Rural outmigration in Northeast Brazil: evidence from shared socioeconomic pathways and climate change scenarios

Linda Márcia Mendes Delazeri
Dênis Antônio da Cunha
Universidade Federal de Viçosa, Departamento de Economia Rural, Programa de Pós-graduação em Economia Aplicada.
Paolo Miguel M. Vicerra
College of Population Studies, Chulalongkorn University – Bangkok.
Lais Rosa Oliveira
Universidade Federal de Viçosa, Departamento de Engenharia Agrícola, Programa de Pós-graduação em Meteorologia Aplicada.

14. População, migração e desenvolvimento

Abstract Climate change negatively impacts agricultural production influencing the rural-to-urban migration options of the population. In this study, we investigate the effects of expected climate change on population distribution and outmigration from rural areas of the Northeast region of Brazil (NEB) over the coming decades under different socioeconomic and climate scenarios. Demographic projection models to 2060 were created based on assumptions of future fertility, mortality, migration, and educational transition. Results reveal that changes in rural population size and composition and rural outmigration may emerge depending on future climatic conditions and agricultural income. The highly-educated population can adapt with changes in climate and avoid income loss while earnings of those with lower education are reduced. The latter's outmigration option is also limited because of lower qualifications. Policies should support economically vulnerable populations especially those dependent on agriculture. Also, policies must accommodate alternative climate change scenarios and their consequences on rural population displacement.
Keywords Climate change, rural-urban migration, population projection.
JEL Code J11, O15, Q56.

Resumo As mudanças climáticas impactam negativamente a produção agrícola e podem influenciar as opções da população rural quanto à migração para áreas urbanas. O objetivo deste estudo é investigar os efeitos das mudanças climáticas esperadas para o futuro na distribuição populacional e a emigração rural nas áreas rurais da região Nordeste de Brasil (NEB) ao longo das próximas décadas sob diferentes cenários socioeconômicos e climáticos. Modelos de projeção demográfica até 2060 foram elaborados baseados em suposições sobre a evolução futura da fecundidade, mortalidade, migração e transição educacional. Os resultados mostram que mudanças no tamanho e na composição populacional e da emigração rural da região dependem das suposições quanto às condições climáticas futuras e dos níveis de renda agrícola das áreas rurais. Além disso, a população com maior nível educacional pode se adaptar às mudanças climáticas de forma a evitar perdas agrícolas. Políticas que abrangem questões relacionadas à emigração rural induzida pelo clima adverso devem direcionar o foco para as áreas rurais de regiões de baixa renda, especialmente para as populações rurais de baixa escolaridade ou cuja subsistência dependa da atividade agrícola. Além disso, as políticas devem ser orientadas e preparadas para a ocorrência de cenários alternativos de mudanças climáticas e para o consequente efeito dessas mudanças sobre o crescimento populacional e sobre o deslocamento da população das áreas rurais para as áreas urbanas.
Palavras-chave Mudanças climáticas, migração rural-urbana, projeção populacional.
Classificação JEL J11, O15, Q56.

1. Introduction

Climate change is a significant challenge faced globally that will manifest its effects differently among communities and in respective economic sectors (International Panel on Climate Change – IPCC 2014; Food and Agriculture Organization of the United Nations – FAO 2016; Cameron 2018; Tol 2018). The shifting climate conditions negatively impact local communities and their economic activities, especially those involved in the agricultural sector (IPCC 2014). Especially in rural areas, where the population depends on subsistence, small-scale, and rain-fed farming, increasing temperatures and shifts in precipitation patterns pose considerable risks to livelihoods (Liehrs, Drees, and Hummel 2016). The inadequate ability of rural households to recover from adverse climate shocks can lead to a cycle of losses and push affected groups into a permanent poverty state (Otto et al. 2017).

In recent years, an increasing number of studies investigated the climate-migration interaction with diverging results. Some observed climate change contribute to increase migration (Thiede et al. 2016; Cai et al. 2016; Mastrorillo et al. 2016; Falco, Galeotti, and Olper 2019), whereas a decline in migration has been reported in others (Cattaneo and Peri 2016; Nawrotzki and Bakhtsiyarava 2017; Nawrotzki and DeWaard 2018). Regardless of the direction of climate variability effects on migration it is likely that the future spatial distribution of the population also will be affected. Although there is this recognition of climate-induced migration flows, there is a shortcoming in empirical evidence on the topic especially at the subnational level.

Few studies have analyzed how expected climate change might contribute to future population changes (Marchiori et al. 2012; Cameron 2018; Oliveira and Pereda 2020). To address this limitation, case studies considering specific regional contexts are required to deliver a distinct picture of the effects of future developments of climate change on internal migration flows and population dynamics. In this study, we seek to understand the impacts of the expected climate change on outmigration and population distribution in rural areas of the Northeast region of Brazil (NEB) over the coming decades under socioeconomic and climate scenarios. Specifically, we apply multi-dimensional mathematical demography methods based on assumptions of future fertility, mortality, migration, and educational transition to performing demographic projections up to 2060. To this aim, we integrate the recently developed storylines of the Shared Socioeconomic Pathways (SSP) with climate scenarios, namely the Representative Concentration Pathways (RCP).

NEB presents a fundamental case study for several reasons. First, NEB is expected to be one of the most affected by climate change. Future climate projections indicate large temperature increases and rainfall reduction, which, along with a tendency for longer periods with consecutive dry days, suggest the occurrence of more intense and frequent dry spells and droughts (PBMC 2014; Marengo, Torres, and Alves 2016). Second, subsistence and small-scale farming are the primary sources of income of the rural population in NEB. Besides the high reliance on agricultural activities for income generation and food production for self-consumption, individuals rely on low-tech cultivation of rein-fed crops, which leaves them extremely vulnerable to unfavorable climate impacts (Brazilian Institute of Geography and Statistics – IBGE 2017). The intensification of adverse climate conditions may decrease subsistence agricultural production, leading to increases in food insecurity and socioeconomic vulnerability of rural households. Lastly, literature has shown that the intensification of climatic adversities has changed the region's rural-urban migration dynamics over the last decades of the 20th century (Delazeri, Da Cunha, and Oliveira 2021). Altogether, these factors imply that NEB provides a unique opportunity to study future rural outmigration response and population distribution in a regional context in response to expected climate change.

The development of population projections plays an essential role in assessing the climate change impacts, as well as in the design of adaptive and coping policies (Crespo Cuaresma

2017). A better understanding of how climate change in NEB might affect the vulnerability and resilience of the rural population in the future could contribute to anticipating the climate-related challenges to be faced over the next decades. Additionally, the analysis of population evolution and its decisions on rural outmigration may provide essential information for planning and implementing government policies in the region.

We contribute to the existing literature in several respects. First, despite the acknowledgment of the impacts of climate change on migration and the expectation that it will continue to shape population distribution in the future, there is no population projection in Brazil that explicitly includes the climate effects. Our analysis contributes to the literature by performing demographic projections in Brazil, considering the effects of expected future climate change on rural outmigration and population distribution under alternative socio-economic and climate scenarios. Besides the demographic components age and gender, disaggregation of the population by education was observed as an important addition because it improves the accuracy of the population projection (Lutz and KC 2011). Moreover, in the context of adaptation to climate change, a series of empirical studies on differential vulnerability to climate hazards have confirmed the dominating role of education as an empowering factor that tends to reduce vulnerability and enhance the adaptive capacity to the negative climate effects (Drabo and Mbaye 2014; Koubi et al. 2016; Bohra-Mishra et al. 2017; Bernzen, Jenkins, and Braun 2019). To the best of our knowledge, our study is the first to produce population projections at the subnational level in Brazil considering educational transition as a demographic component.

The remainder of this paper proceeds as follows. In the next section, we provide our theoretical framework. Then we present our methodological approach, describing our study area, the socioeconomic and climate scenarios, and the population projection method. Later, we present the outmigration scenarios for NEB, followed by the outmigration and population projection results. Finally, we discuss our results and provide the concluding remarks of our work and policy implications.

