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***Review Article***

# Demographic perspectives in research on global environmental change

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*The human population is at the centre of research on global environmental change. On the one hand, population dynamics influence the environment and the global climate system through consumption-based carbon emissions. On the other hand, the health and well-being of the population are already being affected by climate change. A knowledge of population dynamics and population heterogeneity is thus fundamental to improving our understanding of how population size, composition, and distribution influence global environmental change and how these changes affect population subgroups differentially by demographic characteristics and spatial distribution. The increasing relevance of demographic research on the topic, coupled with availability of theoretical concepts and advancement in data and computing facilities, has contributed to growing engagement of demographers in this field. In the past 25 years, demographic research has enriched climate change research—with the key contribution being in moving beyond the narrow view that population matters only in terms of population size—by putting a greater emphasis on population composition and distribution, through presenting both empirical evidence and advanced population forecasting to account for demographic and spatial heterogeneity. What remains missing in the literature is research that investigates how global environmental change affects current and future demographic processes and, consequently, population trends. If global environmental change does influence fertility, mortality, and migration, then population estimates and forecasts need to adjust for climate feedback in population projections. Indisputably, this is the area of new research that directly requires expertise in population science and contribution from demographers.*

**Keywords**: climate change; emissions; environment; population composition; population distribution; population projections; scenarios; vulnerability

## Introduction

The past decade has witnessed a rise in climate change concern in high-income countries (Funk et al. 2020). Even in 2020, when the Covid-19 pandemic overshadowed all other emergencies, concerns about the threat of global climate change persisted: a median of 70 per cent of respondents surveyed in 14 high-income countries saw climate change as a major threat, compared with a median of 69 per cent who reported concerns about the spread of infectious diseases (Fagan and Huang 2020). Similarly for environmental issues, the majority (71 per cent) of respondents surveyed in 2019–20 in 20 middle- and high-income countries reported that they would prioritize environmental protection over job creation (Funk et al. 2020). The share of people who favour the protection of the environment has also risen since 2005–06. Apart from the influence of recent major climate movements and strikes (e.g. the Friday climate strike), the increasing frequency and intensity of extreme weather events including droughts, floods, hurricanes, heatwaves, and forest fires have also contributed to stronger concern about environmental and climate change (Konisky et al. 2016; Zanocco et al. 2019).

Given the salience of climate and environmental issues and their urgency, it is natural for population science to embrace environmental and climate change topics into its research agenda. Indeed, Hunter and Menken (2015, p. 24) argue that 'the time is ripe for population scientists to become more involved in research on climate change'. Demography, as a discipline that studies population-related phenomena, particularly change in population size, composition, distribution, and characteristics in a systematic manner (Nam 1979), is highly relevant to environment and climate change issues. For demographers the entry point to research on the environment conventionally relates to population growth (Pebley 1998). This can be dated back over 200 years, to the Malthusian view that uncontrolled population growth will eventually deplete natural resources and outstrip the earth's carrying capacity. With larger population size being seen as a major driver of environmental problems (Ehrlich and Ehrlich 1990), the earliest engagement of demographers in environment-related issues was predominantly concentrated on population growth.

However, demographic processes are connected with the environment beyond population growth. As illustrated in Figure 1, the human population is closely linked with the environmental system both through the impact of population dynamics on the environment and as an agent being affected by environmental changes. Population size, distribution, and composition are shaped by demographic behaviour, but it is also possible that environmental changes, in turn, impact demographic processes through influencing fertility, mortality, and migration patterns. Meanwhile, anthropogenic activities modify the physical environment and impact land use, air quality, and water, as well as the global climate system. Further, the interrelationships between population and the environment are driven by socio-economic, technological, cultural, and institutional contexts. The interlinkages between population and the environment and their drivers are elaborated next.

## *How population dynamics influence the environment*

Figure 1 presents examples of the channels through which the human population impacts the environment. Population size is positively associated with the demand for natural resources, including fossil fuels, water, and land, since each person requires food and energy to survive. Food production requires not only substantial amounts of water, but also energy. With more mouths to feed, agricultural revolutions lead to changing land use patterns, from small-scale agriculture to large-scale, energy-intensive commercial farming. This in turn can affect levels of pollution, such as air pollution from burning fossil fuels for both production and consumption. Carbon and greenhouse gas emissions as a result of fossil fuel burning subsequently contribute to the rising global average temperature, which has reached 1 degree Celsius (°C) above pre-industrial levels (Seneviratne et al. 2018).

While population size is evidently positively associated with demand for natural resources, individuals' consumption patterns actually vary across the life cycle. Although residential energy use continues to rise with age, transportation energy use peaks around the early 50s then declines at older ages (O'Neill and Chen 2002). It is estimated for the United States (US) population that per capita emissions of $CO_2$ start to decrease with age when a person reaches their late 60s (Zagheni 2011). With the older population being less active and using fewer electrical appliances and less transportation, changing age structures due to population ageing will consequently lead to a reduction in carbon emissions (Liddle and Lung 2010; Liddle 2011; O'Neill, Liddle, et al. 2012; Kluge et al. 2014; Liddle 2014). Apart from age structure, consumption also varies with other demographic characteristics, such as sex and education. For instance, studies in high-income countries (e.g. Germany, Greece, New Zealand, Norway, and Sweden) show that women's emissions are typically lower than men's because of lower meat consumption, less long-distance travel, and higher use of public transportation, among other things (Räty and Carlsson-Kanyama 2010; Shaw et al. 2020). Likewise, educational attainment matters for carbon emissions because while increases in educational levels are positively associated with economic growth, which implies higher emissions, concomitantly higher educational attainment among women is associated with lower fertility and consequently slower population growth (O'Neill et al. 2020). Human impact on the environment and the global climate system therefore also depends on demographic structures and composition.

Similarly, population distribution is highly relevant to environmental and climate changes. It is estimated that urban areas are responsible for approximately 70 per cent of greenhouse gas emissions (Johansson et al. 2012). Higher incomes among urban dwellers are associated with consumption-intensive lifestyles. Consumption of products (tangible goods) and services (intangible goods,

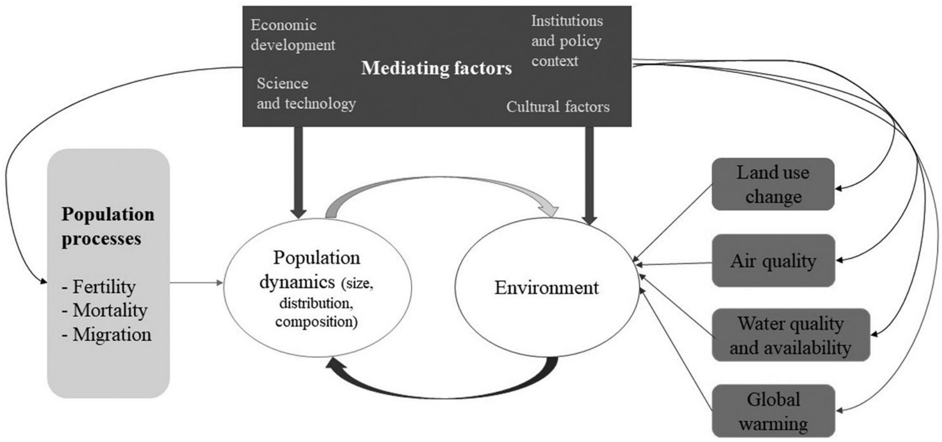


**Figure 1** Conceptual framework describing the relationship between population and the environment
Source: Adapted from Hunter (2000, p. 4 (Figure 1.1)).

such as education, healthcare, culture, recreation, and restaurants) leads to indirect emissions beyond direct energy consumption (Heinonen and Junnila 2011; Ala-Mantila et al. 2014; Gill and Moeller 2018). However, when considering per capita carbon footprint, cities do not necessarily emit more than rural and suburban areas, due to cities' higher population density, smaller dwellings, and shorter transport distances (Dodman 2009; Glaeser and Kahn 2010; Hoornweg et al. 2011). Controlling for wealth, it is found that urban areas in fact have the smallest footprints (Ala-Mantila et al. 2014). This suggests that any analysis of human impact on the environmental and climate systems needs to account for both demographic and socio-economic characteristics and population distribution.

