. 2019). Furthermore, it remains unclear whether and how adverse climate conditions impact migration responses in many parts of the world. In order to understand these complex interactions, case studies considering specific regional conditions are required to deliver a clear picture of the effects of climate change on population displacement. Against this background, in this paper we analyze the impacts of climate change on the Brazilian Northeast region over the last decades of the twentieth century considering the heterogeneities and complexities of the study area and its population. Motivated by the strong consensus in the scientific literature that climate and migration are connected by the agricultural pathway, we focus on the rural–urban migration type.

We base our study in the Brazilian Northeast region for several reasons. Firstly, this region is heavily dependent on agricultural production, and subsistence and small-scale farming are the primary sources of income in rural areas (Brazilian Institute of Geography and Statistics—IBGE 2018). Secondly, this region has a high temporal and spatial irregularity of precipitation and great potential for water evaporation due to high temperatures. The average annual temperature has shown an increasing trend, and the number of rainy days and the amount of precipitation have decreased over the years (Sheffield et al. 2006). The Brazilian Panel on Climate Change (PBMC 2014) estimates that, by the end of the century, the average temperature will increase between 3.5 and 4.5 °C, and the amount of precipitation will reduce by around 40–50% in the study area. The intensification of adverse climate conditions may result in a decrease in subsistence agricultural production, and consequently, an increase in food insecurity and socioeconomic vulnerability of rural households. Lastly, despite being the region with the most substantial proportion of the rural population in Brazil, the Northeast region has the smallest share of agricultural Gross Domestic Product (GDP), which shows the relative poverty of its rural areas compared to other regions of the country (IBGE 2018). Altogether, these factors imply that rural households are especially vulnerable to climate change. Therefore, the Brazilian Northeast region provides a unique opportunity to study the rural–urban migration response in a regional context.

The analysis of climate-induced migration at the local Brazilian context is fundamental. Despite there is a growing academic literature dealing with the impacts of climate change on the livelihood and mobility of the population around the globe, studies on the climate–migration interaction in Brazil, especially at a regional scale, are still limited (Barbieri et al. 2010; Assunção and Chein 2016; Delazeri et al. 2018). A better understanding of the mechanisms in which climate changes affect rural–urban migration flows is a fundamental issue for the effective formulation of well-targeted public policies, particularly in a context of increasingly intense and frequent climatic stresses. Besides, our study contributes to the existing literature by investigating rural–urban migration on a finer spatial scale, taking into account a particular regional context and exploring the climate–migration sensitivity to demographic and socioeconomic characteristics.

The remainder of this paper proceeds as follows. In the next section, we provide our theoretical framework. Then, we present the study area, the data source and database construction, as well as the empirical methods. Later, we present our results, followed by relevant discussions. Lastly, we provide the concluding remarks of our work and policy implications.

Theoretical framework

Differential vulnerability and heterogeneity of migration responses

The impacts of climate change go beyond the biophysical dimension and relate to the social factors underlying vulnerability (Kelly and Adger 2000; Otto et al. 2017). The term vulnerability is commonly defined in climate literature as the susceptibility to be adversely affected by climate change and the capacity to cope and adapt to it (IPCC 2014). Therefore, a broad set of factors, including socioeconomic, demographic, and institutional conditions, determine vulnerability and exposure to climate-related risks, as well as the ability to respond to and recover from the impacts of hazards (Cutter and Finch 2008; Oppenheimer et al. 2014). In this sense, social vulnerability can be differentiated along with personal- and locational-specific factors (Otto et al. 2017).

As stated previously, early contributions to the climate–migration literature have shown conflicting results on the impacts of the first on the latter. While some studies emphasize that adverse climate effects push people into migration (Thiede et al. 2016; Cai et al. 2016; Mastrorillo et al. 2016; Falco et al. 2019), others suggest the constraining effect of climate change on population mobility (Cattaneo and Peri 2016; Nawrotzki and Bakhtsiyarava 2017; Nawrotzki and DeWaard 2018). Despite the diverging results from quantitative estimates on climate-related migration possibly emerge from methodological differences, the asymmetric migration response also relates to the differential vulnerability of places and populations to climate change. Migration studies have established that financial, social, and human capital are important determinants of migration (Cattaneo and Peri 2016; Nawrotzki and Bakhtsiyarava 2017; Nawrotzki and DeWaard 2018), which can partially justify the heterogeneous climate–migration responses found in the literature.

Heterogeneity of migration concerning wealth and education

In rainfed agricultural areas, where a large proportion of a population relies upon agriculture as a primary source of livelihood, climate stress is particularly critical. A firmly established hypothesis in research focused on coping strategies in cases of economic losses related to climatic stressors is that there will be an increase in outmigration (Grace et al. 2018). Households employ migration as a strategy to insure themselves against risks from future climate events and to diversify income streams (Massey et al. 1998). Repeated climate shocks can push affected groups into a persistent state of poverty (Otto et al. 2017). By impoverishing the rural population and worsening their income prospective, adverse climate conditions may shape migration in different ways.

Climate–migration literature has shown that the income level of the affected population is a detrimental factor for heterogeneous migration responses.

Some studies emphasize that low-income individuals are typically the most vulnerable to climate change and who are forced to move as an adaptation strategy (Mastrorillo et al. 2016; Falco et al. 2019). However, there is sometimes a trade-off between the incentives to move, and the resources needed to do so (Cattaneo et al. 2019). In low-income regions, many households in rural communities are heavily dependent on agricultural production for income and self-consumption, and climate change may undermine their already limited financial capital, further reducing their ability to use migration as an adaptation strategy (Cattaneo and Peri 2016). Thus, a strand of the recent literature suggests that liquidity constraints play an essential role in the complex relationship between climate change and migration, indicating that as moving requires resources, the more resourceful are more likely to move (Cattaneo and Peri 2016; Beine and Parsons 2017; Nawrotzki and Bakhtsiyarava 2017; Nawrotzki and DeWaard 2018).

Apart from income status, past research identifies an underlying debate about the importance of demographic characteristics on climate–migration heterogeneous responses (Mastrorillo et al. 2016; Thiede et al. 2016; Bohra-Mishra et al. 2017). Different patterns of population mobility related to climate change may reflect individual differences regarding their perception and ability to respond to climate change, as well as the availability of resources for the adoption of adaptive strategies. Some studies indicate that education strongly matters for individuals' decision to migrate (Drabo and Mbaye 2014; Koubi et al. 2016; Bohra-Mishra et al. 2017; Bernzen et al. 2019).

In the context of rural–urban migration, the capacity to espouse in situ adaptation mechanisms that mitigate the adverse effects of climate change on agricultural production and income may be related directly to the educational level of potential migrants. Higher education levels can contribute to the implementation of adaptive measures that result in non-reduction in agricultural production and, consequently, a reduction in the need to migrate due to climate change. Nevertheless, these individuals remain capable of migrating even in situations of decreasing agricultural production and income caused by adverse climate impacts. Additionally, well-educated individuals might be more likely to opt for migration. Their education level should allow them to find employment at the destination place more easily, and their potential gains from migration might be higher (Koubi et al. 2016; Bohra-Mishra et al. 2017).

Although the migration response to climate change is likely to vary across socioeconomic and demographic subgroups, scientific literature exploring the climate–migration sensitivity by heterogeneous subgroups is limited. Among studies that compared the different climate–migration responses by income subgroups, we mention the work of Cattaneo and Peri (2016), Beine and Parsons (2017), Nawrotzki and Bakhtsiyarava (2017), Nawrotzki and DeWaard (2018), and Falco et al. 2019. Except for the analysis conducted by Nawrotzki and DeWaard (2018), those studies, however, have mostly investigated the relationship between climate change and migration in the international dimension. As for education, as far as we know, the only studies that have examined the climate–migration sensitivity by education level subgroups are the ones conducted by Drabo and Mbaye (2014) and Bohra-Mishra et al. (2017).