2. Climate and Migration

Despite the increasing number of studies involving the climate-migration nexus, there is little consensus concerning the direction and the extent which climate change influence migration. The asymmetric migration responses resulting from climate change among the existing studies could be partially attributed to the employment of different data and methodology. Moreover, it could also relate to the differential vulnerabilities of places and populations to climate change.

The climate-migration literature shows nonlinearities in migration responses to adverse climate shocks across different income strata. Some studies emphasize that low-income individuals are typically the most vulnerable to climate change and more likely to use migration as an adaptation strategy (Mastrorillo et al. 2016; Falco, Galeotti, and Olper 2019). Others suggest that climate change is likely to lead to resource depletion in some of the most deprived areas, making this population the least able and least likely to move (Cattaneo and Peri 2016; Beine and Parsons 2017; Nawrotzki and Bakhtsiyarava 2017; Nawrotzki and DeWaard 2018; Benveniste, Oppenheimer, and Fleurbaey, 2020). Thus, although migration can offer an important option for adapting, vulnerability to climate change does not necessarily lead to higher migration probability. Conversely, in some circumstances, climate change may constrain population displacement, since natural resources provide the capital necessary for livelihood diversification (Cattaneo et al. 2019).

Aside from income status, education attainment also matters for individuals' decision to migrate (Drabo and Mbaye 2014; Koubi et al. 2016; Bohra-Mishra et al. 2017; Bernzen, Jenkins, and Braun 2019; Delazeri, Da Cunha, and Oliveira 2021). 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 implementing adaptive measures that result in non-reduction in agricultural production and, consequently, an abatement in the need to migrate due to climate change. Nevertheless, these individuals remain capable of migrating despite reduction in income caused by adverse climate impacts. People with higher levels of education may be more likely to opt for migration as they are able to engage in employment at the destination more easily, with higher potential gains (Koubi et al. 2016; Bohra-Mishra et al. 2017).

In the Brazilian context, Delazeri, Da Cunha, and Oliveira (2021) have analyzed the relationship between climate change and rural-urban migration in NEB over the last two decades of the 20th century. The authors show that adverse climate conditions acted as limiting factors for agricultural activities and led the population from regions with higher agricultural income levels to implement the migration to urban areas as an adaptation strategy. However, in the most economically disadvantaged rural areas, income constraints caused by climate change restricted migration to urban areas by affecting the population's capability to afford the migration costs. 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. Additionally, the authors highlighted the role of education in shaping migration flows. Even in the most deprived rural areas, higher-educated individuals may experience fewer adverse effects of climate adversities on rural income, possibly because there is higher uptake of mitigation strategies than those with less education. As these individuals may be more likely to afford the migration costs, climate adversities act as inhibitors of rural-urban migration flows to a lesser extent and intensity.

In relation to the above-mentioned historical results by Delazeri, Da Cunha, and Oliveira (2021), the aim of this current study is to investigate how expected climate change may affect outmigration and population distribution in rural areas of NEB over the coming decades under alternative socioeconomic and climatic scenarios.

3. Methodological approach

3.1. Study area

Our study focuses on the Brazilian Northeast region (Figure 1). NEB is home to more than 53 million people and extends through an area of 1.554.257 km^2 which corresponds to 18.3% of the Brazilian territory. Approximately 27% of NEB population live in rural areas, comprising about 14.3 million people.

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. The projected intensification of NEB climatic conditions displays particular relevance since 69.8% of the rural population relies on farming as their primary source of income and food supply (IBGE 2010). The amount and frequency of precipitation for agriculture particularly among farmers who usually do rain-fed subsistence farming and hardly have the opportunity for irrigation. Agricultural infrastructure development in the region was low between 1980 and 2000 whereby only about 4% implemented irrigation techniques in their farming practices (IBGE 2018). In congruence with being the residence of almost half of the national rural population, the region contributed to only a quarter of the total national agricultural GDP between 1980 and 2000 (IBGE 2018). These numbers indicate the relative poverty of NEB rural areas compared to other regions of the country.

Brazil and NEB have an established history of internal migration. In the period of 1991-2000, demographic census data reveal that rural-to-urban migration represented approximately 13.3% of the national internal migration. Estimates indicate that over the last two decades of the 20th century NEB accounted for 40.5% of the total national rural-urban populational displacements (IBGE 1991; 2000). Despite the significant rural outmigration from NEB, we also highlight the high participation of this region in the distribution of the Brazilian rural population over the same period. While this region accounted for approximately 28% of the total Brazilian population, it was the least urbanized region of the country such that it is the location of half of the country's rural population (46.4%) (IBGE 2000). These numbers reflect the importance of this region in retaining rural population. It is then important to consider the exposure to climate risks of this segment of the population.

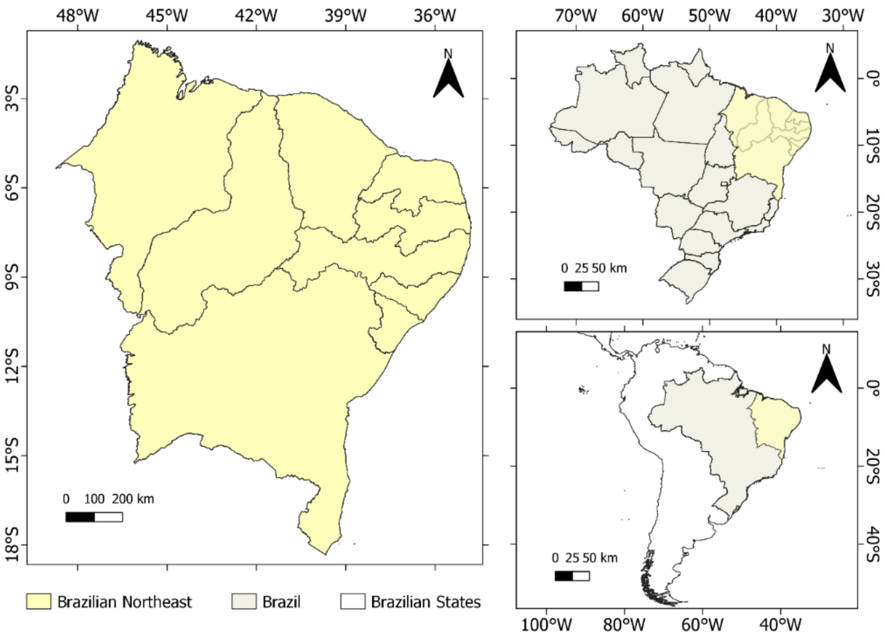

Figure 1. Location of the Brazilian Northeast region.

3.2. Socioeconomic and climate scenarios

In recent years, increasing attention has been given to capacity-building strategies for adapting to the inevitable changes in climate conditions. However, analysis of populations' future vulnerabilities still represents one of the most significant gaps in the assessment of climate change-related risks. Many of the estimates on the likely effects of climate change on populations made so far assume socioeconomic conditions will remain similar to the current ones. Therefore, they cannot support alternative societal development pathways (KC and Lutz 2014; Jiang and O'Neill 2017).

The Shared Socioeconomic Pathways (SSP) are socioeconomic scenarios that provide broad descriptions of future conditions that are important both for the development of Greenhouse Gas (GHG) emissions mitigation strategies and the analysis of societies' vulnerability and ability to adapt to climate change (O'Neill et al. 2017). They are categorized as SSP1, SSP2, SSP3, SSP4, and SSP5, and each scenario depicts different combinations of socioeconomic challenges to mitigation and adaptation. SSP1 describes a sustainable world with low challenges for mitigation and adaptation, SSP2 is a 'Middle of the Road' pathway with intermediate challenges, whereas SSP3 assumes high challenges for both mitigation and adaptation. In SSP4, which is characterized by inequality, challenges are high for adaptation and low for mitigation. SSP5, which is characterized by development driven by fossil fuel intensive economies, has low challenges for adaptation and high challenges for mitigation (Merkens et al. 2016). The storylines underlying the individual SSPs have been discussed extensively in previous work (O'Neill et al. 2014; KC and Lutz 2014).