## *How environmental change affects human populations*

While population dynamics influence the environment and the global climate, at the same time human beings are affected by changes in the environmental and climate systems as shown in Figure 1. The consequences of global warming on human health and well-being are already being felt (Watts et al. 2021). The past couple of decades have witnessed an increase in the frequency and intensity of extreme weather events in different areas of the world: for example, summer heatwaves in Europe, severe floods in India and Southeast Asia, severe droughts in the Sahel and Southern Africa, extreme rainfall from hurricanes in the US, and forest fires in Australia and the US West Coast, to name a few. These unprecedented weather shocks are attributable to the increase in global average temperature induced by the accumulation of anthropogenic greenhouse gas emissions (Abatzoglou and Williams 2016; Oldenborgh et al. 2017; Otto et al. 2018; Harrington et al. 2019; Kew et al. 2019; Kumari et al. 2019). The changing climate affects the human population, for example through changes in livelihoods, agricultural production, economic conditions, health, and well-being (IPCC 2014a). Through these channels, it is likely that climate change will also affect demographic processes, including fertility, mortality, and migration, and consequently future population size, distribution, and composition. With global temperatures on course to rise by 2–5 °C by the end of the century (Collins et al. 2013; Raftery et al. 2017), there is thus a potential feedback loop in human–environment systems, whereby human activities impact the environment and the changing environment in turn affects the human population.

The impacts of environmental and climate change on the human population, however, are not distributed evenly across population subgroups, and the ability to adapt and cope with these changes varies substantially with population characteristics. Differences in physiological susceptibility, hazard exposure, and socio-economic and psychosocial factors influence risk perceptions and capacity to respond, and these underlie demographically differentiated vulnerability (Muttarak et al. 2016). For instance, boys are generally more vulnerable to undernutrition than girls, mainly due to biological differences (Thurstans et al. 2020). However, when households face climate-change-induced food insecurity, in certain contexts such as India there is evidence that girls catch up with boys in terms of their chance of becoming undernourished (Dimitrova and Muttarak 2020). This may be due to preferential feeding practices for boys. Vulnerability to environmental change thus depends not only on the type of climatic hazards but, importantly, also on demographic characteristics. Population composition is therefore highly relevant to societies' vulnerability and adaptive capacity (Lutz and Muttarak 2017).

While demographic characteristics determine the degree of vulnerability and capacity to adapt to environmental change, climate risk also depends on population distribution. Exposure (e.g. to extreme climate and weather events) is one key component of risk (Cardona et al. 2012). If hazard events occur in an uninhabited area, naturally no one is exposed to potentially harmful settings, and therefore there is no climate risk. Given their higher density of population and high concentration of assets, urban centres are more susceptible to this risk and suffer greater casualties because of higher exposure. With approximately 55 per cent of the world's population living in urban areas in 2018, the demographic and geographic distribution of urban agglomerations, coupled with their socio-economic and spatial vulnerabilities, determines the risks posed by natural hazards (Gu 2019).

Vulnerability to climate change is also differentiated by the degree of susceptibility of each subpopulation. While urban areas are characterized by higher exposure to natural hazards, in terms of livelihoods people living in rural areas depend more heavily on climatic factors. Subsistence farmers relying on rainfall are particularly susceptible to climate change impacts, and failure to adjust to climate variabilities can have serious consequences on their health and well-being. Child undernutrition, for instance, is found to increase with both droughts and floods, particularly in rural areas and among agricultural households (Dimitrova 2020; Dimitrova and Muttarak 2020). In such households, where crop yields are linked with food security, children are particularly susceptible to climate-induced extreme weather events and anomalies. Susceptibility is also closely linked with a physiological aspect. For instance, older people are highly susceptible to extreme temperatures during both heatwaves and cold spells because of their low ability to thermoregulate (Baccini et al. 2008; Blatteis 2012; Wanka et al. 2014; Kenny et al. 2017; Arbuthnott et al. 2020). Meanwhile, infants and young children are susceptible to dehydration caused by diarrhoeal diseases, which tend to increase after heavy rainfall and flooding events (Bennett and Friel 2014; Levy et al. 2016).

Hence, not only does *where* the population live matter, but *who* is susceptible and to *what* hazard also underlie vulnerability. The impact of environmental and climate change on human populations thus depends not only on population size but also substantially on their distribution (which determines exposure) and composition (which is linked with susceptibility, vulnerability, and adaptive capacity).

## *Mediating factors underlying the relationship between population and the environment*

The interactions between population and the environment are complex and are driven by many other forces. While population growth drives environmental change, patterns of consumption and production are closely linked with socio-economic development, which also determines population trends. The importance of considering the interconnectedness between systems (including economic and social/cultural systems) in understanding population–environment interactions is highlighted by many scholars (Lutz 1994; Lutz, Fürnkranz-Prskawetz et al. 2002; Martine 2005; Cohen 2010). The role of other factors in driving the impact of human activities on the environment and the level of vulnerability of human populations to environmental changes is coined 'the sphere of the human-made environment' in Lutz, Fürnkranz-Prskawetz et al. (2002, p. 4). People are seen as agents who conduct their social and economic activities under different infrastructures, economies, governments, political systems, social structures, traditions, technologies, and information regimes. Further development of this human-made environment thus influences the ultimate nature of the relationship between population and the environment.

Similarly, factors such as technologies, institutions, and cultures are seen as 'mediating factors' in Hunter (2000, chap. 5), where an extensive review of the role of these factors in mediating the relationship between human population dynamics and the natural environment is provided. Figure 1 presents examples of the factors underlying this relationship. No doubt, advancements in *science and technology* influence production and consumption in all economic sectors, ranging from agriculture and fishery, energy, waste management, construction, and manufacturing to hospitality and tourism. Technological innovations—such as irrigation technologies, development of new crop varieties, structural barriers for protection of coastal resources and flood prevention, and desalination—have been introduced to facilitate adaptation to environmental change. Technological adoption, in turn, also depends on the characteristics of the population, including *culture*.

Culture influences individuals' world views, values, beliefs, and norms and, consequently, how human beings interact with the natural environment (Eisler et al. 2003; Liobikienė et al. 2016). Defined as the 'collective programming of the mind', culture 'distinguishes the members of one group or category of people from another' (Hofstede et al. 2010, p. 5). Cultural values—such as son preference, gender roles, and individualistic vs collectivist culture—influence psychological processes underlying why and how individuals and groups engage in certain social behaviours that can have direct and indirect impacts on the environment (e.g. through fertility behaviour, consumption levels, and preferences). For instance, while an increase in income is generally linked with a rise in meat consumption, this positive relationship is less steep in China and particularly in India as compared with the US (Ausubel and Gruebler 1995; Sans and Combris 2015). As dietary habits are influenced by traditions and customs, almost one-third of Indians follow lacto-vegetarianism (Devi et al. 2014). This shows that culture can alter the interactions between demographic and environmental factors.

Unquestionably, government *institutions and policy context* at the local, national, and international levels are vital in mediating demographic pressure on the environment and mitigating the impact of environmental change. While policy responses such as the Montreal Protocol of 1987 have been successful in reducing global emissions of chlorofluorocarbons (CFCs) through banning products that contain CFCs (Hunter 2000), certain policies, such as community relocation after natural disasters, often exacerbate the vulnerability of disadvantaged population subgroups (Iuchi and Mutter 2020). Governments set up regulations and policies that monitor and incentivize uptake of mitigation and adaptation actions and thus contribute to mediating how people interact with the environment. The Shared Socio-economic Pathways (SSPs)—descriptions of alternative futures of societal development—exemplify, for instance, how different energy and socio-economic development policies could yield varying trajectories of global warming and human vulnerability to environmental and climate change (O'Neill et al. 2014). Likewise, policies that may not be considered directly as environmental policies (e.g. educational expansion) may modify human impact on the environment as well as contribute to vulnerability reduction (Lutz, Muttarak et al. 2014; Lutz and Striessnig 2015).

The bidirectional relationship between population and the environment is hence determined by complex interactions among many other mediating factors, and a better scientific understanding of these interactions is called for (Hunter 2000).

