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Population growth and climate change: Addressing the overlooked threat multiplier

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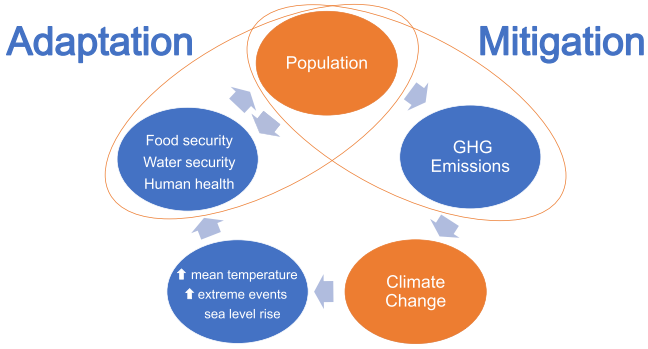
HIGHLIGHTS

- Demographic trends will influence the magnitude of climate disruption and the ability of societies to adapt to it.
- Rights-based policy interventions could decrease fertility rates to levels consistent with low population pathways.
- Following low population pathways would contribute to emission reductions and minimize climate risk.
- Humane policies that slow population growth should be part of a multifaceted climate response

GRAPHICAL ABSTRACT



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ABSTRACT

Demographic trends will play a role in determining the magnitude of climate disruption and the ability of societies to adapt to it. Yet policy makers largely ignore the potential of fertility changes and population growth when designing policies to limit climate disruption and lessen its impacts. Here we argue that rights-based policy interventions could decrease fertility rates to levels consistent with low population pathways. We review country and global level studies that explore the effects of low population pathways on climate change mitigation and adaptation. We then provide rights-based policy recommendations, such as the expansion of voluntary family planning programs that incorporate elements from successful past programs, and highlight current research gaps. In concert with policies that end fossil fuel use and incentivize sustainable consumption, humane policies that slow population growth should be part of a multifaceted climate response. These policies require attention from scientists, policy analysts and politicians.

1. Introduction

Population growth and economic growth are the primary drivers of increasing climate altering emissions (IPCC, 2014a). As it stands, national climate change pledges are not enough to limit global warming to 1.5 °C above pre-industrial levels (Brown et al., 2019), and mitigation scenarios that do reduce emissions consistent with this goal rely on

Abbreviations: BECCS, bioenergy with carbon capture and storage; IPCC, intergovernmental panel on climate change; SSP, shared socioeconomic pathway (for population projections); ODA, overseas development assistance.

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widespread deployment of uncertain technologies, such as bioenergy with carbon capture and storage (BECCS), which would likely have negative consequences for food production, biodiversity conservation and land rights (IPCC, 2018; Lenzi et al., 2018; Smith et al., 2016). Calls for comprehensive, integrated approaches, and arguments to address the primary drivers of anthropogenic climate change, are largely ignored (Bongaarts and O'Neill, 2018; Koch, 2015; Rosales, 2008; Stordalen et al., 2013). There has been some progress in government policies that limit unsustainable consumer behavior (Mundaca et al., 2018; Stoll-Kleemann and Schmidt, 2017), but so far, the international community has largely ignored the potential of population-related policies to reduce risks from global warming (Bongaarts and O'Neill, 2018). For example, while the Intergovernmental Panel on Climate Change's (IPCC) mitigation report on strategies to limit global warming to 1.5 °C noted that reductions in population growth can reduce overall carbon demand and mitigate climate change (IPCC, 2018) and the adaptation report identified modern family planning as an adaptation action that would improve health and simultaneously reduce emissions by slowing population growth (IPCC, 2014b), the climate community has yet to seriously consider such efforts. Compared to the substantial popular and scientific coverage of speculative technologies like BECCS, policies that would slow population growth are overlooked.

As threat multipliers, both climate change and continued population increase will amplify existing risks and create new risks for natural and human systems. Here we focus on the role of population growth. Many studies analyze climate-related effects of population growth on a local or regional scale (Dawadi and Ahmad, 2013; Pricope et al., 2013; Wang and Wang, 2017). However, as population-related policies are typically made at a national level, we focus our discussion on national or global studies. We describe studies that examine how lower population paths can contribute to climate change mitigation and adaptation, and propose strategies to help achieve these lower population paths. Slowing or ending population growth will not sufficiently limit global warming on its own (see Bradshaw and Brook, 2015, 2014; O'Neill et al., 2015)—but neither will reducing per capita consumption (Van Vuuren et al., 2018), or ramping up technological efficiency gains (Mitchell, 2012). Vigorously pursuing comprehensive efforts in the areas of population, consumption and technology provides our best chance to avoid severe climate disruption. In addition, many studies highlight continued population growth as a key driver of future climate risk (Asefi-Najafabady et al., 2018; Jones et al., 2015; Liu et al., 2017), particularly in less-developed countries that have contributed the least to climate change but maintain growing populations (Ahmadalipour et al., 2019; Bathiany et al., 2018). We argue below that slowing population growth, while not a panacea, should be included in humanity's response to the climate crisis.