Although the SSPs have not been developed as instruments of climate policy, climate change projections can be integrated to simulate its potential impacts on mitigation and adaptation challenges (Jiang and O'Neill 2017). The resulting analysis of the interaction between expected future climate change and the related socioeconomic challenges also includes the climate scenarios given by the Representative Concentration Pathways (RCP) (Dellink et al. 2017). The four RCPs (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) represent a range of trajectories of GHG concentrations and associated climate change, which are labeled by their approximate radiative forcing. In general, RCP2.6 and RCP8.5 represent scenarios of low and high GHG atmospheric concentration, respectively, while RCP4.5 and RCP6.0 represent mid-range scenarios (Van Vuuren et al. 2011). Given that each SSP scenario assumes a specific amount of radiative forcing emitted by the end of the 21st century, each RCP can be combined with the SSP that best describes the economic, social, and environmental trajectories responsible for different climate change scenarios in the future (Dellinink et al. 2017; Jiang and O'Neill, 2017).

While the SSPs have a great advantage that can be used by global models with same assumptions, adjusted or revised versions would be needed for the regional assessment. Global narratives fail to incorporate regional specific important drivers. It became necessary to construct adjusted socioeconomic scenarios that can be used for the assessment of climate change impacts, adaptation, and mitigation measures by subnational level to reflect local unique situations (Chen et al. 2020). We present a scenario development that qualitatively links to global SSPs and basic quantitative information of NEB. Our adjusted scenarios were constructed to be coherent with global SSPs, while allowing for focus on regional challenges.

3.2.1. Climate scenarios in NEB

Different Earth System Models (ESM) translate the assumptions about future atmospheric GHG concentrations given by the RCPs into climate variables. In this study we use four ESMs to analyze future climate trends and its potential impacts on rural outmigration in NEB, namely the Hadley Centre Global Environmental Model, version 2 (HadGEM2-ES), the Model for Interdisciplinary Research on Climate (MIROC-ESM), the Meteorological Research Institute Coupled Atmosphere–Ocean General Circulation Model, version 3 (MRI-CGCM3) and the Norwegian Earth System Model, version 1 (NorESM1-M). The selection of these models was based on Pires et al. (2016), who argue that they have an excellent ability to simulate temperature and precipitation variables in Brazil. Figure 2 shows the projections of the average annual temperature (℃) (Panel A) and the average monthly precipitation (mm) (Panel B) in NEB for the period 2006-2065 given by the ESMs under the four RCPs assumptions.

Overall, the ESMs project an increasing trend for mean temperature for all RCPs (Panel A). Notably, under the assumptions of higher GHG emissions under the RCP 8.5, the projections indicate a higher average temperature for this scenario, especially in the second half of the projection period. Regarding the amount of precipitation amount (Panel B), the ESMs, especially the HadGEM2-ES, project high inter-annual precipitation variability. The inter-annual climate variability is particularly relevant for the analysis of rural outmigration in NEB due to its effects on agricultural production and, consequently, on income and food availability in NEB rural areas. As this is the driest Brazilian region and agricultural activities are mostly rain-fed, agricultural production's success depends not only on the amount of precipitation but also on its regularity. Thus, future climate trends presented by the ESMs may substantially affect the migratory dynamics in NEB in the future.

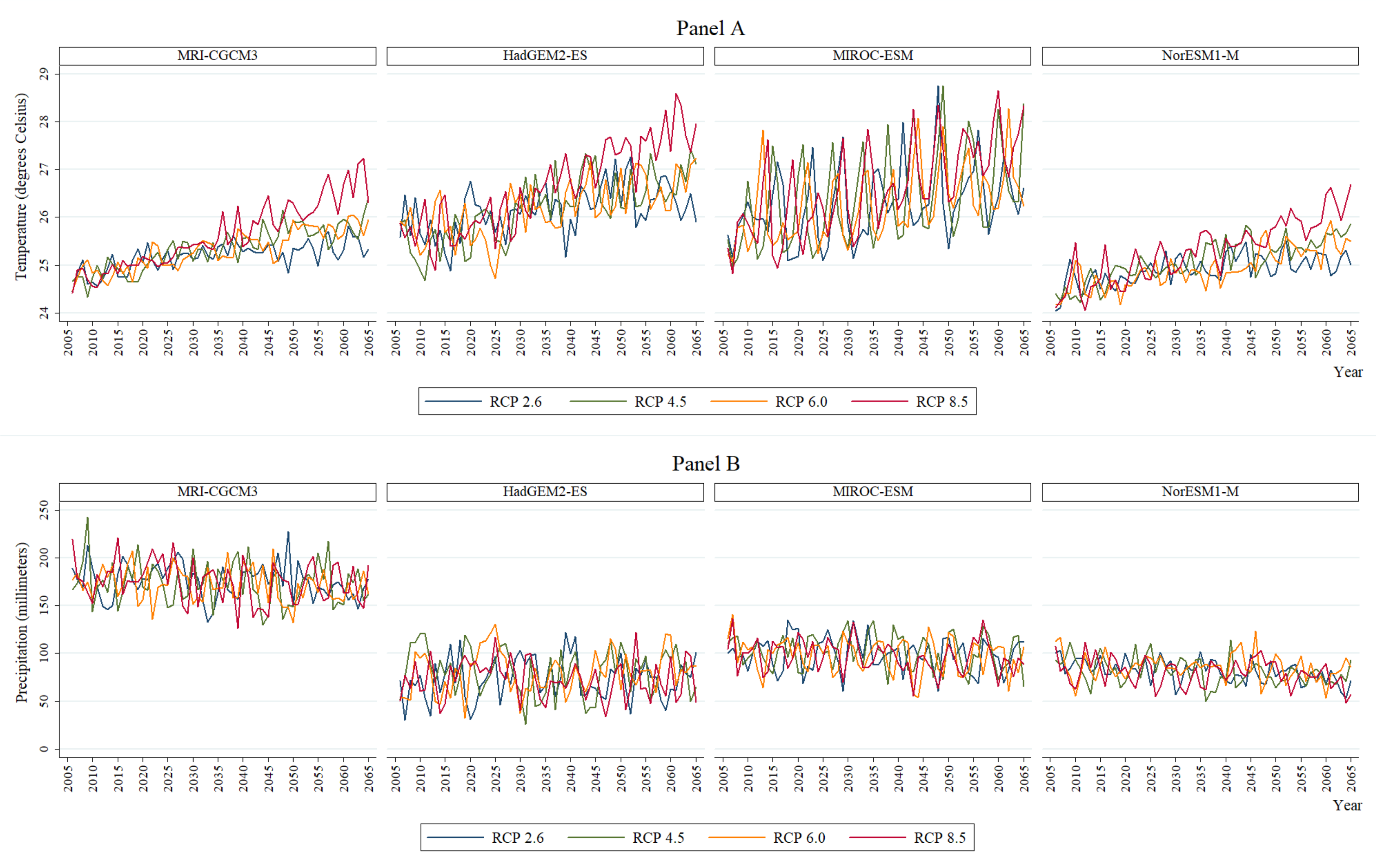

Figure 2. Future trajectories of average annual temperature and precipitation by ESM and RCP.

3.2.2. Population scenarios in NEB

In our study, we project the rural population and the number of rural outmigrants in 187 micro-regions – a grouping of neighboring municipalities based on economic and social similarities – of the Brazilian Northeast region. The high number of micro-regions in NEB made it impossible to analyze the historical trends of the demographic components at the micro-regional level. Thus, we performed the analysis at the state level (9 states) for fertility, mortality, and educational progression components. Regarding the migration component, we follow Delazeri, Da Cunha, and Oliveira (2021), which have aggregated NEB micro-regions according to their per capita agricultural income levels.

In order to meet each SSP storyline, we defined three alternative trajectories for fertility, mortality, and educational transition. Typically, future trends include an optimistic, pessimistic, and business-as-usual trajectory, which represents a scenario of continuation of the current trends. Regarding the outmigration component, we also defined three trends in order to meet the SSP storylines and their implications on climate change scenarios. The data used in this study come from detailed tabulations of the three most recent Brazilian censuses that were conducted in 1991, 2000, and 2010 (the last available). Next, we briefly show how we operationalize the demographic scenarios in terms of Education Attainment Progression Rates (EAPR), Total Fertility Rates (TFR), Life Expectancy at Birth (LE0), and Migration Rates.