In the remainder of this paper, I describe the historical development of the field of population and environment, with a focus on scrutinizing why environmental and climate change research has not become central in population studies. The subsequent section explores the relevance and contribution of demography to climate change research, in terms of both the impact of population dynamics on the climate system and the impact of climate change on the population. Through an extensive review of the development of the field, I describe future directions in integrating demographic perspectives into global environmental change research: research on the impact of climate change on population trends is highly relevant, given the potential climate feedback on demographic processes themselves. The 'Conclusion' highlights the contribution of demography to understanding and forecasting population–environment interactions.

## Historical development of the field of population and environment

With the human population being central to the global environmental and climate systems, demography is a highly relevant field in environmental and climate research. Lutz, Fürnkranz-Prskawetz et al. (2002) in a supplement to *Population and Development Review* propose that population–environment analysis deserves a specific field of study, given a clearly identified unifying research question focusing on the impacts of population dynamics on the natural environment (P–E) on the one hand and the impacts of changes in the natural environment on human populations (E–P) on the other.

While Lutz, Fürnkranz-Prskawetz et al. (2002) argue that a critical mass of scholars working in the population and environment field has emerged, it remains a minor field of study among demographers. This is evident from an international online survey of opinions and attitudes of 970 demographers who were members of the International Union for the Scientific Study of Population (IUSSP) (Van Dalen and Henkens 2012), where study of environmental and climate issues was not listed among the key interests of demographers. Population ageing was ranked top, as the most important population issue facing the world in the next 20 years, followed by mass migration, HIV/AIDS, above-replacement fertility, urbanization, and infant mortality. Despite the ever increasing prominence of climate change in the international community and published debates—for example, the joint award of the Nobel Peace Prize to the Intergovernmental Panel on Climate Change (IPCC) and former US Vice President Al Gore for their efforts to obtain and disseminate information about the climate challenge in 2007; the Paris Agreement adopted in 2015; and the Fridays for Future climate movement—research on environment and climate change remains peripheral in demographic research. This is reflected in the very few sessions dedicated to population and environment in major demographic conferences, such as annual meetings of the Population Association of America (PAA) and European Population Conference (McDonald 2016; Abel et al. 2019). This lack of engagement in environmental and climate-related research also results in under-representation of demographers in major scientific efforts on climate change mitigation and adaptation actions, including the IPCC reports and the United Nations (UN) Climate Change Conferences.

## *Why environmental and climate change issues have been peripheral in demographic research*

The reasons why environmental and climate change issues remain less popular among demographers are summarized in the PAA presidential address published in *Demography* (Pebley 1998) and also the special issue of the *Vienna Yearbook of Demography* which focuses on demographically differentiated vulnerability to climate-related disasters (Muttarak and Jiang 2015). Among the key reasons mentioned, the *bitterness of the debate surrounding the 'limits to growth' issue* plays a major role in influencing present-day demographers in their engagement on environmental and climate change issues. On the one hand, as stated by economists with the cornucopian view (e.g. Ester Boserup and Julian Simon), advances in technology facilitate the provision and production of material items. Not only is population growth seen as non-problematic because technology can overcome limited natural resources, it is also linked with increased productivity (Chenoweth and Feitelson 2005). On the other hand, according to Malthusians (influenced by the work of Thomas Malthus), continued exponential growth of the population will exceed that of food production, which grows arithmetically, hence from the late 1940s when the world population rose rapidly, population growth was viewed as a serious crisis.

Subsequently, the late 1960s and early 1970s saw a rise in concerns about the capacity of the environment to absorb the multiple forms of pollution generated by population and economic growth. This was reflected in a series of publications including a book entitled *The Limits to Growth* published by the Club of Rome in 1972 (Meadows et al. 1972; Ehrlich and Ehrlich 1990). Analysing the interactions between the five basic factors underlying the earth's interlocking resources, based on data up to 1970, Meadows et al. (1972) show that as the world population grows, demand for material wealth increases, leading to higher resource use, higher industrial output, and increasing pollution. The classic model used in this line of research, as Ehrlich and Holdren (1971) propose is the IPAT equation:

$$I = P \times A \times T,$$

where $I$ stands for environmental impact, $P$ for population, $A$ for affluence, and $T$ for technology. This equation has been operationalized and applied by considering $I$ as $CO_2$ emissions, $A$ as GDP per capita and $T$ as $CO_2$ per unit of GDP. Environmental impacts (e.g. emissions) were thus mainly considered as a function of the interactions between population size/growth, affluence, and technology.

Continued population and economic growth is therefore not sustainable, because the earth's supply of resources is finite. Accordingly, in the late 1960s and 1970s population control was seen as an essential means to achieving economic growth and ensuring sufficient environmental resources (McDonald 2016). Many scholars advocated fertility reduction as a means to improve living standards and protect the environment and argued for population policy to be given immediate priority due to the time lag for policy effects to be realized (Jolly 1994). Accordingly, the focus of demographic research was on how to reduce fertility in less developed countries rather than on the interactions between demographic factors and environmental variables (Pebley 1998).

Likewise, the central role population growth plays in global warming has led to a renewed interest in population control in low- and middle-income countries (LMICs). While family planning can potentially contribute to reducing anthropogenic impact on the climate system, population control is a controversial policy solution. Not only is using population control to curb $CO_2$ emissions a contentious ethical issue due to potential violations of women's sexual and reproductive health and rights (Sasser 2018), many demographers see limiting population growth as depriving poorer countries of the 'right to develop' (van Dalen and Henkens 2021). Furthermore, fertility tends to be low in the countries that are mainly responsible for greenhouse gas emissions, while countries with high population growth do not contribute much to climate change (Stephenson et al. 2010). This dilemma, coupled with images of reproductive coercion by governments and non-governmental organizations in some countries, has made demographers ambivalent about the benefits of family planning. Given that the current debate on climate change is related to human activities and greenhouse gas emissions, the historical bitterness of this debate on population growth has made demographers reluctant to engage with climate change and environmental issues (Gage 2016; Peng and Zhu 2016). As a consequence, discussions on population control as a means to fight global warming tend to be dominated by ecologists, biologists, economists, and public health scholars (Bryant et al. 2009; Cafaro 2012; Guillebaud 2016; Ripple et al. 2017).

The second reason for the lack of engagement concerns the perception among many demographers that the *research topics surrounding the environment and climate change*—such as production and consumption, technological advancement, regulations and institutions, disaster vulnerability, and adaption—*are more directly related to other social science disciplines* (e.g. economics, political science, geography) than demography (Pebley 1998; Hayes 2016; Peng and Zhu 2016). As a discipline focusing on the scientific study of human populations, including the drivers of population dynamics and consequences of population change (IUSSP 2017), strictly speaking, the field of environment and climate change involves many other narratives that expand beyond formal demography (Peng and Zhu 2016). Keyfitz (1992) points out that the emphasis on the effects of other variables (e.g. institutions, markets, and feedback effects) undermines the role of population dynamics in driving global environmental change. Therefore, instead of seeing population as closely linked to the environment and climate change, the latter were considered to be irrelevant for demographic research (Pebley 1998).

Furthermore, the *complexity of climate and environmental science and the limitations of data and methods* for integrating the environmental and climate context into the microdata commonly used by demographers are also barriers to a more active engagement of demographers in this field (Hunter and Menken 2015; Hayes 2016). The study of global environmental change requires expertise in natural sciences, as well as skills in spatial statistics, remote sensing, and geographic information systems (Pebley 1998). Given that demography is a discipline with a strong empirical element (Caldwell 1996), the lack of appropriate data and analytical tools in the past has hindered the involvement of demographers on this topic. The lack of engagement of demographers with the climate change research community has resulted in the absence of social and demographic components in conventional climate models (e.g. the IPCC's integrated assessment models). Without consideration of societal and population change, it is not possible to provide an integrated and reliable assessment of future change. Interdisciplinary collaboration can certainly fill this gap, but differences in paradigms and assumptions in natural and social sciences remain an obstacle to cross-disciplinary fertilization.