2. Fertility and population policies

Future population growth will be highly dependent on fertility paths, which can be influenced by policies. There are many factors that influence fertility rates. Indirect factors include average education level (Bongaarts, 2003), economic growth (Balbo et al., 2013), urbanization (Martine et al., 2013), child mortality (Angeles, 2010), cultural factors including religion (Akintunde et al., 2013; Götmark and Andersson, 2020), social norms regarding ideal family size (Ryerson, 2018; Barrett et al., 2020), and influence of the media (de Silva and Tenreyro, 2017). Direct factors include the presence and strength of family planning programs, availability of modern contraception, and rates of contraceptive use (Bongaarts, 2017, 2016; Canning and Schultz, 2012). Collectively, these factors help determine fertility levels, and attention to many or all of them has been a hallmark of some of the most successful voluntary efforts to reduce fertility (Robinson and Ross, 2007). Access to contraceptive information and services is particularly important, because without the knowledge and technology to manage childbearing, the desire for smaller families cannot be reliably acted upon (Coale, 1973; Potts, 2018). When provided with barrier-free access to a variety of modern contraceptive methods, women and couples routinely take advantage of them, as has been demonstrated in many countries around the world (Engelman, 2012; Ross and Stover, 2013). About 100 of 250 countries have brought their fertility rates to or below replacement rate through voluntary family planning policies (United Nations, 2019c).

Despite much progress (Robinson and Ross, 2007; Ross and Stover, 2013), national actions to reduce population growth through improved family planning programs remain controversial in many countries. One contributing reason is sexism: the lingering belief in traditional and religious societies that women's reproductive decisions largely should remain under the control of men (MacQuarrie et al., 2015), and that children are "up to God" (May, 2017). Another reason has been reaction to China's coercive "one-child policy" from 1979, which gradually changed (White, 2016) and recently ended. Prior to enacting this policy, China's formerly high fertility rate had already fallen from about 6.5 in 1970 to about 2.5 children per woman by the end of the decade, partly through voluntary measures and partly through coercion (White, 2016; Whyte et al., 2015; Qin et al., 2018). However, especially from 1979 to 1983 the one child policy involved strong coercive measures including e.g. forced abortion and fines (see White, 2016 for detailed description, and changes in policy over time). These coercive measures in China have been rightly condemned (e.g. Bongaarts and O'Neill, 2018). We believe the best way forward is rights-based family planning, which enables all individuals to have the information, education and means to decide the number and spacing of their children responsibly (Hardee et al., 2013; Johnson, 1995; Starbird et al., 2016; Tucker, 2019). The United Nation's population conferences emphasize that reproductive rights are fundamental human rights (United Nations, 1968, 1994). Several authors (e.g. Conly, 2016, Dasgupta, 2019) argue that other measures, such as economic incentives or disincentives and other actions democratically decided upon, are justified if societies cannot freely achieve sustainable population sizes. Here we emphasize voluntary measures (see also Box 1 and Table 1).

3. Population projections used in the climate literature

In the most common population projections used in the climate change literature, changes in fertility are often assumed with insufficient discussion of the policy changes necessary to achieve them (Cafaro and Dérer, 2019). For example, in the medium variant in its most recent population projections, the United Nations Population Division assumes major reductions in fertility for countries currently above replacement level, informed by country-specific fertility trends and historical fertility transitions (United Nations, 2019a). Underlying this projection is the implicit assumption that there will be continued progress in factors that reduce fertility rates, such as access to family planning information and services. The Highlights of the 2019 World Population Prospects note, "If the international community does not follow through on its commitment to ensure that all men and women are informed and have access to safe, effective, affordable and acceptable methods of family planning of their choice, then future fertility declines may occur more slowly, and future population growth may be faster than what is depicted in the medium variant. Conversely, an accelerated expansion in access to family planning information and services could result in a more rapid fertility decline and a smaller global population in the future than projected under the medium variant." (United Nations, 2019b). However, neither the projections nor their accompanying explanations explicitly specify what changes will be necessary for the international community to follow through on this commitment (O'Sullivan, 2016). The UN projections also include a 95% probability interval, as well as a high and low variant that arbitrarily apply fertility rates 0.5 higher and lower than the medium projection (Fig. 1). However,