3.2.2.1. Educational transition

From the proposition that individuals typically acquire formal education at young ages and that it remains invariant throughout life, we used data from the 2010 Demographic Census to reconstruct educational distributions in population cohorts and produce educational progression trends (Yüceşahin and KC 2015; Lutz et al. 2018). We disaggregated the rural population of NEB states by 5-year age groups, gender, and six educational attainments, namely No Education (E1), Incomplete/Complete Primary (E2), Incomplete Lower Secondary (E3), Complete Lower Secondary (E4), Complete Upper Secondary (E5), and Complete Tertiary (E6). For a given educational attainment level, we defined the Education Attainment Progression Rate (EAPR) to the next educational level as the proportion who completed the next level of educational attainment among those in the current level (KC et al. 2018).

We analyzed each of the trends drown for several cohorts and defined future education scenarios essentially by extrapolating the current trend. For the medium and fast educational progression scenarios, we assumed the EAPRs of each NEB state to converge to the Brazilian EAPRs (at country level) calculated under the assumptions of the SSP2 scenario in the years 2010 and 2060, respectively (Lutz et al. 2018). For the slow educational transition scenario, we follow KC and Lutz (2014) and we assumed that the EAPRs would be fixed over time in the same values observed in 2010.

3.2.2.2. Fertility

There are no data in Brazil that include education-specific fertility rates on state-level by residence zone (rural/urban). Thus, we used available information from the 1991, 2000, and 2010 demographic censuses on the number of children born over the 12 months before the date of each survey, and on the number of children born during each interviewed woman's reproductive life to calculate the education-specific Total Fertility Rates (TFRs) at the NEB rural-state level.

The Brazilian Institute of Geography and Statistics (IBGE 2018) performed projections of TFRs at the state level up to 2060 based on the proposition of convergence to lower fertility levels according to historical trends. However, TFRs projected by IBGE were performed with no disaggregation between rural and urban areas nor by education. Preliminary analysis using data from the latest Brazilian demographic census (2010) has shown that TFRs in rural areas are generally higher than TFRs in urban areas, so we adjusted the TFRs projected by IBGE to the rural level and used them as a baseline for the medium fertility scenario.

We assumed the rural TFR projected for each NEB state as the upper limit for the convergence of the TFR of the reference educational category (Completed Upper Secondary). Following Fuchs and Goujon (2014) and Gietel-Basten, Sobotka, and Zeman (2014), we defined that when the projected rural TFR of each state reached 1.8 children per woman, differentials in education-specific TFRs would converge to fixed relative ratios in accordance with the global standard. Then, we applied a parametric model to obtain the TFRs by educational attainment and by 5-years age cohorts for the period between 2010 and 2060.

For the high and low fertility scenarios, we assumed that TFRs would be, respectively, 20% higher and lower than the projected TFRs in the medium scenario by 2030, and 25% higher and lower than the projected TFRs in the medium scenario by 2050 and thereafter (KC and Lutz 2017). Once we had projected TFRs for the low and high fertility scenarios, we applied the procedures above-mentioned to obtain the rural-state fertility rates by educational category and by 5-years age cohorts.

3.2.2.3. Mortality

There are no education-specific life tables in Brazil, not even at national level. Given the unavailability of reliable data that allows the direct measurement of mortality in rural areas of Brazil by educational attainment, we used the information on child mortality by maternal educational from past demographic censuses (1991, 2000 and 2010) and model life tables to estimate adult mortality differentials. While this may result in a slightly overestimation of mortality differentials as child mortality is more sensitive to education than adult mortality, it is still preferable than disregarding educational differentials (KC 2018).

IBGE (2018) performed projections of Life Expectancy at Birth (LE0) at the Brazilian state level up to 2060 based on the proposition of convergence to higher LE0 according to historical trends. However, the LE0 projected by IBGE was performed with no disaggregation between rural and urban areas nor by education attainment. Preliminary analysis using data from previous demographic censuses (1991, 2000, and 2010) have shown that LE0 in rural areas are generally lower than LE0 in urban areas, so we adjusted the LE0s projected by IBGE to the rural level and used them as a baseline for the medium mortality scenario.

We assumed the rural LE0 for the educational reference category (Completed Upper Secondary) in each NEB state to converge to the rural LE0 projected by IBGE in 2060. Following Garbero and Sanderson (2014), we defined that the difference between LE0 for the highest and the lowest educational categories (E1 and E6, respectively) will converge to six years for males and four years for females in 2060. Then, we used a model life table to construct complete life tables at the rural-state level for the period 2010-2060, for each educational category and gender.

For the high and low mortality scenarios, we assumed that LE0 would be one year per decade lower and higher, respectively, than the projected LE0 in the medium scenario (KC and Lutz 2017). Once we had projected LE0 for the low and high mortality scenarios, we applied the same procedures described in the previous paragraph to construct complete life tables at the rural-state level by educational category and gender up to 2060.

3.2.2.4. Migration

The accurate projection of future migration flows is one of the most significant challenges related to long-term population projections. Unlike other demographic components, there is no theory capable of explaining future migration flows allowing the projection of their trajectories with a low degree of uncertainty (Lutz 2018). The size and types of future migration flows will be shaped by several factors, such as economic growth, which also changes over time and it is under future uncertainties (Sander, Abel, and Riosmena 2014).

In the climate-migration nexus, while it has been long recognized that changes in environmental conditions can have important effects on migration, this relationship has been oversimplified in much of the recent discourse on the impact of climate change. Much of the discussion assumes that there is a simple deterministic effect whereby climate change inevitably implies in population displacement (Sander, Abel and Riosmena 2014). The migration projection should not only be based on a detailed analysis of future trends in climate patterns, but also on a deep understanding of the complex relationship between climate change and vulnerability and adaptation opportunities of the affected population.

Considering specifically the NEB region, Delazeri, Da Cunha, and Oliveira (2021) show that the ability to implement rural outmigration as an adaptation response to climate change depends on the per capita agricultural income level of NEB micro-regions and the educational level of their rural population. Thus, we followed Delazeri, Da Cunha, and Oliveira (2021) and defined the outmigration flows trajectories by education attainment, gender, and age groups for three different groups of NEB micro-regions aggregated by their agricultural income level, which were averaged using data from the 1991 and 2000 censuses. Group 1 is comprised of the micro-regions belonging to the first quintile, which 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.

The development of the assumptions about future rural outmigration and immigration is based on the proposition about the continuation of historical trends. Thus, we assumed gradual decreases (increases) in migration rates for micro-regions that showed a decrease (increase) trend of these rates in the past. For each group of micro-regions and demographic group, we project the rural outmigration rates by adjusting exponential curves up to 2060.

For the elaboration of different scenarios of rural outmigration, we assumed three distinct speeds for the migration rates trajectories and, therefore, we used three different adjustment exponential curves. The fast-trajectory curve assumes that the rate of change in outmigration rates calculated using 1991 and 2000 censuses data will remain fixed over time. The slow-trajectory curve assumes that the rate of change in outmigration rates will decrease rapidly over time. Finally, we assumed that the medium-trajectory curve is the mean of the outmigration rates projected by the fast and slow trajectories.

As for rural outmigration, we used the past immigration rates calculated using the 1991 and 2000 censuses data for the projection of rural immigration rates by adjusting exponential curves up to 2060. For rural immigration in particular, we defined only one scenario, which represents the medium trajectory (KC and Lutz 2014).

3.3. Population Projection Method

We used the multi-state projection model to project the rural population and the number of rural outmigrants in NEB. The multidimensional demographic cohort method for population projection expresses that changes in the population in a given time are given by adding the number of births and immigrants and subtracting the number of deaths and outmigrants. Thus, population cohorts move over time according to the temporal variations of demographic components.

Initially, we obtained the distribution of the rural population of each NEB micro-region in the initial year of the projection period (2010) by gender, five-year age group, and educational level. For each five-year time interval, the population of a cohort moves to the next five-year age group. In each five-year period, we apply specific mortality, fertility, migration, and educational progression rates for each cohort. Then, we obtain the new population distribution by age group, gender, and education for the following five-year period. The procedure is applied for the subsequent five-year periods until the end of the projection period, that is, until 2060 (KC et al. 2012; KC et al. 2014).