Finally, *limitations in funding* also make it challenging for demographers to take a new topic on board. Obtaining a research grant for a cross-cutting theme such as population dynamics and environmental change has proved difficult, especially because a project proposal still tends to be evaluated within a traditional disciplinary specialization. Despite worldwide recognition of the urgency of interdisciplinary research to address global challenges and complex problems such as climate change, there is evidence that in the past, interdisciplinary projects were less likely to be funded (Bromham et al. 2016). In addition, funders of climate change research tend to value natural sciences more than social science approaches (Peng and Zhu 2016). Overcoming this obstacle will facilitate demographers' involvement in this field.

In summary, although study of the three components of population change (namely, fertility, mortality, and migration) remains the central focus of core demographic research, the past two decades have witnessed an increasing engagement of demographers in environmental and climate change research, as well as a widening of interdisciplinary collaborations. The ratification of the Kyoto Protocol in 1997—where industrialized countries were mandated to reduce their greenhouse gases emissions by 5.2 per cent from a 1990 baseline—marked the first step in global efforts to tackle climate change (Böhringer 2003). Climate change mitigation has accordingly gained importance in international scientific and political debates, marking the start of the increasing engagement of demographers in research in the field of climate change.

### *Renewed interest of demographers in population–environment research*

The growing scientific evidence on the role of human activities as a main driver of global warming called for insights from demography in understanding population issues. One prominent contribution of demographers was the development of the population–development–environment (PDE) approach: a system study of the complex interactions between population, development, and environment under an integrated assessment framework (Lutz 1994; Sanderson 1994; Lutz and Scherbov 2000; Lutz, Fürnkranz-Prskawetz et al. 2002; Lutz, Scherbov et al. 2002; Lutz et al. 2004). Based on case studies, this approach combines a historical analysis of a case study country using qualitative and statistical methods with a series of simulation models. By producing different projections under alternative policy-relevant scenarios (e.g. with regard to policies on population, migration and remittances, and energy), the PDE model is also relevant from a policy perspective, allowing decision makers and stakeholders to explore alternative sustainable development paths via easy-to-use tools. In particular, the PDE model uses the population-based approach, which goes beyond the narrow view that only population growth or demographic changes matter for the environment (Lutz and Scherbov 2000). Human beings and their characteristics (e.g. age, sex, education, health, and place of residence) are considered as agents of change in social, economic, cultural, and environmental systems as well as agents whose well-being is directly affected by these changes. These demographic characteristics can be quantified and projected using the tools of multistate demographic analysis and then integrated into systems analysis. The integrated dynamic systems help to identify different policy options and to consider how an intervention influences the interconnected human, social, economic, and environmental systems in a scenario-based manner. The potential of demography in forecasting future population size, composition, and distribution allows for the realistic matching of future societies' characteristics with climate change scenarios (Lutz and Muttarak 2017).

Furthermore, as a result of recent developments, the availability of climate and natural disaster data in the public domain and of repeated cross-sectional and longitudinal individual and household data containing demographic and relevant outcome variables has increased, and this has opened up new opportunities to study the interactions between population and environmental change (Fussell et al. 2014). Many individual and household surveys, such as the Demographic and Health Surveys (DHS), now contain geospatial variables allowing researchers to link demographic data with environmental data. Recent efforts, for instance, by IPUMS Terra, which links population census and survey microdata with land cover, land use, and related climate data, also facilitate the empirical study of human–environment interactions (Haynes et al. 2017; Minnesota Population Center 2021). Simultaneously, advancement in statistical techniques and computing technologies are facilitating the management and analysis of complex, large-scale environmental and demographic data. These new developments in data and computational tools, coupled with the urgency of environmental issues, have encouraged the participation of demographers in the environmental and climate change research field.

## Relevance and contribution of demography to climate change research

That 'people are part of the problem of climate change and part of the solution' (Cohen 2010, p. 158) highlights the centrality of human populations in the global climate system. As a discipline focusing on the scientific study of demographic trends and their drivers, demography can naturally provide insights into demographic challenges in the context of climate change. Indeed, the IPCC's *Fifth Assessment Report* explicitly calls for contributions from social sciences, especially to improve understanding of the social dimensions of climate change and vulnerabilities (IPCC 2014a). Furthermore, the *World Social Science Report* emphasizes the urgency of transforming social science, through more collaboration both within and across scientific fields, into a 'bolder', 'better', and 'bigger' field (ISSC and UNESCO 2013). In particular, it emphasizes the potential of social sciences to deliver solution-oriented knowledge on the challenges posed by global environmental change. This view has in fact already been put forward by Lutz (2012), who advocates using social science research as 'intervention sciences'; this term refers to the social and economic sciences that study the current drivers of social change, how they will transform in the future, and what actions (interventions) can alter the future pathway of events (Lutz 2012). Lutz and Striessnig

(2015) argue that even though human behaviour is less deterministic than the systems and phenomena studied in the natural sciences, it is still feasible to model social change where possible future outcomes are forecasted based on specified uncertainty ranges.

Understanding and predicting social change is of relevance in informing global environmental change policies and solutions; this requires models with predictive power for both the natural and social dimensions. However, scenario-based assessments commonly use present-day socio-economic conditions in assessing future biophysical impacts (IPCC 2014a). Despite the awareness that future societies will differ from those observed today, there remains little effort to project alternative future scenarios of socio-economic and human development (Lutz and Striessnig 2015). This is because it is rather difficult to quantify and develop alternative future scenarios in this field. Lutz and Muttarak (2017) nevertheless argue that certain aspects of societal development can be quantified and forecasted. Population dynamics, in particular, are highly relevant to both the anthropogenic impact *on* climate change and the vulnerability and adaptation *to* climate change. Knowledge and methods in demography can thus be applied to improve our understanding of uncertainties, especially in the domains relevant to climate change mitigation, adaptive capacity, and adaptation planning.

## *Population impact on the climate*

By the 1980s, it had become clear that global average temperature had increased and the planet was warming. Given concern that this might be partly driven by human activities, the IPCC, endorsed by the UN General Assembly, was established in 1988. The IPCC's mandate was to provide a comprehensive review and recommendations regarding research on climate change and its social and economic impacts, including identification of potential response strategies. Since 2001, following the publication of the IPCC *Third Assessment Report* (IPCC 2001), there has been a wide acceptance of anthropogenic climate change. That human activities cause changes to the climate system through burning of fossil fuels, land use change, and consumption has highlighted the relevance of demography in understanding human impact on the global climate system.

Traditionally, the role the human population plays in carbon emissions was considered to be merely through population size or growth (de Sherbinin et al. 2007). When considering the three drivers of carbon emissions in the IPAT equation, moderating population growth (P) and transitioning to a low-carbon economy (T) are viable policy options, given that intervention should not come at the expense of economic growth (A), especially for LMICs. Indeed, 12 per cent of increased emissions in Organisation for Economic Co-operation and Development countries between 1982 and 1997 were attributable to population growth alone (Hamilton and Turton 2002). Bongaarts et al. (1997) thus argues that by reducing global fertility by only half a birth per woman (corresponding with the UN's low-variant population projection (United Nations 1992)), only a 33 per cent reduction in carbon intensity by the end of the twenty-first century would be required to keep total warming below 2 °C. Given that slowing down population growth through reducing fertility can contribute to emissions reduction, there has been a call for the climate community and particularly the IPCC to incorporate population policy explicitly into climate actions (Bongaarts et al. 1997; Bongaarts and O'Neill 2018). Although demographic factors are less important than per capita income and other variables in determining short-term emissions, Lashof and Tirpak (1990) show that the population assumptions are key in explaining the future path of greenhouse gas emissions by the year 2100, meaning that an understanding of the world's changing demography is highly relevant.

*Population projections as a tool for forecasting population impact.* Population projections provide a tool to quantify uncertainty in the future population trends underlying the future path of greenhouse gas emissions. The two most widely used sets of long-range global population projections are the: (1) UN Population Division projections, available since the early 1950s; and (2) projections by the World Population Program of the International Institute for Applied Systems Analysis (IIASA) based outside Vienna, Austria, available from 1994 (Lutz and KC 2010). Since 2011, the IIASA projections have been carried out in the framework of the Wittgenstein Centre for Demography and Global Human Capital (WIC). A comprehensive review of different global population projection methods and assumptions can be found in O'Neill et al. (2001) and Lutz and KC (2010).