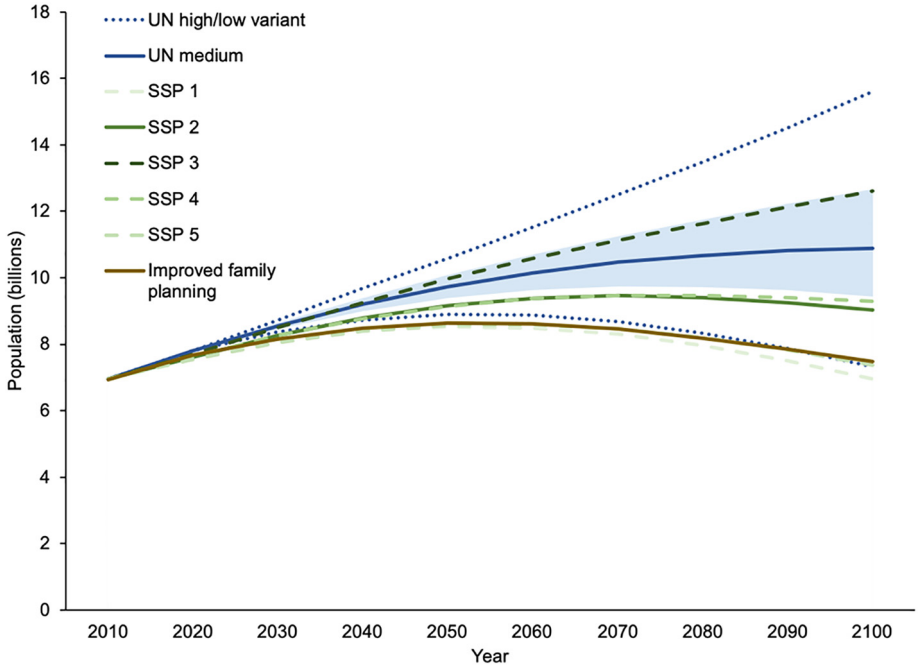

Fig. 1. Projections of global population to 2100. The UN medium, low and high variants (± 0.5 child per woman), Shared Socioeconomic Pathway (SSP) population trajectories, and an improved family planning scenario from O'Sullivan (2018) are shown. UN 95% prediction interval is shaded. The UN medium and SSP 2 are considered the "most likely" trajectories from their respective modeling groups. However, policies that lead to lower fertility could help achieve low population paths.
Data from O'Sullivan (2018); Riahi et al. (2017); and United Nations (2019c).

the 95% probability interval does not take into account new policies that may influence future trends (Abel et al., 2016), and none of the variants are designed to reflect alternative population policies (O'Neill et al., 2015).

In a similar way, the Shared Socioeconomic Pathway (SSP) population trajectories used by the IPCC in its Assessment Reports tend to hide the role explicit policies will play in determining future fertility rates. The SSP population trajectories are based on the five SSP narratives, qualitative descriptions of different socioeconomic futures depending on the degree of mitigation and adaptation challenges (see O'Neill et al., 2017 for details). These narratives were translated into fertility, mortality, migration and education assumptions for high fertility, low fertility, and rich OECD countries (KC and Lutz, 2017). With respect to fertility, country-specific trajectories are informed by historical fertility transitions adjusted to reflect conclusions from country expert meetings, and the degree of female educational attainment (see KC and Lutz, 2017 for detailed methodology). The central feature of this approach is that it explicitly links educational achievement to fertility changes. This is important; however, it remains unclear what policy changes are necessary to achieve the different socioeconomic futures that determine educational outcomes. This gives the impression that population will "take care of itself," solely as a result of exogenous economic forces driving improved educational outcomes (regarding education, see also recent critical evaluation of its role by Psaki et al., 2019). In addition, this approach neglects an important key driver of fertility decline - universal access to family planning information and services. Both the UN and the SSP methodologies conceal the reality that fertility can be influenced by a wide range of policies (Abel et al., 2016; Cafaro and Dérer, 2019).