While climate–migration has been researched actively across the globe in different settings and over different time-periods, there is a lack of evidence and understanding of the interactions between climate change and migration in a finer spatial scale and considering socioeconomic and demographic dimensions. Moreover, inconsistent results found in the related literature support the importance of further empirical research. Considering the high level of exposure and vulnerability to climate change in the Brazilian Northeast region, as well as the evidence of climate–migration responses in other parts of the world, we attempt to fill the literature gap by examining the sensitivity of rural–urban migration flows on climate change by income and education level subgroups. Methodologically, we exploit bilateral rural–urban migration flows for the years 1991 and 2000 and use a gravity migration model. Understanding how rural–urban migration flows, conditioned by specific aspects, respond to climate change is a requirement for the development of public policies and regional planning that considers the specificities of different population groups.

Consistent with the discussed theory and the literature-based evidence, our quantitative analysis is guided by two research questions: (1) Does the climate–migration relationship in the Brazilian Northeast region depend on the agricultural income level of the rural origin areas? (2) Do demographic characteristics, such as the education level of the rural population, change the migration response to climate change? We hypothesize that individuals belonging to higher socioeconomic status, such as residents of wealthier agricultural areas and more educated individuals, are more likely to migrate to urban areas in response to adverse climate conditions than those from lower socioeconomic status.

Methodological framework

Study area

Our study focuses on the Brazilian Northeast region (Fig. 1). The study area has a territorial size of 1,554,257 km^2, which corresponds to approximately 18.3% of the Brazilian territory (8,514,876 km^2). The total population of the region is 53.07 million, of which 14.25 million (26.86%) live in rural areas (IBGE 2010).

For the analysis in our study area, both the migration, agricultural, and climate context are essential. Brazil has an established history of internal migration. According to the 1991 and 2000 Demographic Census data, the rural–urban migration type represented approximately 13.3% of the national internal migration. Estimates indicate that over the last two decades of the twentieth century, the Brazilian Northeast region accounted for 40.5% of the total national rural–urban populational displacements. However, despite the significant rural outmigration from the Northeast region, we also highlight the high participation of this region in the distribution of the Brazilian rural population over the same period. Specifically, in the last decade of the past century (1991–2000), while this region accounted for approximately 28% of the total Brazilian population, it was the least urbanized region of the country, concentrating almost half of the country's rural population (46.4%) (IBGE 2000). Despite the significant participation of the study region in rural–urban migration flows in Brazil, its high participation in the distribution of the national rural population reflects the importance of the region in retaining this population.

The region is quite vulnerable to the effects of climate change, as it is characterized by high annual averages of temperature and low and irregular annual averages of precipitation. Figure 2 depicts the intensification of adverse climate conditions over the last 30 years of the twentieth century. Charts (a), (b), and (c) show the increasing trend of reduction in the precipitation amount, and charts (d), (e), and (f) show

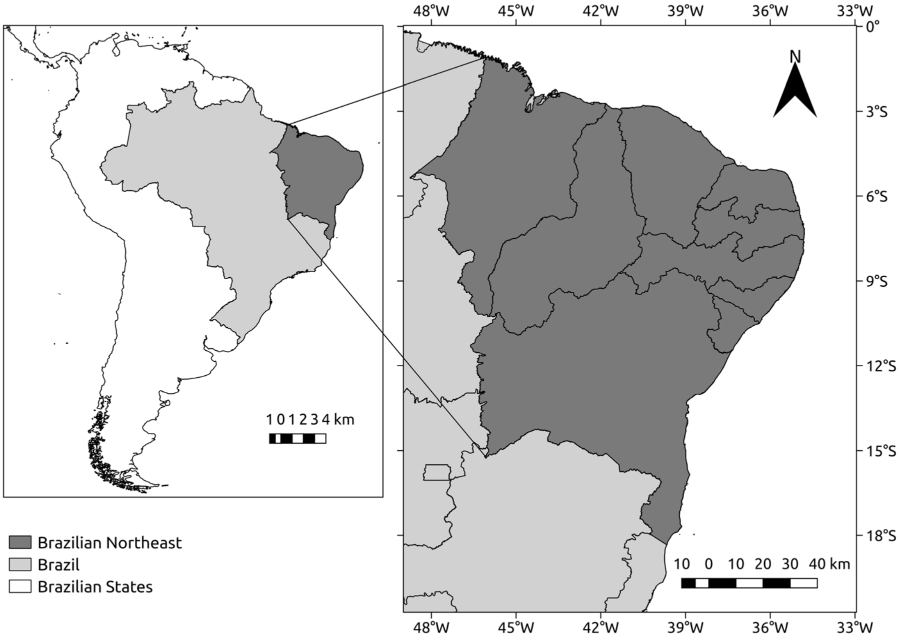

Fig. 1 Location of the Brazilian Northeast region

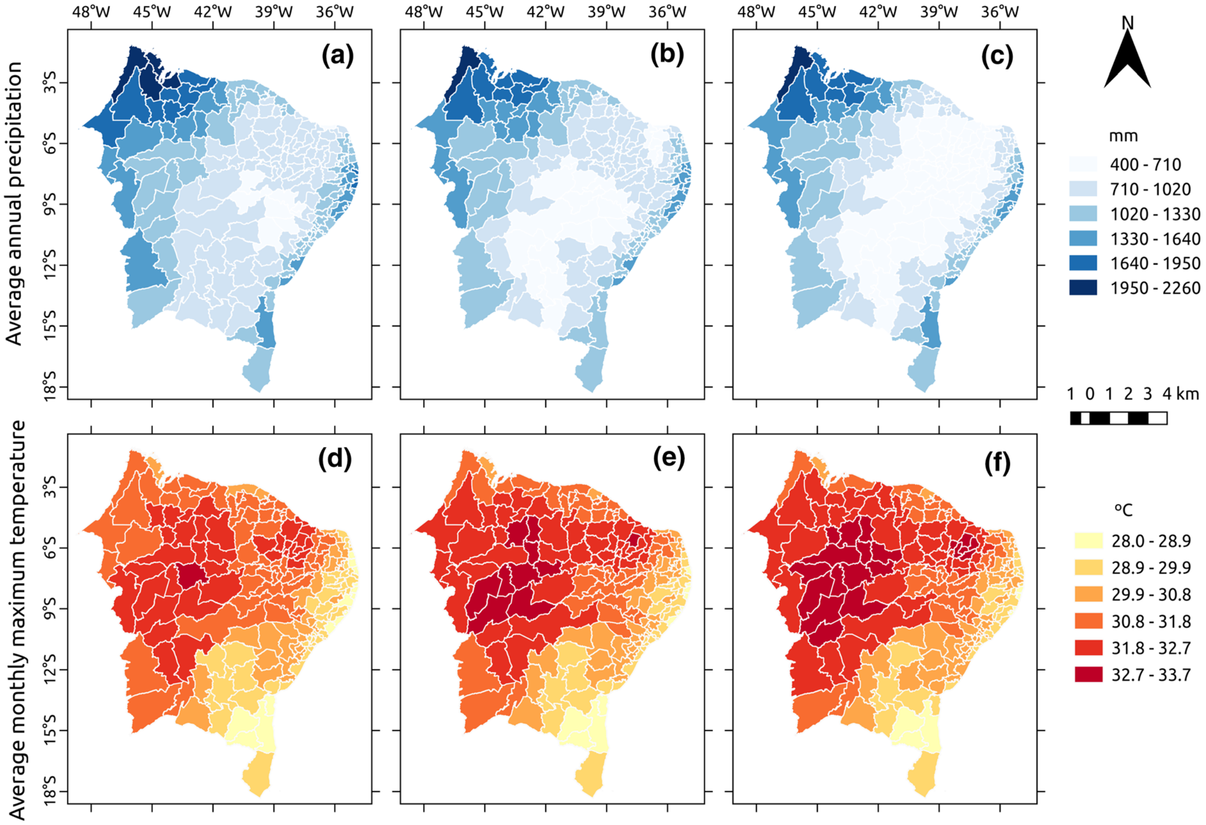

Fig. 2 Precipitation (mm) and maximum temperature (°C) changes in the Brazilian Northeast region over the decades 1971–1980, 1981–1990 e 1991–2000

the increasing trend of average maximum temperature over the period.