The challenge in long-range population forecasting is how uncertainty is dealt with. This has important implications for climate change research. For instance, the medium projections by the UN (United Nations 2015) and WIC/IIASA (Lutz, Butz, et al. 2014) present rather different outlooks of the most likely future trend in world population, with a difference of 1.7 billion people by 2100. While the UN's medium-variant projection from the probabilistic model forecasts that the world population will increase to 10.9 billion in 2100, the WIC/IIASA medium (most likely) scenario projects an increase in global population to 9.2 billion by the end of the century. Such a large discrepancy between the two leading sources of demographic projections is not trivial when considering the impacts of human activities on the climate and environmental system.

Using a technique of probabilistic projection, the UN applies a Bayesian hierarchical model to estimate double logistic curves for total fertility and life expectancy at birth, including probabilistic prediction intervals that give quantitative information about the range of uncertainty in future trajectories (Raftery et al. 2014). Probabilistic models present the likelihood of a future population value in the form of a probability distribution and thus yield only one output instead of multiple scenarios. In contrast, using the approach of expert-argument-based projections, the WIC/IIASA projections rely on an online survey of over 550 international experts and workshops focusing on the future demographic trajectories of specific countries and world regions (Lutz, Butz et al. 2014). The scientific inputs from the survey and workshops are synthesized and quantified, providing numerical assumptions for the calculation of alternative global demographic scenarios to 2060, with extensions to 2100.

Recently, new global population projections have been introduced by the Institute for Health Metrics and Evaluation (IHME). Future population is projected based on complex statistical methods, which model fertility, mortality, and migration rates as a function of relevant covariates: for example educational attainment and contraceptive met need in the case of total fertility; risk factors in the case of age-specific mortality; and socio-demographic index and crude population growth rate in the case of net migration (Vollset et al. 2020). The resulting projected global population is 8.79 billion (6.83–11.8) in 2100 in the IHME reference scenario, even lower than that of the WIC/IIASA medium-scenario projection. This result is driven partly by the assumptions about the impact of women's educational attainment and access to contraception on future fertility trends and scenarios used in the IHME models, which may not be very realistic (Gietel-Basten and Sobotka 2020). The IHME overestimates the effects of contraceptive use and met need for family planning, resulting in a continuation of very low fertility in low-fertility countries and other regions. Furthermore, demographers also question the choice and quality of the underlying data, models, and scenarios used. While the IHME projections have received extensive coverage in the media, Gietel-Basten and Sobotka (2020) note that the choice of population projections used for policy decision making needs to be made with caution.

Since assumptions about the future are fundamental for population projections, the variation in how uncertainty is dealt with in different projection methods influences the results. While probabilistic projections within a short time horizon are reasonably accurate, there is no consensus on the most reliable methods for generating reliable probabilistic bounds to represent the uncertainty of long-range population projections (Lutz and KC 2010; Rozell 2017). WIC/IIASA projections express uncertainty by using different scenarios that are linked to the SSPs developed by O'Neill et al. (2014). The SSPs provide alternative pathways for global social and economic development over the next century and are used in the latest climate models incorporated in the IPCC's *Sixth Assessment Report* (IPCC 2021). While the scenario-based approach has been criticized for its lack of quantification of uncertainty due to the absence of probability intervals, and thus is not useful for providing a range of probable population sizes (Keilman 2020), Rozell (2017) argues that the WIC/IIASA projections are more suitable for analysing climate change policy options. By aligning the demographic scenarios with the SSP scenarios for climate modelling used in IPCC reports, WIC/IIASA projections allow users such as policymakers to answer 'what if … ?' questions, in order to assess the effects of certain policies.

*Population distribution and composition matters for human impact on the climate.* Apart from population size, other demographic processes and changes—including population composition and distribution, ageing, and urbanization—all have implications for consumption and production activities, which in turn influence the emissions driving climate change. A group of demographers argue that research on drivers of climate change which focuses only on specific demographic variables (e.g. total population size) can misrepresent the effects of demographic change on emissions (de Sherbinin et al. 2007; Cohen 2010; O'Neill, Liddle, et al. 2012). Indeed, a knowledge of the spatial distribution of population by geographic region and size of settlement is also fundamental in understanding changes in land use/cover and greenhouse gas emissions. Given the established rural–urban differences in energy consumption, substantial urbanization is found to be positively associated with per capita emissions (Parikh and Shukla 1995; York et al. 2003; Liddle and Lung 2010). In particular, higher income levels in larger metropolitan areas translate into higher consumption levels and emissions (Pachauri and Jiang 2008). Nevertheless, the impact of urbanization on energy use and carbon emissions is not homogeneous across countries. For example, exploring energy and emissions in India and China by a range of urbanization scenarios, O'Neill, Ren et al. (2012) show that because differences in per capita income between rural and urban areas are smaller in India (in baseline data), this explains the smaller effects of urbanization on emissions in India as compared with China. In general, the literature suggests that given the same income level, rural areas show higher per capita emissions than urban areas.

Apart from differences in levels of affluence and development, urban density is also a key factor underlying greenhouse gas emissions (Chen et al. 2008). High concentrations of people and economic activities are found to be associated with lower levels of energy consumption and lower emissions from transport and buildings (Liddle 2014). High population density improves the efficiency of public infrastructure, resulting in efficient public transport systems and local availability of facilities and services. Despite higher consumption due to higher wealth, since population density tends to be higher in urban centres, it remains unclear whether urbanization has a positive or negative effect overall on greenhouse gas emissions. A recent study by Ribeiro et al. (2019) introduces a new approach that accounts for the confounding effects of the roles of population size and population density, including their interactions, on urban emissions. It finds that apart from emissions in urban areas being dependent on population size and population density, larger cities (in terms of population size and area) also benefit from a greater impact of increasing population density on urban $CO_2$ emissions reduction. Demographic methods which account for spatial patterns of population change are thus crucial in the estimation of greenhouse gas emissions.

Changing population composition is also highly relevant in forecasting future carbon emissions. O'Neill, Liddle et al. (2012) show that net of the effect of changes in population size, emissions in particular regions depend considerably on changes in population composition. In particular, given the lower labour productivity of older populations, which consequently translates into declining economic growth, population ageing is projected to contribute to emissions reduction in the long term by up to 20 per cent. As well as changing age structures, a recent study also shows that changes in educational composition have implications on the climate system (O'Neill et al. 2020). The role of education on carbon emissions, however, is rather complex (Lutz and Striessnig 2015). On the one hand, increasing educational levels lead to a desire for smaller family sizes, which in turn contribute to slowing down population growth (especially in high-fertility contexts) and, consequently, lower emissions. On the other hand, education is associated with higher labour productivity and economic growth and, as a result, higher emissions. O'Neill et al. (2020) estimate for the first time the net effects of education on emissions, accounting for its influence on both population growth and economic growth. By the end of the century, projected higher educational attainment under the SSP2 ('middle of the road') scenario in all LMIC regions leads to net higher emissions due to the stronger role of education in promoting economic growth compared with its role in decreasing population. The readily available global population projections by age, sex, and education under different SSP scenarios are hence highly useful in forecasting the impact of human activities on emissions (KC and Lutz 2017).

Future forecasts of energy consumption also depend on which units of analysis are used: individuals or households (MacKellar et al. 1995). Since large portions of energy and energy-related commodities in both residential and transportation sectors are purchased and consumed jointly by household members, estimates and projections of household numbers are argued to be more relevant for forecasting energy consumption (de Sherbinin et al. 2007). Indeed, few cross-national studies show emissions per person to be negatively associated with average household size (Cole and Neumayer 2004; Liddle 2004). With lower energy consumption per person in larger households, a decline in household size following urbanization and industrialization across the globe can thus yield negative environmental impacts (Bradbury et al. 2014). While there has been some progress in curbing population growth, the growing number of smaller households highlights the importance of taking household dynamics into any study of the demographic drivers of climate change.

By providing scientific insights into how current and future population size, distribution, and composition drive climate changing carbon emissions (MacKellar et al. 1995; Gaffin and O'Neill 1997; O'Neill et al. 2005; O'Neill et al. 2010; Jiang and Hardee 2011; O'Neill, Liddle, et al. 2012), demography has made a significant contribution to the field of climate change.