Resolute efforts in multiple policy areas could make a decisive difference for humanity's demographic future, and projections that model the effects of policy changes are essential for these efforts. For example, according to a comprehensive analysis of 59 developing countries, meeting the unmet need for contraception would lower the global fertility rate 20% (Bradley et al., 2012). Policy-based projections that model this impact of universal contraceptive availability, in concert with universal access to primary and secondary education, find that the global population could follow a path lower than SSP 2 (the "most likely" SSP trajectory), resulting in a population size 2–2.5 billion smaller than the UN's medium variant in 2100 (Abel et al., 2016). If national governments and the international community enact policies that address the unmet need for contraception and improve education, a global population lower than the "most likely" scenarios is possible.

Another recent policy-based projection found that an improved family planning scenario could achieve a global population path similar to the UN low variant and SSP 1 throughout the century (O'Sullivan, 2018). This scenario (depicted as the "improved family planning" scenario in Fig. 1) assumes that countries with above-replacement fertility rates achieve the average path of fertility decline realized by 16 countries' historical voluntary family planning programs (such as South Korea and Iran, whose family planning programs are detailed in Box 1). For a full list of the 16 countries and detailed methodology, see O'Sullivan (2018). Of course, an important caveat is that future family planning programs may not reduce fertility as rapidly as past programs. However, even if they fail to reduce fertility rates as fast as projected, a healthier population whose members have greater reproductive freedom would be good in and of itself (Engelman and Johnson, 2019).

The important point is that demography is not destiny. Our future population path is amenable to comprehensive policy interventions. Direct and indirect policy levers, such as improved education for girls and young women, the expansion of family planning programs, publicizing the benefits of smaller families, and media outreach could slow future population growth modestly by midcentury and substantially toward the end of the century (O'Neill et al., 2015). And as we show below, slowing population growth could reduce

climate-altering emissions and increase the adaptive capacity of the most vulnerable societies.

Box 1
Successful family planning programs: countries where fertility rates declined rapidly provide lessons that can be applied to high-fertility countries today.

Voluntary family planning programs have been successful at reducing fertility in many parts of the world (Robinson and Ross, 2007). Well-planned programs contributed to rapid decreases in fertility in many countries beginning as early as the 1960s (de Silva and Tenreyro, 2017). In 11 such countries, fertility fell from more than 6 to less than 3 children per woman over periods ranging between 10 and 27 years (Roser, 2017). Fig. 2 depicts the rapid fertility decline of relatively poor, low-income countries that implemented strong family planning programs, starting between 1965 and 1990 (Fig. 2 from O'Sullivan, 2013). These rates contrast with the slow decline overall in less and least developed countries. Countries with strong population-focused voluntary family planning programs quickly achieved fertility reduction below or at replacement-level.

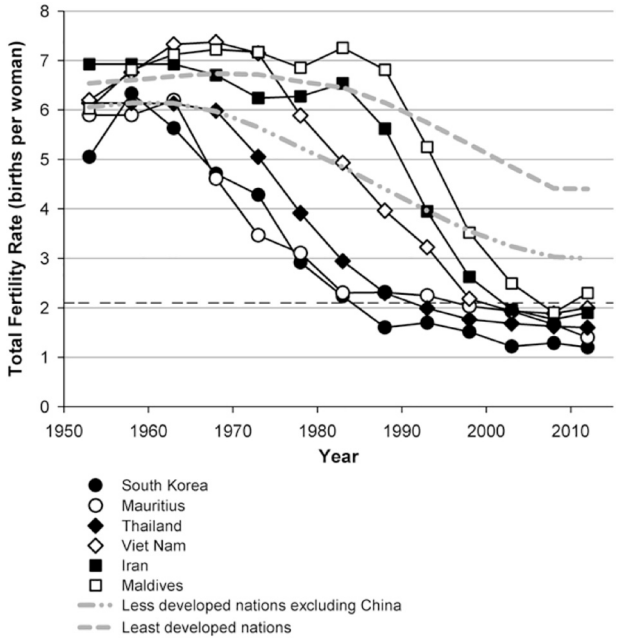

Fig. 2. Total fertility rate for selected countries which implemented population-focused voluntary family planning programs between 1965 and 1995, compared to less and least developed countries overall. The horizontal dotted line is replacement-level fertility.
From O'Sullivan (2013).