The worsening of the climatic conditions of the Brazilian Northeast region displays particular relevance since 69.8% of the rural population relies on agriculture as their main activity (IBGE 2010). Although the study region accounted for almost half of the national rural population, between 1980 and 2000 this region contributed to only a quarter of the total national agricultural GDP (IBGE 2018). These numbers indicate the relative poverty of the rural areas of the region compared to other regions of the country. The low performance of the regional agricultural sector is attributed partially to the low levels of regional rural infrastructure. Over the last two decades of the past century, only a small portion of farms in the region implemented irrigation techniques (approximately 4%), making the rural households highly dependent on the amount and frequency of precipitation (Da Cunha et al. 2015a, b; Herwehe and Scott 2017; Vieira et al. 2020). In addition to the low technological availably to deal with the direct climate effects on agricultural production, rural workers also had low access to technical guidance over the same period, which was barely five times lower than the national average (Cunha et al. 2018; Hagel et al. 2019).

Data on rural outmigration, climate, and agricultural productivity in the region may indicate that the effects of climate change on agricultural production have negatively impacted the livelihood and income generation of this population and, consequently, the regional rural population distribution. While climatic adversities can be highlighted as one of the main factors that accentuated social problems and that acted as push-forces from the rural areas of the Brazilian Northeast region, these adversities may also have contributed to the maintenance of part of the population in rural areas. Altogether, this data reinforces the need for climate–migration research in this region.

Data and measurement

Migration data comes from the 1991 and 2000 Demographic Census (IBGE 1991, 2000), which provide individual responses to a query of the location of residence five years before each survey. Using this information, we compared the previous and current locations of residence to classify an individual as migrant or non-migrant. Since we are particularly interested in rural–urban migration, we defined the migrant as the resident of the urban area of a municipality that five years before the date of each Demographic Census survey was living in the rural area of the same or different municipality. It is important to note that although a more recent Demographic Census was carried out in 2010, this Census did not investigate migration in the rural–urban dimension. Because of that, the analysis period ends in the year 2000.

For this study, we selected the 187 micro-regions of the Brazilian Northeast region as rural origin areas. As for urban destination places, we selected 137 meso-regions of Brazil. Micro-region is defined as a grouping of neighboring municipalities based on economic and social similarities. Similarly, meso-region is a territorial unit with homogeneous physical, economic, and social characteristics, which results from micro-regions grouping. We then used the individual migration data at the municipality level to generate aggregated rural origin (at micro-region level) to urban destination (at meso-region level) migration flows. Following prior research (Nawrotzki et al. 2015; Mastrorillo et al. 2016; Nawrotzki and DeWaard 2018; Falco et al. 2019), the sample includes only individuals aged 20–59 years old at the time of each Census.

For climate variables, we have collected gridded daily average maximum temperature and total precipitation data from 1970 to 2000 from the Meteorological Forcing Dataset developed by the Terrestrial Hydrology Research Group (THRG) (Sheffield et al. 2006) at a 1.0° spatial resolution. To capture long-term cumulative exposure to climate changes, we use positive maximum temperature and negative precipitation mean anomalies. Anomalies are calculated as the deviations of micro-regions' annual mean from their long-run mean (1970–2000), divided by the corresponding long-run standard deviation. Following prior research (Beine and Parsons 2015; Mastrorillo et al. 2016; Nawrotzki and DeWaard 2018), to evaluate the effect of heat extremes, we replaced negative values with zero for positive maximum temperature anomalies. Similarly, to evaluate the effect of negative extremes in rainfall, we replaced positive values with zero for negative precipitation anomalies.

Agronomic research shows that the concentration of adverse climate conditions in a short time window may be more detrimental for agricultural production than the long-run cumulative exposure (Lobell et al. 2013; Schlenker and Roberts 2009). As such, we computed two climate measures reflecting the frequency of climate extremes of precipitation and temperature. These indices correspond to the number of days in a year in which precipitation amount was below 1 millimeter (mm) and the number of days in a year in which maximum temperature was above the 90th percentile of the base period (1970–2000) (Alexander et al. 2006).

The adverse effects of climate change on agricultural production may not be immediate, as the decision to migrate may not occur immediately after the perception of these effects. Moreover, due to the existence of costs associated with geographical mobility, migration is delayed until alternative adaptation strategies are either not feasible or no longer available (Coniglio and Pesce 2015; Nawrotzki et al. 2015; Thiede et al. 2016). Thus, consistently with previous research (Mastrorillo et al. 2016; Nawrotzki and Bakhtsiyarava 2017), we used the averages of climate variables for the period between 1 and 5 years before each demographic census year, which directly corresponds to the time window during which rural outmigration occurred.

Moreover, we included some key control variables based on geographic and sociodemographic factors. As for geographic factor, we include the geographical distance, in kilometers (km), between the centroids of the origin and destination locations, as well as an indicator of origin–destination contiguity, as proxies for migration costs. The choice of covariates is based on the previous literature that employs gravity models to estimate bilateral migration flows in the context of climate change (Coniglio and Pesce 2015; Mastrorillo et al. 2016; Dallmann and Millock 2017; Beine and Parsons 2017; Nawrotzki and DeWaard 2018).

In line with prior research (Mastrorillo et al. 2016; Nawrotzki and DeWaard 2018), to account for sociodemographic factors, our model control for the percentage of males and the percentage of the adult population (aged 17 and older) not married in the rural origin. We also control for educational attainment, including a variable that captures the share of the rural adult population that has completed primary school. As migration data, this additional set of sociodemographic data comes from the 1991 and 2000 Demographic Census (IBGE 1991, 2000).

Classic migration models (Lewis 1954; Harris and Todaro 1970) state that rational individuals migrate in response to economic incentives, such as wage differentials between origin and destination regions. Although some studies have included the wage differential between destination and origin areas as a migration driver (Beine and Parsons 2015; Coniglio and Pesce 2015), others have emphasized the potential endogeneity between climate and income (Dell et al. 2014; Cattaneo and Peri 2016; Dallmann and Millock 2017). As rural income may itself be affected by climate variables, its inclusion to the models may introduce an overcontrolling bias and lead us to faulty conclusions. Therefore, in order to measure the full effect of climate on rural–urban migration, we do not control for wage differentials in our estimation.