## *Impact of climate change on population*

More recently, the interest in population dynamics in climate change research has also extended to the identification of vulnerable populations and their locations through estimating the distribution and size of populations potentially at risk of exposure to climatic hazards (de Sherbinin 2014; López-Carr et al. 2014; Harrington and Otto 2018). Population dynamics are unquestionably relevant to the understanding of hazard exposure and vulnerability. The IPCC's *Fifth Assessment Report* defines vulnerability as 'the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt' (IPCC 2014b, p. 5). Population size is linked with vulnerability since rapid population growth and high population density increase the number of people exposed to climate impacts and put pressure on the provision of basic services and infrastructure (Jiang and Hardee 2011).

*Demographically differentiated vulnerability: Present and future.* The impacts of climate change are not distributed evenly across population subgroups, and the ability to adapt and cope with climate change varies substantially with population characteristics (Muttarak et al. 2016). Demographic concepts and methods can be applied to identify demographically differentiated vulnerability that results from differences in physiological susceptibility, hazard exposure, and socio-economic and psychosocial factors influencing risk perceptions and capacity to respond. For instance, mortality rates from tsunamis are generally higher in women than men due to women's lack of swimming ability (a physiological aspect underlying vulnerability) (Neumayer and Plümper 2007) and to the caregiving role that prompts women to stay behind helping children and the elderly (a psychosocial factor underlying vulnerability) (Yeh 2010; Frankenberg et al. 2011). In contrast, men are more likely to perish from floods and storms due to higher engagement in outdoor activities and greater risk-taking attitudes (exposure and a psychosocial factor underlying vulnerability) (Doocy, Daniels, et al. 2013; Doocy, Dick, et al. 2013; Zagheni et al. 2016).

Apart from differentials in susceptibility and exposure, the ability to cope with climatic shocks also varies with demographic and socio-economic characteristics. For example, women's vulnerability to climate hazards is not only associated with differentials in physiological susceptibility but also with their socio-economic position. Limited access to formal credit markets, for instance, makes female-headed households in South Africa more vulnerable to income loss due to climatic shocks (Flatø et al. 2017). A demographic characteristic may also interact with socio-economic characteristics, thus producing further differentials in vulnerability and adaptive capacity. While education is generally found to have a protective effect against vulnerability to climatic shocks (Muttarak and Lutz 2014), it is also reported that mothers' education has a stronger effect in mitigating drought-induced childhood undernutrition than fathers' education (Dimitrova 2020). Differential gender roles, whereby women are more likely to be involved in childrearing, may explain this finding. Children are reported to benefit from the better health knowledge and access to healthcare of highly educated mothers, which prevent children being undernourished when the household experiences climatic shocks (Dimitrova and Muttarak 2020). Accounting for demographic differentials in coping capacity is thus fundamental for vulnerability reduction efforts.

Following the inauguration of WIC in Vienna in 2010, a group of demographers proposed education as an important source of population heterogeneity (KC et al. 2010; Lutz 2010; Lutz and KC 2011; Lutz and Skirbekk 2014). At the societal level, the role of education extends beyond influencing population dynamics. Changes in educational composition in a population are found to be key drivers of economic growth (Lutz et al. 2008; Lutz et al. 2019) and increasing life expectancy (Lutz and Kebede 2018), and even of promoting democracy (Lutz et al. 2010). It is also shown that providing quality education for all can promote achievement of the sustainable development agenda (Lutz 2017; Bengtsson et al. 2018). This argument is based on a series of evidence showing the (sometimes causal) links between education and other life domains, such as labour market, health, and gender equality. Given the importance of education for various desirable outcomes, unsurprisingly there is consistent evidence showing that education can contribute to reducing vulnerability and enhancing adaptive capacity (Muttarak and Lutz 2014).

The mechanisms through which education directly and indirectly influences vulnerability and adaptive capacity are thoroughly discussed elsewhere (Muttarak and Lutz 2014; Hoffmann and Muttarak 2017; Dimitrova and Muttarak 2020). Muttarak (2021) and Bengtsson et al. (2018) provide a comprehensive review of evidence on the role of education in reducing vulnerability in various domains. These mechanisms range from education equipping individuals with better risk perception, better disaster preparedness, lower morbidity and mortality, and faster recovery from natural disasters to individuals having more diversified adaptation options. Changing the educational composition of the population can therefore influence the future impact of climate risks on population health and well-being (Lutz, Muttarak et al. 2014; O'Neill et al. 2020).

Using existing methodological tools to forecast future population distribution and composition, recent studies combine empirical analysis of demographically differentiated vulnerability with multidimensional cohort component population projections to forecast future societies' vulnerability and adaptive capacity. For example, based on a regression analysis estimating mortality from climate-related disasters as an indicator of vulnerability (Striessnig et al. 2013), Lutz, Muttarak et al. (2014) project future disaster deaths by applying education coefficients to the demographic scenarios underlying the SSPs. SSP scenarios are useful in this context, given that different scenarios underlie different socio-economic development pathways and their corresponding mitigation and adaptation challenges. By exploiting the readily available estimates of population size and composition (e.g. by age, sex, and education) by SSP scenario up to the year 2100 (KC and Lutz 2014, 2017), it is possible to forecast the vulnerability of future societies (Lutz and Muttarak 2017).

*Spatial heterogeneity: Present and future.* Climate risks depend not only on the degree of vulnerability but also on exposure. Rather than considering exposure as a simple, static description of geographical location associated with the risk of climate events, Martine and Schensul (2013) argue that exposure itself is shaped by a range of social and demographic processes. Apart from asking in '*what* place?', it is necessary to consider '*who* is exposed?' and '*why* them?' (Martine and Schensul 2013, p. 11). Therefore, population characteristics need to be accounted for when analysing spatial population distribution. In order to provide meaningful projections of the spatial distribution of population that allow for identification of subpopulations vulnerable to the impact of climate change, demographic models that capture population heterogeneity at a smaller spatial resolution than the global scale are required.

Various spatial downscaling procedures with varying levels of complexity can be performed, especially to match with the scenario-based assessment of global change, future impacts, vulnerability, and sustainable development (Zoraghein and O'Neill 2020). In particular, spatial projections that are consistent with the global change narratives describing future pathways of societal development (e.g. the SSPs) are highly relevant for policy planning. Unlike most existing spatially explicit global projections, which use simple scaling techniques or trend extrapolation (Bengtsson et al. 2006; van Vuuren et al. 2007; Hachadoorian et al. 2011), Jones and O'Neill (2016) produce a set of global spatial population projections at a resolution of 1/8° (7.5 arcminutes) using their previously developed gravity-based population downscaling model (Jones and O'Neill 2013). National-level projections of urban and rural population change are downscaled, consistent with the demographic assumptions in each SSP narrative. A subsequent work by Gao (2017) further downscales the projections by Jones and O'Neill (2016) at a resolution of 1 km (about 30 arcseconds) to match the needs of some studies that require data with a finer spatial resolution. These spatial projections of population can be matched with high-resolution downscaled climate and hazard projections to identify future climate risk (Smith et al. 2019; KC et al. 2020).

Although spatial heterogeneity is well captured in spatially explicit population projections, other dimensions of demographic heterogeneity have not been explicitly considered. In their recent work, Zoraghein and O'Neill (2020) produce spatial population projections by rural and urban residence for each state in the US at high resolution (1 km). While this new approach advances our knowledge of the rural and urban population change patterns of each US state, other demographic characteristics underlying vulnerability and adaptive capacity are not factored in. In an attempt to capture observable demographic dimensions of population heterogeneity, KC et al. (2018) develop a five-dimensional model of India's population by state, rural/urban place of residence, age, sex, and level of education. They show that a model that does not factor in education differentials, and stratifies only by place of residence and state, projects India's population size to reach 3.1 billion in 2100, as compared with 1.6 billion in the model stratifying only by level of education. The latter realistically accounts for the improvement in women's education in India, which is a key determinant of fertility rates (Dreze and Murthi 2001). As previously discussed, education plays a key role in vulnerability reduction and enhancing adaptive capacity, hence projections that do not consider such relevant demographic characteristics as education will undermine efforts to identify vulnerable populations. This approach, which focuses on population heterogeneity at the subnational scale, allows researchers to answer the questions of *who* is vulnerable and to identify *why* this is the case. However, refined spatial scales representing the local climate impact are not captured here.