South Korea provides one very successful family planning example. In 1961, the South Korean government adopted a national family planning policy as part of its long-term economic development plan, with a goal to reduce the annual population growth rate by 1% by 1971 through increasing contraceptive use by married couples (Kim and Ross, 2007). Some key components of the Korean program were high levels of funding from the national government combined with decentralized program management; education about contraceptive methods and its associated benefits; and information diffused through radio, movie shorts, sound trucks and printed materials such as posters and leaflets (Kwon, 2001; Noble and Potts, 2008). Home visits and group meetings were common and played an important role in rural areas; for example, mothers' clubs provided contraception in over 19,000 villages (Whang, 1981). The program had strong political support: top leaders, including the president and prime minister, publicly endorsed and privately supported the new viewpoints. International aid was also important, and the private organization Planned Parenthood Federation of Korea handled much of the public education. A decrease in the annual population growth rate from 2.9% to 2% was achieved in less than one decade and this success contributed to economic and social development in the country (O'Sullivan, 2013).

Another successful voluntary family planning program was implemented in Iran in the 15-year period from 1988 onwards (Abbasi-Shavazi et al., 2009; Moore, 2007). The program was supported by Islamic leaders, who declared that modern family planning was consistent with the Koran (Sadat Moinifar, 2007). Educational programs at schools, colleges and through mass media were important, as were increased access to free contraceptives and direct advice to couples before marriage. A bill in 1993 removed economic incentives for large families. In total, 15,000 health houses and mobile clinics served the countryside, and in rural areas, fertility dropped from 8.1 to 2.1 in one generation (Simbar, 2012). One novel strategy at the time was to involve males as much as possible, by emphasizing male contraceptive methods, such as condoms and vasectomies (Roudi-Fahimi, 2005).

These successes in Iran, South Korea and other countries show that fertility rates can decline quite rapidly, facilitated by voluntary, rights-based family planning programs. Besides access to free contraception, key features of successful programs included support from cultural and political leaders, mobile support teams, public education campaigns, and international financial support (Robinson and Ross, 2007). Utilizing these and other proven strategies, such successes could be duplicated in many countries where fertility rates remain high today—particularly if their citizens and leaders recognize that doing so is a key component of an integrated climate response (Bongaarts and O'Neill, 2018).

4. Mitigation: The potential role of population

Mitigation refers primarily to actions that result in the prevention or reduction of climate-altering greenhouse gas emissions. Studies that substitute different population projections in economic models find that following the UN low variant rather than the medium variant throughout the century could reduce global and national carbon emissions from energy use by 40% (O'Neill et al., 2010) and 35% (Casey and Galor, 2017), respectively. In contrast, if efforts to achieve the fertility declines necessary to slow population growth are insufficient and the global population path follows the UN high variant to 2050, an additional 102.96 $GtCO_2$ would be emitted (Hawken, 2018) [note that these methodologies use the 2004 (O'Neill et al., 2010) and 2015 (Casey and Galor, 2017; Hawken, 2018) UN population projections, which have since been revised]. Nations that have successfully ended their population growth already benefit from population-related emission reductions. For example, according to a decomposition analysis of emissions in Japan's 2019 National Greenhouse Gas Inventory Report, 6% of their decline in energy-related carbon emissions from 2013 to 2017 was attributable to a decreasing population (Japanese Ministry of Environment, 2019).

Slowing population growth is broadly comparable with other emission reduction strategies, and a fully integrated approach that includes slowing population growth will lead to the greatest emission reduction. For example, in an integrated assessment exploring alternative pathways to a 1.5° target that reduce the need for negative emission technologies, Van Vuuren et al. (2018) found that following the lowest SSP

population trajectory was as effective as renewable electrification by the end of the century, reducing annual emissions 25% compared to the SSP 2 baseline scenario (Fig. 3, data from Van Vuuren et al., 2018). Cumulatively, the low population scenario is comparable with sustainable lifestyle changes, reducing cumulative emissions by about 9% compared to the baseline scenario (Van Vuuren et al., 2018). When all the scenarios are combined, including an agricultural intensification scenario and non CO_2-emission reduction scenario, cumulative net emissions are 50% lower than baseline scenario (Van Vuuren et al., 2018), highlighting the importance of integrated efforts across multiple sectors.