The projection methods we applied were developed by the International Institute for Applied System Analysis (IIASA) (KC and Lutz 2017). We used the R Package Multi-State Demography (MSDem) for the population projection (Wurzer, KC, and Speringer 2018).

4. Scenarios for rural NEB

In order to project the future NEB rural population, we considered the assumptions about education, technology, income, and urbanization of each SSP storyline. Additionally, we combined the assumptions about GHG emissions of each SSP scenario with the RCP scenarios to infer the potential impacts of climate change on the rural outmigration decision. Next, we briefly describe the SSP storylines combining them with the results found by Delazeri, Da Cunha, and Oliveira (2021) about the heterogeneities of climate change impacts on rural outmigration in NEB by the per capita agricultural income level of each group of micro-regions and the educational level of their rural population (hereinafter referred to as NEB-SSP).

NEB-SSP1 assumes high investments in education, fast technological development, increasing agricultural production and income, and low population growth. Additionally, it assumes urban areas with adequate infrastructure, which makes them attractive destinations. Due to the rapid educational transition, urban labor markets increasingly demand high-skilled workers. Low levels of GHG emissions are translated into low increases in average temperature and low reductions in precipitation trends. Although this scenario assumes educational improvement and further technological development that could facilitate adaptation to adverse climate conditions, we assume that educational and technological improvements will not be achieved equally in all NEB rural areas.

In rural areas with more significant financial constraints, workers engaged in agricultural activities, especially those with lower educational attainment, generally have reduced capabilities to implement technologies to cope with adverse climate effects. While this scenario does not imply a substantial intensification of the adverse climate conditions, it assumes the continuation of climate conditions that harm agricultural production in the absence of in situ adaptation strategies. Therefore, moderate increases in technological availability and limited knowledge about strategies to mitigate the adverse climate effects on agricultural production will result in only moderate increases in the agricultural income level of the rural population.

Although the moderate increase in income could make this rural population more able to afford the migration costs, it is likely that the less educated population will not migrate to urban areas. Since this scenario assumes that the urban labor market will require high-skilled workers, we expect that potential rural outmigrants may not be qualified enough to be absorbed by the urban labor market, making this population remain in rural areas. In this case, rural outmigration would not be constrained by the worsening of climate conditions, but by the low expectation about the absorption of low-skilled workers in urban labor markets instead.

Regarding the highly-educated rural population, greater knowledge about access and implementation of technologies may enable them to implement mechanisms to mitigate the impacts of the adverse climate conditions on agricultural production. As a result, their agricultural income may increase. However, due to the highly developed urban labor market, this population may have higher expectations about income in the urban areas. Since agricultural income increases, the rural population is more able to afford the costs of rural outmigration. Besides, given the expectation about job opportunities in urban labor markets, they will have increased incentives to migrate to urban areas.

Considering the population from rural areas with the highest agricultural income level, this scenario assumes that higher income availability could enable workers engaged in agricultural activities to access and implement technologies that could facilitate adaptation to adverse climate effects. Consequently, it assumes increases in rural income levels. Despite the existence of highly attractive urban areas, the less educated rural population will have low incentive to migrate, both due to the increasing income in rural areas, which would reduce the need to leave them, and due to the low expectation about their absorption by the urban labor markets. Regarding the higher-educated rural population, the high attractiveness of the urban areas, the mechanization of agricultural activities, and the expectation about their absorption by the urban labor markets may imply substantial incentives to migrate to urban areas, even in a scenario of increasing agricultural income.

NEB-SSP2/SSP4[1] assumes modest investments in education, moderate technological innovations, and, consequently, moderate increases in agricultural income. Ongoing trends in GHG emission are translated into moderate increases in temperature and moderate reduction for precipitation. The access and implementation of technological innovations will remain uneven in NEB rural areas. In rural areas with lower agricultural income levels, the positive effects of moderate technological innovation on agricultural production will be less than proportional to the intensification of the adverse climate conditions. Consequently, this scenario assumes agricultural income reduction and the rural population's low ability to cover the outmigration costs, resulting in suppressing effects on rural outmigration, with higher intensity for the less educated population.

Although the population of rural areas with the highest agricultural income level has greater access to technologies and greater capability to implement in situ adaptation strategies, the gains in technology may not be sufficient to cope with the adverse climate conditions. Consequently, this scenario assumes a moderate reduction in agricultural income levels and higher incentives for rural outmigration for the population at all education levels.

NEB-SSP3 assumes low investments in technological development and education, which results in low economic growth in both urban and rural areas. Due to fast population growth, urban areas will expand unplanned and unorganized. Besides, limited employment opportunities will make urban areas very unattractive. Gradual increases in GHG emissions will be translated into increases in temperature, water shortage, and irregular precipitation distribution. Because of the intensification of the adverse climate conditions and the low capability of the rural population to implement in situ adaptation strategies, this scenario assumes reductions in agricultural production, income constraints, and, consequently, restrictions in the adoption of rural outmigration. It also assumes that the outmigration restrictions will be even more significant for the most vulnerable population groups, such as the rural population from the poorest areas and the population with the lowest education attainment. In addition to the absence of incentives to migrate to urban areas due to its low attractiveness,

[1] In a regional context as opposed to the global context of SSPs, the assumptions of scenarios NEB-SSP2 and NEB-SSP4 become equivalent, so that the results of population and outmigration projections performed for both scenarios also are the same. Thus, the projection results for these scenarios are referred to as NEB-SSP2/4 and are based on the continuation of the observed historical trends.

budget constraints will imply that the population will have no choice but to remain in rural areas.

NEB-SSP5, as well as the NEB-SSP1, assumes high investments in education, rapid technological development, and great attractiveness of urban areas. It also assumes that, due to the fast education transition, urban labor markets will increasingly demand high-skilled workers. However, this scenario assumes high GHG emissions, which imply a significant intensification of adverse climate conditions, such as significant increases in temperature and reduction and temporal variability of precipitation.

As assumed by the NEB-SSP1, despite the significant technological development, technology will not be distributed evenly across rural areas. In rural areas with lower income levels, only moderate access and implementation of technologies will not be enough to enable the population to undertake in situ strategies to adapt successfully to increasing adverse climate conditions. Thus, NEB-SSP5 assumes that the agricultural income level will not increase enough to enable the rural population to afford the migration costs. In rural areas with the highest income levels, greater access to technologies, and greater capability to cope with highly adverse climate shocks will increase agricultural income. However, this income increase will be proportionally lower than the expected income in urban areas, making the rural population of these areas more likely to leave. Due to the high demand for skilled workers in the urban labor markets, the rural population with low and medium educational attainment will have less incentive to migrate to urban areas. Therefore, they will remain in rural areas. Concerning the highly-educated rural population, the expectation of absorption in the urban labor markets may make them more prone to leave the rural areas.

5. Results

Toward investigating how future rural population in NEB would respond to different scenarios of climate change and socioeconomic development, we apply the multi-state projection model to each one of the 187 NEB micro-regions. Figure 3 presents the rural population (Panel A) and rural out-migration trajectories (Panel B) of NEB under the assumptions of the NEB-SSP and RCP scenarios.

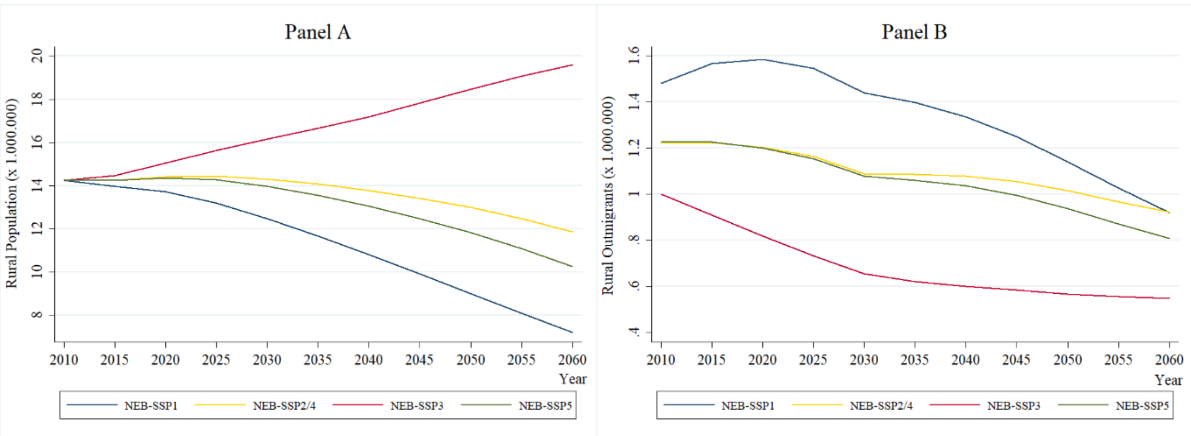

Figure 3. Population (Panel A) and outmigration (Panel B) dynamics in NEB rural areas by NEB-SSP.