Producing a meaningful set of population projections that simultaneously accounts for both spatial and demographic heterogeneity is highly challenging. Wardrop et al. (2018) propose a bottom-up approach for producing population estimates for small areas or high-spatial-resolution grids. Relying on microcensuses collected for small defined areas, the method then links microcensus data to spatial covariate data using statistical models to predict population numbers for unsampled locations too. These bottom-up mapping methods have been used to derive population distributions and demographics at a small spatial resolution (Tatem 2017; Leasure et al. 2020). Alegana et al. (2015), for instance, use a Bayesian hierarchical spatio-temporal model to estimate the proportion of under-five year olds in $1 \times 1$ km squares in Nigeria based on geolocated household surveys. This method allows them to overcome the limitations of population census data, which for many countries are unreliable, outdated, and of coarse spatial resolution. The WorldPop research group based at the University of Southampton have been at the forefront of producing gridded population counts and age-sex structure proportion data sets (Pezzulo et al. 2017). These data can potentially be used as input data for population projections.

Exploiting the 2011 Population and Household Census and microsurvey data (i.e. DHS 2006 and 2011) for Nepal, KC et al. (2016) perform population projections for Nepal and its 75 districts for the period 2011–31 by age and sex based on the cohort component method, treating each district as a state in a multistate framework. The results are further interpolated annually for 4,051 Village Development Committees and municipalities in Nepal. Likewise, Striessnig et al. (2019) apply regression tree methods to model age structure change at a county level using US censuses, producing for the first time gridded spatial population projections by age structure which are consistent with the SSPs. The technical possibility of producing multidimensional population projections for small-scale spatial unit is promising. With the increasing availability of subnational population data and geo-referenced surveys, coupled with computational power and advanced statistical techniques, spatially disaggregated population estimates and projections which explicitly account for population heterogeneity could become a significant area of research (Wardrop et al. 2018). Expertise in demography is thus highly relevant here.

## Future directions in integrating demographic perspectives in global environmental change research

The impacts of climate change on human health and well-being have already been experienced by populations around the world. With global temperatures on course to rise by 2–5 °C by the end of the century (Collins et al. 2013; Raftery et al. 2017), scaling up both mitigation and adaptation actions in order to reduce human impact on the climate system and minimize the climate risks should be made a priority. Given the centrality of the human population in the global climate system and the urgency of climate change issues, there has never been a 'next best time for demographers to contribute to climate change research' (Gage 2016, p. 19). Like the Chinese proverb that says the best time to plant a tree was 20 years ago, the time is now ripe for active engagement of demographers in environmental and climate study.

In particular, the past decade has seen significant advancements in demographic and social data and in computational tools, making complex environmental and climate data more accessible to demographers (Hunter and Menken 2015). The increasing availability of geo-referenced demographic data, together with alternative data sources such as mobile phone and social media data, has made it possible to match such data with climate and environmental data with appropriate spatial units and scales. This has allowed researchers not only to provide better analysis and assessment of human impact on the global climate system and of differential vulnerability and adaptive capacity but also to ask new relevant questions in this field.

### *Climate impact on population dynamics*

As shown in Figure 1, which depicts the reciprocal relationship between population and the environment, the dynamics of climate change are influenced by the human population as much as population dynamics are influenced by the changing climate. It is reasonable to assume that climate change can also influence demographic *processes*, given that the impact of climate change on human health and well-being is already being felt. The IPAT equation, which describes the impact of human activities on the environment, can be extended to consider climate feedback on population trends. It can be written as:

$$I = P(I) \times A \times T$$

where $P(I)$ refers to population, which is a function of environmental and climate impact. Through impacting fertility, mortality, and migration, the effects of climate change on the key demographic components successively influence future population size, distribution, and composition, which in turn have implications for resource demand and on the environment alike.

The notion that environmental conditions can influence demographic behaviour is not new. In their commentary piece arguing for the timely involvement of population scientists in climate change research, Hunter and Menken (2015) raise a relevant point about the already existing environmental aspects in classic demographic theories. Caldwell's classic theory of wealth flows, for instance, perceives children's contribution to labour within agricultural households as an economically rational response to familial wealth flows (Caldwell 1976). If the negative impacts of climate change on agricultural production reallocate labour towards agriculture, and agricultural income increases due to scarcity of agricultural products, the higher returns to working in agriculture will result in higher fertility (Casey et al. 2019). While the theoretical model calls for the consideration of the role of environmental change on demographic behaviour, empirical research on this issue is scarce (Hunter and Menken 2015). To date, there is no comprehensive and quantitative assessment of the impact of climate change on future population (Cohen 2010).

Indeed, what is missing from the empirical literature is an understanding of the direction, the mechanisms, and the extent to which climate change affects and will affect demographic outcomes. The scarcity of scientific studies on the current and future impacts of climate change on population dynamics impedes the advancement of knowledge on future population trajectories and, consequently, hampers policy efforts to anticipate demographic challenges under future climate change. Future demographic research to address the following questions will be fundamental to understanding climate feedback on population, allowing for more accurate inclusion of demographic variables representing the human systems in the IPCC's integrated assessment models (Jiang and Hardee 2011):

(1) In what direction and to what extent does climate change influence fertility, mortality, and migration (the three demographic components underlying population change)?
(2) What are the mechanisms through which climate change influences fertility, mortality, and migration?
(3) How do the impacts of climate change on demographic outcomes vary by population subgroup?
(4) How does climate change affect future population size, composition, and structure, based on its effects on fertility, mortality, and migration?

### *Potential impacts of climate change on fertility, mortality, and migration*

While some research progress has been made regarding the climate's impact on health and well-being, there is no scientific consensus regarding the direction and extent to which climate change will influence population dynamics. Although climate change affects every world region, LMICs will be hardest hit, given their higher level of social vulnerability and lower capacity to cope with and adapt to the changes. This coupled with their typically equatorial location puts low-income countries in the most vulnerable position in terms of temperature extremes (Herold et al. 2017). Both the direct and indirect (e.g. via shifting the underlying environmental and social determinants) impacts of climate-change-induced extreme temperatures and events on demographic processes can thus be particularly strong in LMICs.

The impact of climate change on *fertility* can operate via direct and indirect channels. Climate change affects fertility directly through physiological effects, such as reduction of fecundity in extremely high temperatures or increased risks of malaria infection in the wet season (Philibert et al. 2013; Barreca et al. 2018). Meanwhile, experience of child death (e.g. due to extreme climate events) may result in child mortality replacement with new births (Kraehnert et al. 2019). Climatic conditions also affect fertility indirectly, for example through influencing crop yields and income, whereby favourable socio-economic resources promote childbearing (Pitt and Sigle 1998; Andriano and Behrman 2020). In contrast, negative climatic conditions affect maternal nutritional status, change time use patterns, increase physically demanding activities, and reduce household resources, factors which in turn contribute to reducing fertility (Grace 2017; Sellers and Gray 2019; Davenport et al. 2020). Another channel through which climate change can affect fertility is the increasing concerns about climate issues, as these may suppress fertility intentions (Arnocky et al. 2012; De Rose and Testa 2015). With limited evidence on the impact of climatic factors on fertility, especially in LMICs (Grace 2017), it remains unclear how climate change will affect future fertility rates.

Regarding *mortality*, there are a number of studies on the effects of extreme events, particularly extreme temperatures or heatwaves (Martens 1998; Burgess et al. 2014; Achebak et al. 2019; Son et al. 2019), and the effects of exposure to hydro-meteorological hazards (Doocy, Daniels, et al. 2013; Doocy, Dick, et al. 2013) on mortality. Similarly, there is evidence that extreme weather events and temperatures increase infant mortality (Kudamatsu et al. 2012; Flatø and Kotsadam 2014; Geruso and Spears 2018), possibly due to poorer health of newborns in terms of low birthweight or shorter length at birth, which are influenced by weather and temperature shocks (Deschênes et al. 2009; Andalón et al. 2016). However, these studies typically focus on one climatic factor or one specific type of natural hazard. As discussed earlier, a specific population subgroup is not vulnerable to all types of climatic hazards since vulnerability depends on their degree of susceptibility, risk exposure, and adaptive capacity. There is thus a need for a synthesis of the evidence on climate-related mortality that considers differential vulnerability.