Model specification and estimation methods

We base the econometric specification on a random utility model which individuals choose between remaining in their place of residence or migrate to another place to maximize their utility (Beine and Parsons 2015; Coniglio and Pesce 2015; Cai et al. 2016; Mastrorillo et al. 2016; Dallmann and Millock 2017). We model rural–urban migration flows between each origin–destination pair exploiting a panel data structure, and using a gravity model, which recently has emerged as a useful tool for studying climate–migration dynamics at the aggregate level. In order to get a better understanding of climate-driven effects on rural–urban migration in the Brazilian Northeast region, we estimate a gravity model using the Poisson Pseudo Maximum Likelihood method (PPML) (Santos Silva and Tenreyro 2006). The PPML specification can be formally written as follows:

$$\frac{N_{ijt}}{POP_{it}} = \beta_0 + \beta_1 TMP_{i\tau} + \beta_2 PCP_{i\tau} + \beta_3 CONT_{it} + \beta_4 DIST_{ij} + \sum_{k=5}^{7} \beta_k Z_{it} + \psi_i + \phi_{jt} + \varepsilon_{ijt}$$

where N_{ijt}/POP_{it} is the ratio between the number of rural outmigrants from micro-region i to meso-region j and the rural population of i; t = 1991, 2000 are census years; $TMP_{i\tau}$ and $PCP_{i\tau}$ are the climate variables Maximum Temperature and Precipitation, respectively, measured as anomalies or as the frequency of extremes indices over the time intervals τ = 1986–1990, 1995–1999. $CONT_{ij}$ is a dummy variable for origin–destination pairs that share borders or are the same, and $DIST_{ij}$ is the geographic distance between i and j (in km). Z_{it} is a vector of sociodemographic origin controls. In line with prior research (Mastrorillo et al. 2016; Nawrotzki and DeWaard 2018) for climate variables, distance, and sociodemographic controls, we have used the natural logarithm form. The dependent variable (Ni_{jt}/POP_{it}), however, had been kept in levels due to the high proportion of zero migration flows between origin–destination pairs (84.8%) (Santos Silva and Tenreyro 2006).

Since we are interested in assessing the role of climate change as a rural outmigration driver, we do not use any time-varying covariate to capture the influence of urban characteristics on migration (Beine and Parsons 2015; Coniglio and Pesce 2015; Mastrorillo et al. 2016). However, we use time-destination fixed effects (φ_{jt}) to control for the unobserved heterogeneity of destination meso-regions that varies over time. ψ_i are the time-independent origin fixed effects that capture the unobservable spatial heterogeneity across origin micro-regions; ε_{ijt} are error terms clustered at dyadic level (origin–destination); and β_0 is a constant term.

In order to test whether micro-regions with different average rural income have different migration responses to climate change, we have disaggregated the overall sample into different groups according to their levels of agricultural income per capita, averaged for the years 1991 and 2000 (Fig. 3). The use of subsamples differentiated by income levels is consistent with the approach used previously by Cattaneo and Peri (2016); Beine and Parsons (2017); Nawrotzki and Bakhtsiyarava (2017) and Nawrotzki and DeWaard (2018). Group 1 is comprised of the micro-regions belonging to the first quintile, which

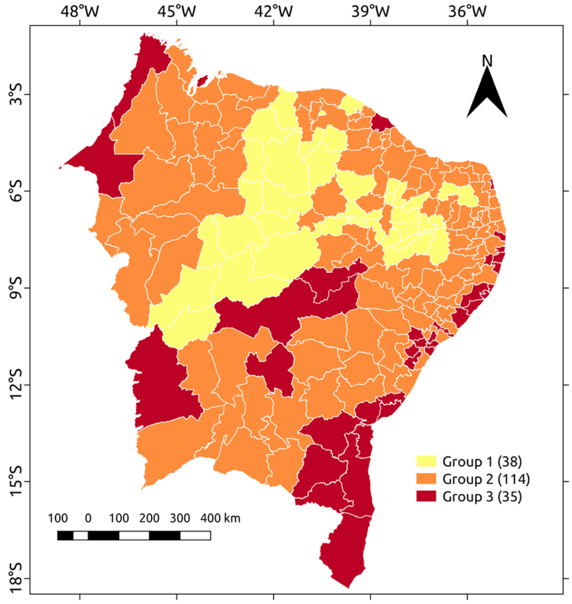

Fig. 3 Groups of micro-regions of the Brazilian Northeast region according to their level of agricultural income per capita

are the ones with the lowest agriculture income levels. Group 3 contains the micro-regions with the lowest financial constraints, comprising the ones belonging to the fifth quintile. Lastly, Group 2 is comprised of the micro-regions belonging to the second, third, and fourth quintiles of the per capita agricultural income distribution.

If financial constraints exist, we would expect the adverse effects of climate change on agricultural production and income to reduce the ability of rural population in micro-regions with the lowest agricultural income levels to cover the costs related to geographical mobility and, thus, hamper rural outmigration. On the other hand, we expect that adverse weather conditions boost rural outmigration in micro-regions with higher agricultural income levels (Cattaneo and Peri 2016; Beine and Parsons 2017).

In order to further improve our understanding of the climate–migration link, we examined the importance of education in the migration decision in response to climate factors. Specifically, we have disaggregated migration flows into five education levels: (a) no education, (b) incomplete or completed primary, (c) incomplete lower secondary, (d) completed lower secondary, and (e) completed upper secondary. If education shapes rural–urban migration in our study area, then we would expect more educated individuals to be more migration-responsive (or less migration-restricted) to changes in climate compared to less educated ones. Summary statistics on migration and climate variables by agricultural income, education groups, and census year can be found in the "Appendix" (see Table 5).

Empirical results

The effect of climate change on rural–urban migration according to micro-regions agricultural income level

Toward answering our first research question (Does the climate–migration relationship in the Brazilian Northeast region depend on the agricultural income level of the rural origin areas?), we apply our model for different subsamples of rural–urban migration flows disaggregated by per capita agricultural income levels. Table 1 summarizes the results relating to the effects of climate change on rural–urban migration, where each of the columns represents one out of three origin micro-regions groups. Panel A details our results concerning climate anomalies, while Panel B presents the average effect of climate change measured as frequency indices of extremes of temperature and precipitation.

Estimation results from Panels A and B of Table 1 show different patterns of the effects of climate variables on rural–urban migration across origin micro-regions groups. The coefficients of these variables suggest that the heterogeneity of the rural population's migratory sensitivity to temperature increases and water shortages is conditioned by the agricultural income level of the micro-regions. The negative and significant coefficients of the climate variables indicate that increases in the number of days with extreme temperatures and with precipitation levels lower than 1 mm may have contributed to the reduction of rural–urban migration rates in micro-regions with the lowest levels of agricultural income (Group 1). Due to the low level of technological infrastructure available in the rural areas of the economically disadvantaged micro-regions and the financial constraints to the implementation of alternative adaptive strategies, adverse climate conditions may have translated into a decline in agricultural income. Consequently, small farmers from these

Table 1 Impacts of climate change on rural–urban migration by groups of micro-regions