Panel A of Figure 3 shows how the four NEB-SSPs' population trajectories differ from one another over the projection period. Under the NEB-SSP3 scenario, the projection implies a substantial increase in the rural population, while projections under the other scenarios imply reductions in the rural population by 2060. This variation between population trajectories is due to different assumptions regarding demographic components. For NEB-SSP3, due to the assumptions of the high fertility rate, low life expectancy, slow educational progression, and restrictions on outmigration from rural areas caused by climatic adversities, especially of the population with lower agricultural income level and low educational attainment, NEB rural population is expected to increase gradually and reach 19.5 million in 2060. In contrast, the NEB-SSP1 scenario projects a sharp reduction in NEB rural population until the end of the projection period, resulting from a decreasing fertility rate, fast educational progression, and expressive rural outmigration. In numerical terms, this scenario projects that the region's rural population may be reduced by approximately 50% compared to the initial year of the projection period (2010), reaching around 7 million in 2060.

The rural outmigration dynamics under the storylines of socioeconomic scenarios and the consequent implications of climate change (Panel B) is consistent with the population trajectories in each NEB-SSP scenario presented in Panel A. Regarding the NEB-SSP1 scenario, the non-intensification of unfavorable climate conditions due to the low levels of GHG emissions resulting from high mitigation efforts, coupled with technological advances resulting from high efforts for adaptation, imply in assumptions of increased agricultural production and income. While it could reduce the need for rural displacement motivated by environmental reasons, the assumption of attractive urban areas could boost rural outmigration. Thus, the combination of increased agricultural income and high urban attractiveness favors the population displacement from rural to urban areas. Consequently, the absolute number of rural outmigrants projected by this scenario is the highest in the entire projection period, and it decreases over time due to the projected population reduction.

Regarding the NEB-SSP3 scenario, the assumptions of increased GHG emissions and low mitigation efforts, with the consequent intensification of adverse climatic conditions, summed with the slow technological development and the consequently limited adaptation capacity, would reduce agricultural production and income in the region. Due to income restrictions, the rural population becomes less able to employ migration to urban areas as an adaptation mechanism to climate change's harmful effects. As a result, this scenario is translated into the lowest absolute numbers of rural outmigrants throughout the projection period.

We highlight that despite the increasing population trajectory over time, the absolute number of outmigrants shows a decreasing trajectory. The increasing rural population due to high fertility rates, slow educational and technological progress, combined with the increasing inability to employ rural outmigration, have significant consequences. Not only the rural population increases at an accelerated rate, but it also increases under adverse socioeconomic conditions. In addition to the intensification of unfavorable climatic conditions, which alone constitutes an obstacle to the food production to feed the growing population, the projected population's educational attainment would remain low, which implies the perpetuation of existing barriers to the adoption of mitigation measures against climate shocks. The feedback effects that each of these factors have on the others may result in the intensification of poverty in NEB's rural areas.

Overall, the NEB-SSP2 scenario projects gradual rural population reduction trends because of a moderate reduction in the fertility rates and moderate educational progress. The NEB rural population is projected to remain at similar absolute numbers until 2025, and only after then, it would start to decrease. The gradual reduction in fertility rates and the gradual educational improvement in NEB would reduce the rural population size since the initial year of the projection period. However, the maintenance or slow decrease in the number of rural outmigrants over the period 2010-2025 acts as an obstacle to decreases the rural population.

The maintenance of the average number of outmigrants at similar levels throughout the initial projection period might be due to the gradual intensification of adverse climatic conditions according to the observed historical trends. On the one hand, the intensification of climatic adversities could amplify rural outmigration in areas with higher socioeconomic status. On the other hand, it could have a suppressive effect on rural outmigration in areas with lower agricultural income levels and in population groups with lower educational attainment.

The migration component's importance in the design of NEB's future rural population can be better visualized when comparing the population trajectories under the NEB-SSP1 and NEB-SSP5 scenarios (Panel A). These scenarios share the same assumptions about the trajectories of fertility, mortality, and educational progression. In contrast, they only differ on the assumptions for the rural outmigration component. Since we made our assumptions about rural outmigration based on future climate scenarios, the projected population difference between these scenarios could be attributed integrally to the impacts of expected climate change on outmigration. Specifically, while the NEB-SSP1 scenario assumes that the NEB's climate would not be negatively intensified due to the low level of GHG emissions and the high mitigation efforts, NEB-SSP5 assumes that high GHG emissions levels would result in climatic adversities intensification. Therefore, the assumptions of the NEB-SSP5 scenario would restrict rural outmigration by decreasing agricultural production, especially for regions with lower levels of per capita agricultural income and for the less educated population.

The rural outmigration trajectories in NEB-SSP1 and NEB-SSP5 scenarios presented by Panel B of Figure 3 confirm the importance of climatic conditions on rural population displacement in NEB. The intensification of harmful climatic effects given by the NEB-SSP5 scenario might restrict rural outmigration in the region and, therefore, slow down the decreasing population trend resulting from the assumptions of low fertility rates and fast educational progression. Thus, the difference between the population and outmigration dynamics of these socioeconomic scenarios highlights how the climate component could shape the population size through the outmigration component.

6. Discussion

Scenarios describe plausible consistent views of the future, which can be used by scientists and policymakers to explore the challenges of global environmental change, given an appropriate level of spatial and sectoral detail (Mitter et al. 2020). We developed four qualitative and quantitative scenarios for population and rural outmigration in NEB based on the global SSPs. From the storylines of socioeconomic scenarios, assumptions about the impact of future climate change on rural outmigration, and analysis on the trajectories of the rural population and rural outmigration under different NEB-SSP scenarios, we could infer that the differences in size and composition of the rural population and rural outmigration in NEB may emerge from different assumptions regarding future climatic conditions and different levels of agricultural income in NEB's rural areas.

The results demonstrate that the agricultural income level of the NEB's micro-regions might determine the population's ability to employ adaptive strategies to mitigate the adverse effects of climate change. Particularly, the projections showed that regardless of the climate scenario, in rural areas with more significant financial restrictions, populations may have less capacity to implement technologies, contributing to the greater effects of climatic adversities on production and agricultural income. Due to reduced income and food production for self-consumption from agricultural activities, migration to urban areas could be considered an adaptation strategy. However, income restrictions caused by climatic adversities, more or less severe depending on the climate scenario, may reduce these populations' financial capacity to bear the costs associated with migration. Overall, socioeconomic scenarios that assume moderate and high levels of GHG emissions mitigation and adaptation challenges (NEB-SSP2 and NEB-SSP3, respectively) imply that the adverse effects of climate change might result in the maintenance of the population in rural areas in a persistent poverty situation.

In rural areas with higher levels of agricultural income per capita, the greater financial availability of the population to employ adaptive strategies, given the continuation or intensification of the negative effects of climate change, may result in smaller agricultural production and income reductions. Even under scenarios that assume moderate and high challenges to mitigate GHG emissions (NEB-SSP2 and NEB-SSPs 3 and 5, respectively), the population of rural areas with less financial constraints would still be able to afford the migration costs to urban areas.