With respect to climate impacts on *migration*, the past decade has seen a remarkable increase in the number of empirical studies focusing on climatic or environmental drivers of migration (Hoffmann et al. 2020, 2021). However, there is little empirical consensus concerning the direction and extent to which these factors influence migration (Piguet et al. 2018; Borderon et al. 2019). Environmental change is found to contribute to increasing human migration in some studies but to constraining migration in others (Piguet 2010; Black et al. 2011; Hunter et al. 2015; Berlemann and Steinhardt 2017; Borderon et al. 2019; Cattaneo et al. 2019; Vinke et al. 2020). There is also a lack of unified understanding about the demographic profiles of migrants, that is, who moves and who stays in the context of climate change. Without evidence-based knowledge and consensus in scientific findings, it is not possible to anticipate the direction and magnitude of the effects of climate change on fertility, mortality, and migration.

## *A call for better knowledge on the impact of climate change on population dynamics and way forward*

The lack of comprehensive scientific knowledge about how climate change is likely to impact future fertility, mortality, and migration trends in different parts of the world makes it difficult to forecast future population size and structure realistically. A knowledge of future population trends and the vulnerability of different population subgroups is crucial for understanding the socio-economic costs of climate change and, consequently, for policy design. Neither of the two most widely used sets of global population projections factors in the possible consequences and associated discontinuities that may result from climate change. The UN population projections are based on an extrapolative Bayesian hierarchical model, which essentially assumes that countries less advanced in the process of demographic transition will follow the path of the more advanced countries (United Nations 2019). This, by definition, does not include possible new discontinuities, such as those potentially caused by climate change. The expert-argument-based global population projections by age, sex, and level of educational attainment up to 2100 produced by WIC/IIASA in 2014 (Lutz, Butz et al. 2014) and 2018 (jointly with the European Commission's Joint Research Centre (Lutz et al. 2018)) rely on the judgements of over 550 population experts on a large set of predefined substantive arguments about the future drivers of fertility, mortality, and migration trends. Although climate change was listed as a possible factor driving mortality and migration, the population experts surveyed in 2011–2012 largely dismissed climate change as a relevant driver of population dynamics, presumably because not much research on these topics had been conducted by that time.

Indeed, the concern about potential misrepresentation of future population is raised by Jones and O'Neill (2016) as a caveat in their spatially explicit, global-scale population projections: if people move away from drought-ridden regions or low-elevation coastal areas that face rising sea levels, for instance, then not accounting for the climate driver of migration or urbanization will mislead their spatial projections of future population size and distribution. If climate change does influence fertility, mortality, and migration, the underlying assumptions for future population trajectories will need to account for the impacts of climate change on these demographic processes. Quantifying the effects of climate change on population dynamics would also lead to improvements in the predictive ability of forecasts and projections. Jones and O'Neill (2016) consequently highlight that considering climate feedback on population dynamics should be given high priority in the future.

From a policy perspective, it is crucial to understand exactly how climate change will affect livelihoods and well-being. A knowledge of the mechanisms through which climate change influences demographic and socio-economic outcomes would allow an appropriate intervention on the right dimension to be designed. Agricultural production, food access, food prices, and income losses are routinely referred to as key channels by which climate operates (Henry and Dos Santos 2013; Hunter et al. 2014; Cattaneo and Peri 2016). For instance, in the context of childhood undernutrition induced by exposure to floods and droughts (Muttarak and Dimitrova 2019; Dimitrova 2020; Dimitrova and Muttarak 2020), knowing how these climatic hazards affect child health would allow the design of an appropriate intervention to alter the course of malnutrition. Despite the growing number of empirical studies on the impacts of climate change, there is a lack of understanding about the *mechanisms* by which climate affects demographic and socio-economic outcomes (Gemenne et al. 2014; Carleton and Hsiang 2016; Mueller et al. 2020). Indeed, there is a need for empirical research which address these issues. This could help to foster policy efforts to modify the mediating factors in order to minimize risks associated with climate change.

Demographers already have the methodological tools to assess, quantify, and forecast the impact of climate change on population trends. Such empirical analysis of fertility, mortality, and migration could include changing climatic conditions in a local area as an exogenous determinant of the demographic processes. Population projections could explicitly include climate feedback on key demographic behaviours when building up assumptions about future population trends. The analysis of mechanisms through which climate change influences demographic and socio-economic outcomes could use structural equation modelling, which allows for explicit identification of the structural relationships between all the variables included in the model and a distinction between direct and indirect effects (Fan et al. 2016). Therefore, technically, available statistical techniques and models in demography and other social sciences can already handle the new research directions proposed.

As for data sources, some existing relevant data can readily be applied. For these exercises, data that are either geo-referenced or uniquely identifiable by geographical location are required. Examples of global gridded climate and natural disaster data include: (1) climate data from the Climatic Research Unit at the University of East Anglia, available from 1901 (Harris et al. 2020); (2) drought events from the Global Drought Observatory, available from 1951; (3) flood events from Dartmouth Flood Observatory, available from 1985; and (4) natural disaster events from the Emergency Events Database (EM-DAT). Demographic data with information on geographical locations can be sourced from various surveys. These include: (1) the DHS, nationally representative repeated cross-sectional surveys with detailed information on population characteristics and maternal and child health; and (2) the Integrated Public Use Microdata Series International database, comprising census microdata for 102 countries, available from 1960. Socio-economic data which are particularly relevant for the analysis of mechanisms include: (1) the Normalized Difference Vegetation Index, remote sensing-based vegetation measures used as an indicator of agricultural yields (Boschetti et al. 2009); (2) food prices data from the Food Price Monitoring and Analysis database, which collects monthly prices for several food commodities in selected markets in LMICs; and (3) conflict data from the Uppsala Conflict Data Program, recording worldwide violent conflict from 1989.

Given data availability, population scientists have the right skills and expertise to embrace this new research agenda. Such efforts will provide foundations for our knowledge about future fertility, mortality, and migration under climate change. With climate change consequences already being felt, and increasing levels of public concern and civic activism (Capstick et al. 2015; O'Brien et al. 2018), it is highly timely to assess the climate consequences on population trends. This will not only contribute to shedding light on scientific uncertainty about the direction and magnitude of the impact of climate change on population dynamics but will also provide scientifically sound evidence for policies.

## Conclusion

The centrality of the human population in the environmental and climate system and the urgency of tackling climate change mark the importance of demography at this present time of climate crisis. Significant advances have been made in understanding human impact on the environment and global climate. Not only do estimates and forecasts of population size and growth allow for projections of future emissions and corresponding climate change, but a knowledge of population composition and distribution also contributes to a more precise assessment of the human impact. Similarly, estimation and projection of population heterogeneity allow for the identification of vulnerable subpopulations and assessment of future societies' adaptive capacity. Population projections which are consistent with the global socio-economic development narratives —the SSPs—provide understanding of how different development policies shape mitigation and adaptation challenges (Hunter and O'Neill 2014). Spatially explicit population estimates and projections at a local or regional scale are also useful in identifying the population exposed to climate risks. Although research on environmental and climate change remains relatively marginal compared with other topics in population studies, demographers have already made significant contributions to the understanding of the interrelationship between humans and the environment and climate.

Regrettably climate change is already happening, and it is not possible to reverse many of its catastrophic effects. While drastic emissions reductions and low-carbon transformations are urgently required to limit global warming to below 2 °C by the end of the century, enhancing adaptive capacity is also key to minimizing the climate's impact on human populations. Since global climate change is here to stay, there is no better time for demographers to engage actively in climate research. With readily available data and advanced methodological and computational tools, improved population projections which account for both demographic and spatial heterogeneity will, in the coming decades, contribute greatly to locating *where* vulnerable subpopulations live and *who* they are. Likewise, a comprehensive and systematic assessment of the impacts of climate change on current and future population trends would help the scientific community to build more realistic scenarios about populations trends under the rapid pace of climate change and inform the international debate over the social costs of climate change. With these new research agendas, the next generation of demographic research on environmental and climate change should make a large contribution to better social and environmental policy design and policy planning in the longer time horizon.

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