Ultimately, it is the cumulative emissions of greenhouse gases that will determine atmospheric carbon concentration and therefore global temperatures and climate disruption. Models that consider atmospheric feedbacks show that future population growth is the leading source of socioeconomic uncertainty (Walsh et al., 2017). In a carbon-climate model that includes linkages and feedbacks among demographic, economic, land, carbon and climate systems, the baseline scenario projects an atmospheric carbon concentration of 712 ppm and an average temperature increase of 2.8 °C through the end of the century (Walsh et al., 2017). Shifting from the 2015 UN medium variant projection to the low variant resulted in an atmospheric carbon concentration 77 ppm lower (635 ppm), which is consistent with limiting global temperature increase below 2.0 °C (Collins et al., 2013; Van Vuuren et al., 2011). Even if the low variant is not achieved, but instead the lower bound of the 2017 UN 95% probability interval, peak temperature would be 0.6 °C lower than if the medium variant was followed, given no other mitigation measures (Budolfson and Spears, 2020; Gerland et al., 2014). In sum, although fertility reduction policies cannot be the sole approach to climate mitigation, they could make an important contribution.

5. Adaptation: minimizing exposure to risk

Adaptation refers to actions that aim to reduce human societies' vulnerability to climate change impacts. In general, scenario analyses show that faster population growth is associated with greater human exposure to risks such as flooding (Lincke et al., 2014) and water stress (Satoh et al., 2017). The larger the future population, the more people will be exposed to climate related risks as climate disruption continues to worsen. According to the most recent UN medium variant, the population in less developed regions may increase 47% by 2100, from 6.5 billion to 9.6 billion, compared to a 2% decrease in more developed regions (United Nations, 2019c). In addition to pressures from a growing population that can weaken countries' adaptive capacities, people living in developing countries are the most vulnerable to climate risks (Jiang and Hardee, 2011) and disproportionately exposed to climate impacts (Bathiany et al., 2018). The compounding effects of these threats necessitate tackling both population growth and climate change to adequately adapt to climate disruption.

A review of global or national studies that examine human exposure to extreme heat, one increasingly important climate impact, shows that the interaction between climate and population is often the largest driver of future exposure, more important than changes in climate or population alone (see Fig. 4, data from Asefi-Najafabady et al., 2018; Dapeng et al., 2018; Jones et al., 2015; Liu et al., 2017). Additionally, depending on the socioeconomic circumstances, addressing population growth can be more effective than climate mitigation itself in minimizing climate-driven risks. For example, addressing population growth would be more effective than reducing emissions to minimize drought risk in developing African countries, since lower population paths reduce both socioeconomic vulnerability and exposure to drought (Ahmadalipour et al., 2019). This is not to say that strategies to slow population growth should take the place of efforts to limit emissions. Rather, researchers and policymakers must acknowledge that population growth is a component of climate risk, particularly in countries with rapid population growth, and develop risk reduction strategies in response (Liu et al., 2017).

According to some studies, future regional food security and global water security are driven primarily by population increase raising demand, and only secondarily by climate change (Hall et al., 2017; Smirnov et al., 2016). The increase in food demand from population growth will likely augment climate disruption, as it increases emissions from the second-most greenhouse gas intensive sector (agriculture, forestry and other land use), necessitating greater adaptation measures to address food insecurities (Conijn et al., 2018). Population growth could reverse progress to eliminate undernourishment in areas of expected increase in crop production (Dawson et al., 2016), and amplify