Regarding the assumptions on educational progression in NEB's rural areas, the projection results showed that education might be a significant component in shaping future outmigration and population distribution. Regardless of the level of agricultural income in the micro-regions, the population with higher educational levels may have greater knowledge about better agricultural practices and rural credit options. Thus, this population may be under less negative impacts of climate change on agricultural production. In this case, education could mitigate possible income decreases and reduce the need to leave rural areas for environmental reasons. On the other hand, even in scenarios of extreme intensification of climatic adversities (NEB-SSP5), education could contribute so that the income reductions are not high enough to restrict migration. In addition, even if migration to urban areas becomes necessary, education may be an essential factor in shaping employment opportunities in these areas.

Despite the recognition of the impacts of climate change on population distribution, only a few empirical studies have sought to include the effects of such changes on outmigration or population projections. Marchiori et al. (2012) analyzed the impacts of climate anomalies on future migration flows between countries in Sub-Saharan Africa. The authors considered only one climatic scenario for the projection of outmigration rates and obtained the estimated number of outmigrants by multiplying these rates by the projected population. In addition, they obtained the number of outmigrants projected for the future based on only one population projection scenario (scenario of continuation of historical trends) and the authors did not consider the possible implications of outmigration on the final projected population in each period of time. Cameron (2018) analyzed the impacts of climate change on the future population distribution arising from changes in New Zealand's internal migration flows. Despite using four climate change scenarios (given by the same RCPs we used in this study), the authors used only one population projection scenario (SSP3). Additionally, the author associated non-compatible climatic scenarios to the socioeconomic scenario used, that is, he considered climatic scenarios that have much less or much greater radiative forcing than the radiative forcing assumed by the SSP used.

In the national context, Oliveira and Pereira (2020) performed simulations of the impacts of changes in the average temperature on the aggregate rates of internal migration and the regional distribution of the Brazilian population in the future. The authors used two future climate scenarios to infer the likelihood of migration between Brazilian regions. For the quantification of the number of outmigrants at the regional level based on the estimated migration rates, the authors carried out the population projection until 2040 based only on historical population growth rates. Similar to Marchiori et al. (2012), the authors did not consider the outmigration effect on the final population of Brazilian regions in each period of time.

Compared to studies available in the literature regarding the interrelationships between climate change and future migration, this study advances in three respects: (i) it considers the four climatic scenarios and the five existing socioeconomic scenarios and associates them based on the proximity of their radiative forcing values; (ii) it estimates the number of rural outmigrants over the next decades from the projected population in each period of time and allows, in each period, the population size to change based on the projected migratory flows. Thus, it considers that the sizes of the population and rural outmigration are interrelated and have mutual effects; (iii) it performs population projections at the subnational level using alternative socioeconomic and climate scenarios.

7. Conclusions

The population projections performed in this study represent an advance in the literature on the relationship between climate change and population distribution. In addition to the standard demographic components (age and gender structure), assumptions about the progress in education systems over time have been included explicitly in the projections. Given that education is related closely to populations' capability to cope with challenges of mitigation and adaptation to climate change, the projections contribute to identifying the vulnerabilities of populations by quantifying them in terms of their adaptive capacities. Additionally, we performed population and outmigration projections considering alternative socioeconomic scenarios, resulting in much broader representations of the social changes that may occur along with changes in demographic dimensions.

It is important to note that estimates of the potential number of people affected by the climate's adverse effects that would need and effectively use rural outmigration as an adaptive mechanism are under numerous uncertainties. The difficulties in accurately predicting how climate change would impact the population distribution are attributed partially to the relative levels of uncertainty about future climate variables. Moreover, it is not possible to accurately predict human behavior, so the performed projections are only a representation of what could happen in the future based on speculations about socioeconomic and climatic factors. Despite its uncertainties, the projections performed in our study could provide guidance for policymakers. The anticipated knowledge about possible climate and population trajectories could contribute to the development of policies that are oriented and prepared for the possible effects of climate change on rural population displacement.

Although it represents an improvement in methodological terms about the connections between climate change and population dynamics, our study has some limitations. The analysis of rural outmigration based on historical data from only two demographic censuses allowed us to verify the increasing or decreasing trend of outmigration rates for specific micro-regions and population groups. However, it did not allow us to infer the speed of these trajectories over time. As more data about migration between rural and urban areas in Brazil become available in the coming years, future research could overcome this limitation. Therefore, it would be possible to analyze the past migration flows with a greater accuracy degree and infer their trajectories over the coming decades.

References

Beine, Michel and Christopher Parsons (2017) Climatic factors as determinants of international migration: Redux. *CESifo Economic Studies* 63(4), 386–402.

Benveniste, Hélène, Michael Oppenheimer, and Marc Fleurbaey (2020) Effect of border policy on exposure and vulnerability to climate change. *Proceedings of the National Academy of Sciences* 117(43), 26692–26702.

Bernzen, Amelie, J. Craig Jenkins, and Boris Braun (2019) Climate change-induced migration in coastal Bangladesh? A critical assessment of migration drivers in rural households under economic and environmental stress. *Geosciences* 9(51), 1–21.

Bohra-Mishra, Pratikshya, Michael Oppenheimer, Ruohong Cai, Shuaizhang Feng, and Rachel Licker (2017) Climate variability and migration in the Philippines. *Population and Environment* 38(3), 286–308.

Cai, Ruohong, Shuaizhang Feng, Michael Oppenheimer, and Mariola Pytlikova (2016) Climate variability and international migration: The importance of the agricultural linkage. *Journal of Environmental Economics and Management* 79, 135–151.

Cameron, Michael (2018) Climate change, internal migration, and the future spatial distribution of population: a case study of New Zealand. *Population and Environment* 39, 239–260.

Cattaneo, Cristina and Giovanni Peri (2016) The migration response to increasing temperatures. *Journal of Development Economics* 122, 127–146.

Cattaneo, Cristina, Michel Beine, Christiane J. Fröhlich, Dominic Kniveton, Inmaculada Martinez-Zarzoso, Marina Mastrorillo, Katrin Millock, Etienne Piguet, and Benjamin Schraven Beine (2019) Human Migration in the Era of Climate Change. *Review of Environmental Economics and Policy* 13(2) 1–19.

Chen, He, Keisuke Matsuhashi, Kiyoshi Takahashi, Shinichiro Fujimori, Keita Honjo, and Kei Gomi (2020) Adapting global shared socio-economic pathways for national scenarios in Japan. *Sustainability Science* 15, 985–1000.

Crespo Cuaresma, Jesus (2017) Income projections for climate change research: A framework based on human capital dynamics. *Global Environmental Change* 42, 226–236.

Delazeri, Linda Márcia Mendes, Dênis Antônio Da Cunha, and Lais Rosa Oliveira (2021) Climate change and rural–urban migration in the Brazilian Northeast region. *Geojournal* (in Press).

Dellink, Rob, Jean Chateau, Elisa Lanzi, and Bertrand Magné (2017) Long-Term economic growth projections in the Shared Socioeconomic Pathways. *Global Environmental Change*, 42, 200–214.

Drabo, Alassane and Linguère Mously Mbaye (2014) Natural disasters, migration, and education: An empirical analysis in developing countries. *Environment and Development Economics* 20, 767–796.

Falco, Chiara, Marzio Galeotti, and Alessandro Olper (2019) Climate change and migration: Is agriculture the main channel? *Global Environmental Change* 59, 1–26.

Food and Agriculture Organization of the United Nations (FAO) (2016) The State of food and agriculture: Climate change, agriculture, and food security. http://www.fao.org/3/a-i6132e.pdf.

Fuchs, Regina and Anne Goujon (2014) Future fertility in high fertility countries. In Lutz, Wolfgang, Willian P. Butz, and Samir KC (ed.), *World population & human capital in the twenty-first century – an overview*, pp. 147–225. Oxford University Press.

Garbero, Alessandra and Warren Sanderson (2014) Forecasting mortality convergence up to 2010. In Lutz, Wolfgang, Willian P. Butz, and Samir KC (ed.), *World population & human capital in the twenty-first century – an overview*, pp. 650–665. Oxford University Press.

Gietel-Basten, Stuart, Tomáš Sobotka, and Kryštof Zeman (2014) Future fertility in low fertility countries. In Lutz, Wolfgang, Willian P. Butz, and Samir KC (ed.), *World population & human capital in the twenty-first century – an overview*, pp. 39–146. Oxford University Press.