	(1)	(2)	(3)
Panel A			
Precipitation negative anomaly	−0.1871	0.0177	−0.1289***
	(0.1214)	(0.0242)	(0.0359)
Maximum temperature positive anomaly	−0.4403*	0.0088	0.1684*
	(0.2570)	(0.0825)	(0.0902)
Distance (km)	−0.7417***	−0.6822***	−0.5914***
	(0.0356)	(0.0217)	(0.0289)
Contiguity	2.5816***	2.5037***	2.3117***
	(0.2124)	(0.1353)	(0.1886)
Share of males (%)	3.2260	−4.7799**	8.9365***
	(2.4345)	(2.2281)	(3.4114)
Share of primary school enrollment (%)	−0.1724*	0.2115	−0.2779**
	(0.1029)	(0.1395)	(0.1394)
Share of unmarried persons (%)	0.5161	1.4793***	1.7496**
	(0.6693)	(0.5109)	(0.7878)
Panel B			
Precipitation < 1 mm (days)	−2.7202***	0.1193	−1.3239*
	(1.0312)	(0.3793)	(0.6875)
Maximum temperature > 90th percentile (days)	−0.8726***	−0.2191*	0.5298**
	(0.2524)	(0.1220)	(0.2185)
Distance (km)	−0.7421***	−0.6823***	−0.5922***
	(0.0355)	(0.0217)	(0.0290)
Contiguity	2.5876***	2.5028***	2.3131***
	(0.2126)	(0.1353)	(0.1884)
Share of males (%)	7.7948***	−4.7458**	8.6042***
	(2.6016)	(2.2454)	(3.3379)
Share of primary school enrollment (%)	−0.0416	0.2075	−0.2785**
	(0.1081)	(0.1391)	(0.1404)
Share of unmarried persons (%)	−0.3517	1.4793***	1.8647**
	(0.6373)	(0.5109)	(0.8078)
Observations (pairs)	7980	28,272	8400

Panel data analysis. PPML estimates. Dependent variable: 5-year rural–urban migration flows. All specifications include constant, time-invariant origin fixed effects and time-varying destination fixed effects. Robust standard errors clustered at dyadic level (*ij*) are reported in parentheses

***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$

micro-regions may have lacked the financial resources to migrate to urban areas, leading to decreased rural outmigration rates.

As we move to the subsample of micro-regions with intermediate per capita agricultural income level (Group 2), the number of statistically significant coefficients of climate variables reduces. Although we still find the significant effect of frequent extremes of temperature on hinder migration, this effect presents a lower magnitude and a lower statistical significance than the one found for Group 1. Despite the statistically significant negative effect of precipitation variables on rural–urban migration for the subsample of micro-regions with the highest income level (Group 3), we found positive and statistically significant effects for temperature variables. This result may indicate that maximum temperature increases, measured both as the anomaly as the frequency of extreme index, may have contributed to boosting rural–urban outmigration. The higher levels of agricultural income in micro-regions with lower financial constraints may have contributed to the adoption of alternative adaptive measures in situ, such as greater access to irrigation and technical assistance, and seeds that are more resistant to climate shocks. As a result, the effects of climate change on agricultural production and income may not have been sufficient reason to hinder migration to urban areas.

Concerning geographic aspects, results show that the proxies for the migration costs are important factors for rural–urban migration. As expected, distance and common borders are, respectively, negatively and positively associated with the size of migration flows. This observation is consistent with the contention that migrants generally prefer to move short distances, given the migration costs. Concerning demographic factors, we find no consistent results about the gender and education composition of rural origin areas. Regarding the marital status, we find that migration increases with the share of unmarried persons in the rural origin areas, which indicates that the costs of migration might be higher for those who have a spouse.

Consistent with our hypothesis, our results are in line with the findings of Cattaneo and Peri (2016), Beine and Parsons (2017), Nawrotzki and Bakhtsiyarava (2017), and Nawrotzki and DeWaard (2018), which also have shown that migratory responses to climate change depend on the financial ability to implement outmigration by the population negatively affected by adverse climate conditions.

The effect of climate change on rural–urban migration according to education level

In order to further improve our understanding of the climate–migration link, we examined the importance of education in the migration response to climate factors. Toward answering our second research question (Do demographic characteristics, such as the education level of the rural population, change the migration response to climate change?), we apply our model for different samples of rural–urban migration flows disaggregated by education levels. Given that we found different migration patterns for micro-regions with different agricultural income levels (Table 1), the analysis of the importance of the educational dimension also considers the income dimension. The estimates with rural–urban migration rates disaggregated by educational levels including climate anomalies and frequency of climate extremes are presented in Tables 2 and 3, respectively. Assuming that the role of sociodemographic controls in the relationship between climate change and rural outmigration is already considered partially when disaggregating rural–urban migration flows by education, such controls were not included in these estimates.

The results presented in Tables 2 and 3 are generally consistent with the results presented in Table 1 regarding the divergent migratory behaviors across micro-regions with different agricultural income levels. Regarding the educational level, the results suggest significant differences among the rural population of the region. For the group of micro-regions with the highest income constraint (Group 1), the effects of frequent climate extreme on restricting migration to urban areas are more intense in low schooling groups and decreases as the educational level rises. These effects are especially noteworthy for the frequency of temperature extremes variable (Table 3), which presents a higher number of negative and statistically significant coefficients.

In low-income rural areas, education can contribute to mitigating the adverse climate effects on agricultural production. Higher levels of education are often translated into better knowledge about cropping techniques, financial credit options, and more resistant seeds, for example. Therefore, education may be a mechanism through which agricultural production decreases due to adverse climate impacts implies a less suppression effect on migration for individuals with higher education levels compared to the less educated ones.

Regarding the group of micro-regions with the lowest financial constraints (Group 3), we mostly find a positive and statistically association between climate variables and rural–urban migration flows, which emerges mainly from the effects of temperature. However, our findings indicate that the effect of climate variables on inducing migration to urban areas is higher among less-educated groups and smaller (or even negative) and not statistically significant among the population of higher educational level. These results may indicate that in micro-regions with higher agricultural income levels, education is an important factor, which shapes migration decisions to urban areas in different ways.

On the one hand, if the rural population of these micro-regions is more conducive to have the necessary financial resources to adopt technologies that mitigate the impacts of unfavorable climate conditions, the lack of knowledge to apply them by the rural population with lower education levels could result in reduced

Table 2 Impacts of climate anomalies on rural–urban migration by educational level and by groups of micro-regions

	(1)	(2)	(3)
No education			
Precipitation negative anomaly	−0.0015	0.0162	−0.0201
	(0.1771)	(0.0354)	(0.0667)
Maximum temperature positive anomaly	−0.2069	0.0856	0.2135*
	(0.4860)	(0.1132)	(0.1241)
Distance (km)	−0.7265***	−0.6719***	−0.6548***
	(0.0316)	(0.0208)	(0.0388)
Contiguity	2.8767***	2.6691***	2.2209***
	(0.2098)	(0.1364)	(0.2294)
Observations (pairs)	6308	23,712	6685
Some primary/primary			
Precipitation negative anomaly	−0.2424	−0.0836**	−0.0888
	(0.1778)	(0.0357)	(0.0566)
Maximum temperature positive anomaly	−0.2357	−0.0030	0.1838*
	(0.3937)	(0.1188)	(0.1044)
Distance (km)	−0.7781***	−0.7178***	−0.6018***
	(0.0372)	(0.0251)	(0.0370)
Contiguity	2.5586***	2.4945***	2.3795***
	(0.2346)	(0.1613)	(0.2575)
Observations (pairs)	5852	24,966	7070
Incomplete lower secondary			
Precipitation negative anomaly	0.0207	0.0583*	0.0561
	(0.1596)	(0.0333)	(0.0503)
Maximum temperature positive anomaly	−0.1013	0.0705	0.2687**
	(0.3789)	(0.1130)	(0.1132)
Distance (km)	−.7548***	−0.6763***	−0.5791***
	(0.0509)	(0.0263)	(0.0274)
Contiguity	2.6066***	2.3680***	2.1411***
	(0.2861)	(0.1561)	(0.2124)
Observations (pairs)	5928	25,764	6965
Complete lower secondary			
Precipitation negative anomaly	−0.3696*	−0.0590	−0.1053*
	(0.2078)	(0.0453)	(0.0622)
Maximum temperature positive anomaly	−1.1642**	−0.0873	0.2471*
	(0.5813)	(0.1612)	(0.1420)
Distance (km)	−0.7176***	−0.7031	−0.5554***
	(0.0669)	(0.0309)	(0.0434)
Contiguity	2.5055***	2.0172***	2.2630***
	(0.3946)	(0.1653)	(0.2795)
Observations (pairs)	4636	21,660	5355
Complete upper secondary			
Precipitation negative anomaly	0.2092	0.0451	−0.1353*
	(0.2466)	(0.0473)	(0.0783)
Maximum temperature positive anomaly	0.4247	0.2913*	0.3211
	(0.4870)	(0.1776)	(0.2046)
Distance (km)	−0.7787***	−0.6985***	−0.6071***
	(0.0553)	(0.0297)	(0.0360)
Contiguity	1.9964***	2.1806***	2.1584***
	(0.3937)	(0.1612)	(0.2256)
Observations (pairs)	3952	20,748	4970