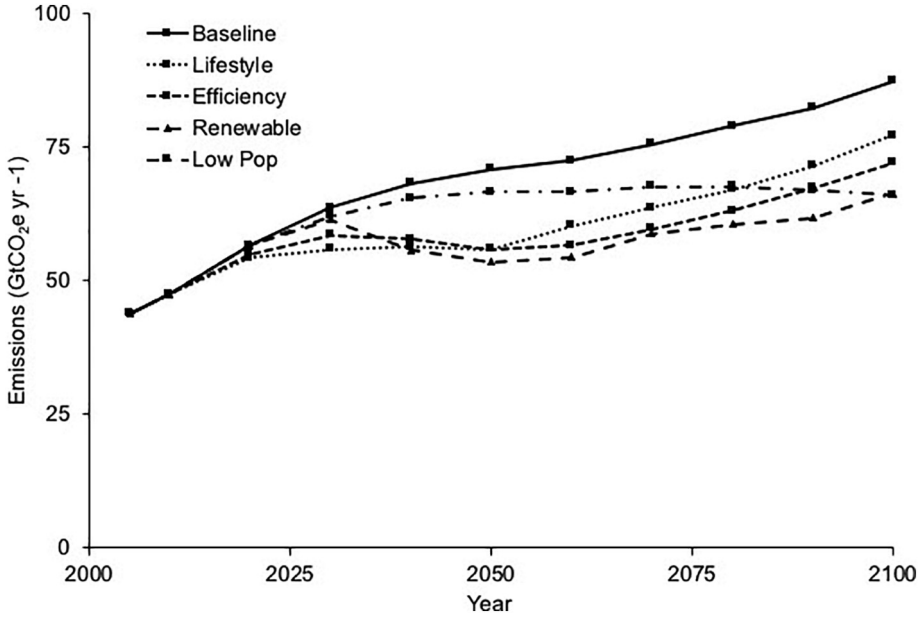

Fig. 3. Emission reduction potential from lifestyle change, energy and material efficiency, rapid renewable electrification, and low population scenarios, compared to a middle-of-the-road baseline (SSP 2). The low population scenario assumes the SSP 1 population trajectory. See Table A.1 in appendix for all scenario assumptions.
Modified from Van Vuuren et al. (2018).

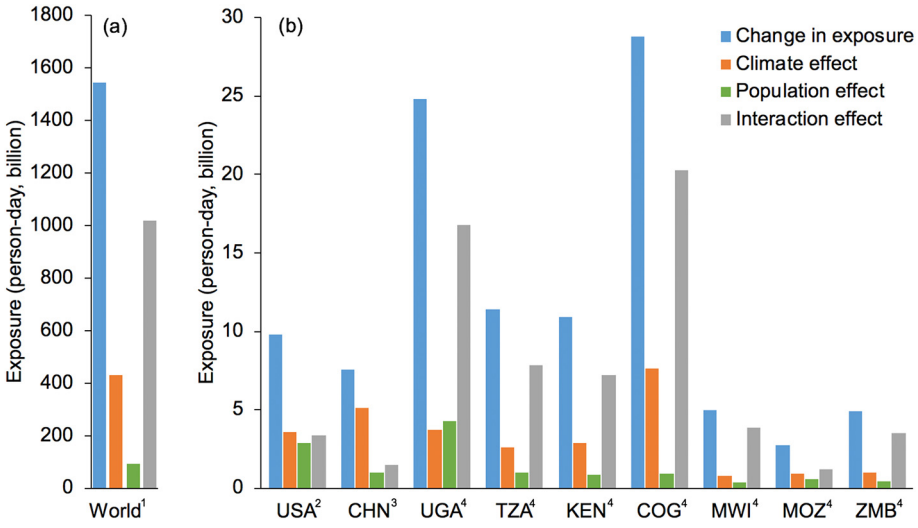

Fig. 4. Change in exposure to heat stress, disaggregated into components. The contributions of climate change, population, and the interaction between the two are shown at the global (a) and national (b) levels. Heat stress is calculated as the annual number of days or set of days above at least 35 °C multiplied by the number of people exposed. 35 °C is the temperature threshold associated with heat-related mortality (Mora et al., 2017). The three letter ISO country codes are displayed; country data from Asefi-Najafabady et al. (2018)[4]; Dapeng et al. (2018)[3]; Jones et al. (2015)[2]; Liu et al. (2017)[1]. See Table A.2 in Appendix for models and input specifications.

undernourishment in areas of expected crop decline (Hall et al., 2017). In addition, global hydrological models indicate population change explains a larger part of the overall change in projected water scarcity than changes in climate, at all levels of warming (1 °C, 2 °C, or 3 °C) (Schewe et al., 2014). Population-related policies that focus on reducing desired family size and increasing contraceptive prevalence rates could increase global per capita water availability (Gunasekara et al., 2013) and compensate for the likely effects of climate disruption on national food security (Moreland and Smith, 2012). These policies, in tandem with technologies that increase crop production, mitigate wasteful consumption and improve infrastructure and management practices, would help reduce the impact of climate disruption on food and water security (D'Odorico et al., 2018; Godfray et al., 2010).