Instituto Brasileiro de Geografia e Estatística (IBGE) (1991) 1991 Demographic census: Microdata. Rio de Janeiro: IBGE.

Instituto Brasileiro de Geografia e Estatística (IBGE) (2000) 2000 Demographic census: Microdata. Rio de Janeiro: IBGE.

Instituto Brasileiro de Geografia e Estatística (IBGE) (2010) 2010 Demographic census: Microdata. Rio de Janeiro: IBGE.

Instituto Brasileiro de Geografia e Estatística (IBGE) (2017) Censo Agropecuário 2017 - Resultados preliminares. https://sidra.ibge.gov.br/pesquisa/censo-agropecuario/censo-agropecuario-2017.

Instituto Brasileiro de Geografia e Estatística (IBGE) (2018) *Projeções da população: Brasil e unidades da federação*. Coordenação de População e Indicadores Sociais. Rio de Janeiro: IBGE, 58 p.

Intergovernmental Panel on Climate Change (IPCC) (2014) Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jiang, Leiwen and Brian C. O'Neill (2017) Global urbanization projections for the Shared Socioeconomic Pathways. *Global Environmental Change* 42, 193–199.

KC, Samir, Marcus Wurzer, Markus Speringer, and Wolfgang Lutz (2018) Future population and human capital in heterogeneous India. *Proceedings of the National Academy of Sciences* 115, 8328–8333.

KC, Samir and Wolfgang Lutz (2014) Alternative scenarios in the context of sustainable development. In Lutz, Wolfgang, Willian P. Butz, and Samir KC (ed.), *World population & human capital in the twenty-first century – an overview*, pp. 591–627. Oxford University Press.

KC, Samir and Wolfgang Lutz (2017) The human core of the shared socioeconomic pathways: Population scenarios by age, sex, and level of education for all countries to 2100. *Global Environmental Change* 42, 181–192.

Koubi, Vally, Spilker, Gabriele Spilker, Lena Schaffer, and Thomas Bernauer (2016) Environmental stressors and migration: Evidence from Vietnam. *World Development* 79, 197–210.

Liehr Stefan, Lukas Drees, and Diana Hummel (2016) Migration as Societal Response to Climate Change and Land Degradation in Mali and Senegal. In Joseph A. Yaro and Jan Hesselberg (ed.), *Adaptation to Climate Change and Variability in Rural West Africa*, Pp. 147–169. Springer.

Lutz, Wolfgang (2018) Introduction: population and migration. In Lutz, Wolfgang, Anne Goujon, Samir KC, Marcin Stonawski, and Nikolaos Stilianakis (ed.), Demographic and Human Capital Scenarios for the 21st Century: 2018 assessment for 201 countries, pp. 12–17. Publications Office of the European Union.

Lutz, Wolfgang and Samir KC (2011) Global human capital: Integrating education and population. *Science* 333, 587-592.

Marchiori, Luca, Jean-François Maystadt, and Ingmar Schumacher (2012) The impact of weather anomalies on migration in sub-Saharan Africa. *Journal of Environmental Economics and Management* 63 (3), 355–374.

Marengo, José, Roger R. Torres, and Lincoln M. Alves (2017) Drought in Northeast Brazil: Past, present, and future. *Theoretical and Applied Climatology* 129, 1189–1200.

Mastrorillo, Marina, Rachel Licker, Pratikshya Bohra-Mishra, Giorgio Fagiolo, Lyndon D. Estes and Michael Oppenheimer (2016) The influence of climate variability on internal migration flows in South Africa. *Global Environmental Change* 39, 155–169.

Merkens, Jan-Ludolf, Lena Reimann, Jochen Hinkel, and Athanasios T. Vafeidis (2016) Gridded population projections for the coastal zone under the Shared Socioeconomic Pathways. *Global and Planetary Change* 145, 57–66.

Mitter, Hermine, Anja-K. Techen, Franz Sinabell, Katharina Helming, Erwin Schmid, Benjamin L. Bodirsky Ian Holman, Kasper Kok, Heikki Lehtonen, Adrian Leip, Chantal Le Mouël, Erik Mathijs, Bano Mehdi, Klaus Mittenzwei, Olivier Mora, Knut Øistad, Lillian Øygarden, Jörg A. Priess, Pytrik Reidsma, Rüdiger Schaldach, and Martin

Schönhart (2020) Shared Socio-economic Pathways for European agriculture and food systems: The Eur-Agri-SSPs. *Global Environmental Change* 65, 102159.

Nawrotzki, Raphael and Maryia Bakhtsiyarava (2017) International climate migration: Evidence for the climate inhibitor mechanism and the agricultural pathway. *Population, Space, and Place* 23(4), 1–16.

Nawrotzki, Raphael and Jack DeWaard (2018) Putting trapped populations into place: Climate change and inter-district migration flows in Zambia. *Regional Environmental Change* 18, 533–546.

O'Neill, Brian, Elmar Kriegler, Keywan Riahi, Kristie L. Ebi, Stephane Hallegatte, Timothy R. Carter, Ritu Mathur, and Detlef P. van Vuuren (2014) A new scenario framework for climate change research: The concept of shared Socio-economic Pathways. *Climate Change* 122, 387–400.

O'Neill, Brian, Elmar Kriegler, Kristie L. Ebi, Eric Kemp-Benedict, Keywan Riahi, Dale S. Rothman, Bas J. van Ruijven, Detlef P. van Vuuren, Joern Birkmann, Kasper Kok, Marc Levy, and lWilliamSolecki (2017) The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change* 42, 169–180.

Oliveira, Jaqueline and Paula Pereda (2020) The impact of climate change on internal migration in Brazil. *Journal of Environmental Economics and Management* 103, 102340.

Otto, I., Reckien, Diana Reckien, Christopher P. O. Reyer, Rachel Marcus, Virginie Le Masson, Lindsey Jones, Andrew Norton, and Olivia Serdeczny (2017) Social vulnerability to climate change: A review of concepts and evidence. *Regional Environmental Change* 17, 1651–1662.

Painel Brasileiro de Mudanças Climáticas (PBMC) (2014) Base científica das mudanças climáticas. Contribuição do Grupo de Trabalho 1 do Painel Brasileiro de Mudanças Climáticas ao Primeiro Relatório de Avaliação Nacional sobre Mudanças Climáticas, COPPE, Rio de Janeiro, RJ, Brasil.

Pires, Gabrielle, Gabriel M. Abrahão, Livia M. Brumatti, Leydimere J. C. Oliveira, Marcos H. Costa, Spencer Liddicoat, Etsushi Kato, and Richard J. Ladle (2016) Increased climate risk in Brazilian double cropping agriculture systems: implications for land use in Northern Brazil. *Agricultural and Forest Meteorology* 228-229, 286–296.

Sander, Nikola, Guy, J. Abel, and Fernando Riosmena (2014) The future of international migration. In Lutz, Wolfgang, Willian P. Butz, and Samir KC (ed.), *World population & human capital in the twenty-first century – an overview*, pp. 333–396. Oxford University Press.

Thiede, Brian, Clark Gray, and Valerie Mueller (2016) Climate variability and inter-provincial migration in South America, 1970–2011. *Global Environmental Change* 41, 228–240.

Tol, Richard (2018). The economic impacts of climate change. *Review of Environmental Economics and Policy* 12(1), 4–25.

Van Vuuren, Detlef P., Jae Edmonds, Mikiko Kainuma, Keywan Riahi, Allison Thomson, Kathy Hibbard, George C. Hurtt, Tom Kram, Volker Krey, Jean-Francois Lamarque, Toshihiko Masui, Malte Meinshausen, Nebojsa Nakicenovic, Steven J. Smith, and Steven K. Rose (2011) The representative concentration pathways: an overview. *Climatic Change* 109, 5–31.

Wurzer, Marcus, Samir KC, and Markus Speringer (2018) MSDem: Multi-State Demography. R package version 0.0.4.1/r19. https://R-Forge.R-project.org/projects/msdem/

Yüceşahin, Mustafa and Samir KC (2015) Demographic and Human Capital Heterogeneity in Selected Provinces of Turkey: A Scenario Analysis Using Multidimensional Population Projection Model. *Economics and Sociology* 8(3), 215–244.