Panel data analysis. PPML estimates. Dependent variable: 5-year rural–urban migration flows. All specifications include constant, time-invariant origin fixed effects and time-varying destination fixed effects. Robust standard errors clustered at dyadic level (*ij*) are reported in parentheses

***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$

Table 3 Impacts of frequency of climate extremes indices on rural–urban migration by educational level and by groups of micro-regions

	(1)	(2)	(3)
No education			
Precipitation < 1 mm (days)	−3.7532***	0.1565	1.0200
	(1.4375)	(0.4834)	(1.0145)
Maximum temperature > 90th percentile (days)	−0.9561***	−0.1518	0.6245*
	(0.3604)	(0.1824)	(0.3648)
Distance (km)	−0.7279***	−0.6720***	−0.6551***
	(0.0317)	(0.0208)	(0.0390)
Contiguity	2.8814***	2.6689***	2.2185***
	(0.2100)	(0.1365)	(0.2302)
Observations (pairs)	6308	23,712	6685
Some primary/primary			
Precipitation < 1 mm (days)	−1.7825	0.1678	−0.4724
	(1.4056)	(0.1799)	(0.9342)
Maximum temperature > 90th percentile (days)	−0.1137	−0.0515	0.5609*
	(0.3472)	(0.5131)	(0.3410)
Distance (km)	−0.7783***	−0.7177***	−0.6016***
	(0.0372)	(0.0251)	(0.0372)
Contiguity	2.5573***	2.4951***	2.3845***
	(0.2359)	(0.1615)	(0.2575)
Observations (pairs)	5852	24,966	7070
Incomplete lower secondary			
Precipitation < 1 mm (days)	−2.0090	0.5206	1.9218**
	(1.5818)	(0.4985)	(0.8832)
Maximum temperature > 90th percentile (days)	−1.0573***	−0.0791	0.6183**
	(0.3423)	(0.1657)	(0.2761)
Distance (km)	−0.7553***	−0.6762***	−0.5786***
	(0.0507)	(0.0263)	(0.0274)
Contiguity	2.6166***	2.3682***	2.1420***
	(0.2866)	(0.1560)	(0.2119)
Observations (pairs)	5928	25,764	6965
Complete lower secondary			
Precipitation < 1 mm (days)	−2.2262	−0.2292	−0.1003
	(1.8001)	(0.5790)	(0.9490)
Maximum temperature > 90th percentile (days)	−1.0258**	−0.1404	0.7694**
	(0.4797)	(0.2277)	(0.3318)
Distance (km)	−0.7208***	−0.7029***	−0.5551***
	(0.0674)	(0.0309)	(0.0436)
Contiguity	2.4882***	2.0163***	2.2669***
	(0.3977)	(0.1653)	(0.2806)
Observations (pairs)	4636	21,660	5355
Complete upper secondary			
Precipitation < 1 mm (days)	0.4695	−0.7335	−1.5395
	(2.4915)	(0.7456)	(1.2088)
Maximum temperature > 90th percentile (days)	−0.8910**	−0.0485	0.6995
	(0.4508)	(0.2766)	(0.4849)
Distance (km)	−0.7772***	−0.6983***	−0.6082***
	(0.0542)	(0.0296)	(0.0357)
Contiguity	2.0021***	2.1792***	2.1555***
	(0.3909)	(0.1609)	(0.2249)
Observations (pairs)	3952	20,748	4970

Panel data analysis. PPML estimates. Dependent variable: 5-year rural–urban migration flows. All specifications include constant, time-invariant origin fixed effects and time-varying destination fixed effects. Robust standard errors clustered at dyadic level (*ij*) are reported in parentheses

***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$

agricultural production and income. In that case, considering that the rural population of these micro-regions are more likely to be able to afford the migration costs, decreasing agricultural production and income due to climate adversities could lead them to migrate to urban areas. On the other hand, financial availability for the adoption of technologies and the knowledge to apply them may result in unreduced or increased agricultural production and income, even in situations where there are persistence and intensification of the climate condition. In other words, achieving higher levels of education may favor the adoption of adaptive measures in situ that are efficient enough to reduce the need to migrate to urban areas due to adverse climate effects.

Overall, our findings suggest that education may shape the migration decision in different ways, depending not only on the educational level of the rural population but also on the average agricultural income level of the affected micro-region. Although we have previously hypothesized that the most educated individuals are more likely to migrate, our findings are only partially consistent with our hypothesis. Although we could not find a positive association between climate variables and rural–urban migration for all the subsamples of individuals with the highest education level, we did find that the negative association between them is smaller for the most educated groups of individuals belonging to the lowest agricultural income group. Therefore, our results indicate that education is particularly relevant for economically disadvantaged rural areas since it helps to attenuate the suppression effect of climate change on migration.

In a general view, our results indicate that it is crucial to consider the specific context in which climate stressors could influence the migration decision. The results are also consistent with studies that challenge the general agreement that climate change invariably induce population mobility, suggesting that for the most vulnerable groups, negative climate shock may, instead, constrain migration (Cattaneo and Peri 2016; Bohra-Mishra et al. 2017; Nawrotzki and Bakhtsiyarava 2017; Nawrotzki and DeWaard 2018). Overall, our findings suggest that rural–urban migration in the Brazilian Northeast region might be more about maximizing livelihood security rather than coping with livelihood failure (Hampshire 2002; Grace et al. 2018).

Discussion

Within the nexus of climate change and migration, the latter is often regarded as an adaptation strategy to the former, particularly for the most vulnerable agricultural communities, where the agricultural sector represents the primary source of income of the population. However, although migration may offer an important option for adapting to adverse climate effects, it is questionable if the most vulnerable population is indeed able to take advantage of this strategy. Along with previous findings (Cattaneo and Peri 2016; Bohra-Mishra et al. 2017; Nawrotzki and Bakhtsiyarava 2017; Nawrotzki and DeWaard 2018), our results suggest the general agreement that the most financially disadvantaged individuals are the most prone to migrate must be critically discussed.

Our study provides evidence of differential socioeconomic vulnerability to climate change impacts and climate–migration responses in the Brazilian Northeast context. Our findings suggest that adverse climate effects on agricultural income do not necessarily induce rural outmigration. Conversely, under some circumstances, climate change may constrain migration to rural areas. Although the rural population living in low-income agricultural areas have higher incentives to migrate because they tend to have limited capacity to employ in situ adaptation measures, they often lack the resources to afford migration.

Table 4 Agricultural activities indicators by groupings of micro-regions

Group	Occupation—Agricultural sector	Own consumption	Nonpaid activities	Total
1	73.38	32.40	16.36	48.76
2	71.35	27.79	14.94	42.73
3	63.74	11.40	10.08	21.48

Consequently, some of them might be trapped in intense and persistent poverty in rural areas.

As our study points to heterogeneous climate–migration responses, understanding the reasons behind the non-linearities in the climate–agriculture–migration nexus is very important from a policy perspective. Data from the 2000 Census show that among the total number of people with ages between 20 and 59 years living in the rural areas of the Brazilian Northeast region, approximately 70% are engaged in agricultural activities. Among this sub-population, 25.3% live in subsistence or produce for their own consumption, and 14.2% work in unpaid activities to help household members. The disaggregation of these data by per capita agricultural income level shows the heterogeneity of the micro-regions groups in terms of vulnerability to adverse climate impacts on subsistence and provide a more comprehensive understanding of our results (Table 4).

In general, while micro-regions belonging to Group 1 present share of individuals working in agricultural activities higher than the regional average, Group 3 shows lower shares. It may indicate that, in comparison to micro-regions with low- and middle-income levels, a smaller part of the rural population with lower financial constraints is subject to the effects of adverse climate conditions on income. Table 4 additionally highlights the heterogeneity of the micro-regions in terms of vulnerability regarding the impacts of climatic conditions on subsistence. In the group of micro-regions with the lowest agricultural income per capita, approximately one-third of the rural population is engaged in agricultural activities produced for their own consumption, and more than 16% works in agricultural activities without being paid to help a household member. In the group with the highest level of agricultural income, however, these values are around 11% and 10%, respectively. These values may indicate that the effects of unfavorable climate conditions on agriculture in the poorest micro-regions may not necessarily be measured in income since barely half of the population in the group of micro-regions with the highest financial constraints are not paid for what they produce. Thus, it supports our results, whose values indicate that the intensification of climate adversities reduces the possibility of covering the costs associated with rural outmigration and, therefore, inhibits migratory flows towards urban areas.

On the other hand, the lower participation of people engaged in agricultural activities and working in unpaid activities in the rural areas of the micro-regions with less financial constraints may indicate that the subsistence of this population is less vulnerable to the adverse effects of unfavorable climate conditions. Considering that the proportion of individuals who are effectively paid for working in agricultural activities is higher in wealthier rural micro-regions, this population may be more likely to bear the costs of migrating to urban areas in situations of intense and frequent climate shocks.

Additional analysis using data from 1991 and 2000 Demographic Census helps us to further understand to what extent the educational attainment of the rural population is consistent with the regional distribution of rural non-migrants in Brazil. Rural non-migrants living in the Brazilian Northeast region have, on average, less than two years of study, while rural–urban migrants are generally more educated than rural non-migrants. Low qualification and low access to education might constitute a considerable barrier to rural–urban migration, which assists in understanding the reasons why our study region still retains the most substantial share of the national rural non-migrant population. Since the education level of the rural population is, in general, positively correlated with agricultural income, the low educational level of the population in more deprived rural areas could induce a vicious poverty cycle by contributing to inhibit or postpone migration to urban areas.

Since the end of this study's analysis period, the government has taken several measures to minimize the impacts of climate adversities on the rural population, such as emergency drought relief policies, drought insurance payments for smallholders, and cash transfer programs. By mitigating the harmful effects of climate change on rural production, these programs and policies may have affected both the need to migrate to urban areas and the ability to implement migration as an adaptive measure.

Among the emergency water supply programs, the construction of small reservoirs and dams and hydraulic channels that transport water to drier regions represented initiatives for relief response to water deficit (Gutierrez et al. 2014; Alvalá et al. 2019; Marengo et al. 2020). Notably, in 2003 the Federal Government created the 1 Million Cisterns Program, later complemented by the Water for All Program, in

2011, which proposed the construction of cisterns to capture rainwater as a form of water supply during the drought periods. In 2005, the “Operação Carro-Pipa” came into effect, which provides for the distribution of drinking water by trucks to rural families impacted by drought (Gutierrez et al. 2014).

In addition to initiatives to mitigate the adverse climate impacts in situ, cash transfer programs have been implemented, with potential impacts on the Northeast rural population’s income level over the past two decades. In 2002 the Federal Government implemented the “Garantia Safra” program, which offers insurance payment to small farmers after the occurrence of severe droughts or excessive rainfall that results in agricultural losses of at least 50% of the agricultural production at the municipal level (Alvalá et al. 2019). Other national cash transfer programs, such as the “Bolsa Família”, in place since 2003, have contributed to the reduction of inequality and extreme poverty not only in rural areas but throughout the national territory. This program strives to benefit all Brazilians living in poverty and assists many of the drought-affected population (Campos 2015).

Studies show that drought emergency relief policies, combined with social protection programs, have played an essential role in reducing socioeconomic vulnerability and supporting families and small rural farmers in the Northeast region (Machado Filho et al. 2016; Herwehe and Scott 2017). Despite the implementation of different public policies, most efforts are still focused on mitigating impacts in an attempt to provide emergency responses to a given drought situation (Cunha et al. 2015). However, such emergency relief policies may have been insufficient to withstand prolonged droughts (Marengo et al. 2017). Additionally, rural insurance security policies, such as “Garantia Safra”, still represent a significant challenge for the agricultural sector. The literature highlights difficulties resulting from the low diffusion of instruments, high administrative costs, high risks, and the farmer’s lack of credibility to adhere to the insurance. Moreover, successive years of low rainfall, with consequent recurrent and systematic losses over the past decade, jeopardize the program’s sustainability (Santana and Santos 2019).

Although there has been a significant improvement in the quality of life indicators over the last years, research focusing on low-income rural households shows that high levels of vulnerability, as measured by food security, remain high even after the implementation of cash transfer programs (Lindoso et al. 2014; Lemos et al. 2016; Nelson et al. 2016). According to the 2013 Supplementary Food Security Survey (IBGE 2013), about 50% of the Northeast rural population is in food insecurity. It suggests that cash transfer programs such as “Bolsa Família”, although necessary to address poverty, have not been sufficient to avoid the risk of food insecurity during drought events and to decrease drought vulnerability significantly (Cunha et al. 2015; Bedran-Martins and Lemos 2017).

Concerning rural outmigration, as mentioned before, these policies may have partially contributed to changing incentives for migration and affecting the ability to implement it as an adaptive measure. However, given the limited role of these policies in reducing vulnerability and food insecurity raised by the literature, it is possible that its effects on the Northeast rural population distribution over the past 20 years have not been significant. Unfortunately, the lack of more recent data on rural–urban migration in Brazil limits our understanding of the region’s migratory dynamics after the implementation of these policies.

Finally, it is important to highlight the intensification of climate conditions that could harm agricultural production over the coming years (Sheffield, et al. 2006). Considering the current low levels of adaptive capacity of the rural population in the Northeast region of Brazil, these changes could potentially increase local vulnerability. By reducing agricultural income and food security and, consequently, the need and capability of the rural population to leave rural areas, climate change may contribute to maintaining the rural population of the region in a situation of deep and increasing poverty. Thus, it is necessary to build strategies to fight against food insecurity risks that are not limited to income transfer initiatives or emergency relief actions. Policymakers should foster proactive policies that include rural development, rational water management, and programs that offer income generation opportunities adapted to the local environmental context.

Conclusion

Using a gravity panel dataset, we investigate the effects of climate change on rural–urban migration in the Brazilian Northeast region. The results suggest that the effects of climate change are heterogeneous across different areas depending on their average agricultural income level. In low-income rural areas, where rural outmigration may not be a viable option for most people due to the limited capacity to afford migration costs, the intensification of climatic adversities may result in reductions in agricultural production and income. Consequently, when the rural population of economically disadvantaged locations is unable to stop farming, there might be less migration to urban areas. On the other hand, in rural areas with higher levels of agricultural income, migration to urban areas could be a mechanism to adapt to the intensification of adverse climate effects.

The analysis also indicated that education is a preponderant factor for the migration decision. Especially in rural areas with lower agricultural income levels, individuals with higher educational levels may suffer reduced impacts of climate adversities on agricultural production and income, possibly because they are better able to take mitigation measures than the less educated population. Consequently, more educated individuals from the most impoverished rural areas may be more capable of affording the migration costs, which establishes that education might be instrumental and part of the mechanism for the rural population to escape the poverty trap.

Although our study provides robust empirical evidence of the relationship between climate change and rural outmigration, there are a couple of limitations that should be noted. Migration data at the microregion level covering the entire Brazilian Northeast region are only available decennially, which means we were unable to capture rural–urban migration at a finer temporal scale. The last demographic census conducted in Brazil, which was in 2010, did not investigate migration on the rural–urban dimension. As a result, it limited the time horizon of our analysis, making it impossible to incorporate more recent information on the role of climate change on this type of migration flow. Due to limitations regarding how the individual data were used in our study to build rural–urban migration rates for each subgroup, it was not possible to include interaction effects to show if the differences between economic and demographic groups are statistically significant. Nonetheless, the primary purpose behind the sensitivity analysis by groups was to demonstrate the heterogeneous migration responses to climate change across subgroups, which we could achieve through our analysis. Finally, despite the recognition that differences in the cost of living between rural origin areas and urban destination areas and the existence of social networks of potential migrants may influence migration decisions, we were unable to incorporate these dimensions into the empirical estimates due to the unavailability of data.

With these limitations in mind, our findings lead to a number of important policy implications. Contrary to many studies that have mostly pointed to the positive relationship between the intensification of adverse climate conditions and migration in situations of declining agricultural productivity, our findings suggest this relationship depends on the different socioeconomic contexts of rural populations. In view of the above, we emphasize the need to concentrate efforts on low-income rural areas of the Brazilian Northeast region, and especially on small farmers whose livelihoods depend on agriculture. Planners and policymakers need to recognize the characteristics of rural areas that can trap rural populations and develop programs to reduce climate vulnerability and support in situ adaptation. Given the importance of agriculture to livelihoods in the region, especially in less developed rural areas, governments could help increase livelihood resilience by facilitating access to improved seeds and crop varieties, providing farmers with the knowledge about cropping techniques and expanding irrigation infrastructure where feasible. Furthermore, policies and programs should be designed for the provision of credit that allows rural households to finance the implementation of such adaptation strategies.

Considering that education might contribute to mitigating the adverse climate effects on agricultural production and has proved to be a major factor in the relationship between climate change and migration, policies should focus on improving access to education in rural areas, both in terms of quantity and quality. Education could not only temper the effects of climate change on the rural–urban migration flows by facilitating the adoption of adaptive measures in situ, but it can also change prospects for employment and better wages in urban areas.

Agriculture adaptation, which enhances rural household earnings capacities, could reduce incentives to leave the rural areas or, at least, may provide them the financial means to move to urban destinations. When in situ adaptation options are insufficient or ineffective, migration to urban areas may constitute the best option available for livelihood security. Since migration represents an available coping and adaptive strategy through which rural households may react to climate change, policy planners should assist and manage climate-related rural outmigration flows. In conclusion, while our study area does not represent all rural areas in the developing world, it provides an important case study to evaluate established theories of migration responses to adverse climate effects in highly vulnerable subsistence locations.

Author's contribution All authors have contributed sufficiently to the scientific work, approved the final manuscript, and are aware of this submission. Therefore, they share collective responsibility and accountability for the results.

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Code availability Not applicable.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical standard Authors wish to declare that they have complied with all the ethical standards as it is required by journal of GeoJournal.

Appendix

See Table 5.

Table 5 Summary statistics

Variables	Year	Group 1				Group 2				Group 3			
		Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Overall rural–urban migration rate	1991	0.1571	0.0380	0.0762	0.2689	0.1403	0.0442	0.0545	0.2711	0.1477	0.0563	0.0288	0.3458
	2000	0.1091	0.0310	0.0536	0.2129	0.1050	0.0404	0.0301	0.3240	0.1907	0.1416	0.0597	0.7760
Rural–urban migration rate (no education)	1991	0.1144	0.0392	0.0430	0.2411	0.1014	0.0404	0.0302	0.2245	0.1054	0.0471	0.0260	0.2548
	2000	0.0797	0.0290	0.0239	0.1619	0.0733	0.0361	0.0121	0.2574	0.1339	0.1075	0.0362	0.5817
Rural–urban migration rate (some primary/primary)	1991	0.1749	0.0355	0.1085	0.2683	0.1589	0.0431	0.0642	0.2890	0.1713	0.0603	0.0285	0.3688
	2000	0.0843	0.0336	0.0366	0.1948	0.0826	0.0433	0.0138	0.3488	0.1721	0.1399	0.0225	0.7191
Rural–urban migration rate (incomplete lower secondary)	1991	0.2851	0.0350	0.1882	0.3616	0.2674	0.0538	0.1142	0.3705	0.2505	0.0723	0.0439	0.4134
	2000	0.1269	0.0340	0.0714	0.2328	0.1218	0.0445	0.0316	0.3287	0.2049	0.1449	0.0673	0.8160
Rural–urban migration rate (complete lower secondary)	1991	0.3088	0.0423	0.1663	0.3909	0.2918	0.0620	0.0498	0.4829	0.2585	0.0757	0.0263	0.4138
	2000	0.2276	0.0763	0.0833	0.4197	0.2265	0.0790	0.0574	0.4751	0.3002	0.1596	0.0598	0.8856
Rural–urban migration rate (complete upper secondary)	1991	0.4662	0.1659	0.2150	0.9232	0.4246	0.1485	0.1670	0.7707	0.3280	0.1260	0.0251	0.6392
	2000	0.3096	0.0936	0.0970	0.5651	0.3290	0.1149	0.0000	0.6282	0.4469	0.1691	0.1603	0.9432
Maximum temperature positive anomaly	1991	0.5260	0.0717	0.3825	0.6437	0.5096	0.1279	0.2811	0.7620	0.6068	0.1571	0.3488	1.0996
	2000	0.9727	0.1526	0.7644	1.3248	1.0792	0.1922	0.7609	1.4232	1.0413	0.2283	0.4423	1.4789
Precipitation negative anomaly	1991	0.2818	0.1445	0.1182	0.7496	0.2653	0.1800	0.0000	0.6915	0.2818	0.1445	0.1182	0.7496
	2000	0.5478	0.1277	0.3049	0.7278	0.5621	0.1453	0.3167	0.9148	0.6183	0.1541	0.3818	0.9003
Maximum temperature > 90th percentile (days)	1991	39.62	3.95	32.37	49.23	38.89	5.12	32.25	51.94	44.34	5.44	32.66	52.96
	2000	55.09	5.14	44.34	66.70	58.89	6.95	43.50	73.79	54.36	7.31	44.69	73.28
Precipitation < 1 mm (days)	1991	227.35	25.56	168.8	266.2	212.03	29.35	128.4	264.6	195.32	33.12	105.6	255.6
	2000	245.82	24.95	180.2	277.8	225.92	29.30	139.6	279.0	206.21	31.28	107.4	268.0

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