6. Policy recommendations

We suggest increased support for the full range of rights-based policy interventions that lower fertility and in turn slow population growth. These include indirect actions such as investments in girls' education, opportunities for women to join the work force, and the promotion of small family sizes; as well as direct actions such as family planning programs that include affordable access to all types of safe, effective contraception for men and women. Many of these policies are synergistic, and utilizing the entire suite of policy interventions will result in faster fertility declines than investments in only one (Jiang and Hardee, 2014). For example, education could help change mindsets and overcome the cultural obstacles to contraceptive use, making family planning programs more effective (Bongaarts, 2016; Lutz, 2014). Similarly, family planning improves girls' access to education by improving household finances and increasing parents' ability to invest in each child, reducing the need for girls to care for siblings at home, as well as avoiding teenage pregnancies. It is imperative that all these efforts avoid coercion (see Section 2). The conclusions of the International Conference on Population and Development in Cairo (1994), called for a rights-based approach to enable all individuals to have the information, education and means to decide responsibly the number and spacing of their children (United Nations, 1994). Family planning is a human right, according to the United Nations and human rights advocates around the world (United Nations, 1968). See Table 1 for an overview of the scope of effective and acceptable population-related policies.

In many remaining high fertility countries, particularly in Sub-Saharan Africa, ideal family size remains high (Bongaarts and Casterline, 2013; May, 2017). This means that even if the unmet need for contraception is met, fertility will still remain well above replacement level. Efforts to change fertility preferences through information campaigns that present evidence on the health and socioeconomic benefits of contraception and smaller families have proven influential in the past and are particularly effective when they have the support of political and cultural leaders (Box 1). Mass media and entertainment-education are also useful strategies to advance small family norms (de Silva and Tenreyro, 2017; Ryerson, 2018). For example, soap operas invoking a strong narrative with relatable role models were effective in reducing fertility rates in Brazil (Chong et al., 2012). In concert with investments that address low education levels and high levels of child mortality, the promotion of small family norms will expedite the rate of fertility decline in areas of high desired fertility (Bongaarts, 2011).

Table 1
Selected list of population-related policies that provide climate change mitigation and adaptation benefits.

Type of action	Policy instrument	Examples of intervention mechanism
Direct	Reproductive health and family planning	Improve health care to reduce child mortality rate; provide access to free reproductive health care, including all types of safe, effective contraception; integrate family planning and safe motherhood programs into primary health care systems
Indirect	Information	Government pamphlets explaining the health and financial benefits of small families; entertainment-education programs to model small family sizes and egalitarian social norms
	Education	Improve access to education, particularly girls' education; provide comprehensive sexuality education with age-pertinent material through all years of schooling
	Laws and regulations	Raise the minimum legal age for marriage; restrict child labor; mandate compulsory primary and secondary education
	Tax policy and subsidy controls	Provide incentives and opportunities for women to join the labor force; plan for population reduction in ageing societies; eliminate tax incentives to raise fertility

Relatedly, all individuals and couples must have access to the contraceptive information and services necessary to act upon their fertility preferences. Gender equitable policies that eliminate barriers to contraceptive use should be complemented with expanded family planning programs that provide universal access to all types of safe, effective contraception. Although family planning is a human right (Greene et al., 2012), support for family planning programs is low on the international agenda, comprising only 1% of all overseas development assistance (ODA) in 2015 (Bongaarts, 2016). The growing movement to link family planning and climate adaptation could improve this figure as family planning becomes increasingly recognized as a cost-effective strategy eligible for adaptation funding (Engelman, 2016; Hardee et al., 2018; Mogelgaard, 2018). However, even with support from many low-income countries (Hardee and Mutunga, 2010) and the IPCC (IPCC, 2014b), this recognition has yet to be taken up by most politicians. National and international policymakers should take advantage of this opportunity and include family planning in national adaptation plans and multisectoral climate projects (Mogelgaard, 2018). Additionally, the proportion of ODA allocated to family planning should be increased to at least 2%, and the governments of developing countries should expand their own funding by an equivalent proportion (cf. Bongaarts, 2016). To facilitate this, family planning must be recognized as an investment with wide-ranging health, socioeconomic and environmental benefit which returns many dollars in avoided health and education costs, and improved economic development for each dollar spent (Kohler, 2012; Stephenson et al., 2010; Tucker, 2019).

It is important to note that policies that reduce population growth could indirectly influence other emission drivers. For example, lowering fertility could stimulate economic growth, increasing per capita affluence and consumption (O'Sullivan, 2013; Casey and Galor, 2017), which could counterbalance some of the potential emission reductions (O'Neill et al., 2010). Education and sociological transformations will likely play a role in coping with these prospective feedbacks, as younger and more educated people tend to show more sustainable behavior and a positive attitude to change (Lutz and Striessnig, 2015). Other governmental levers, like investing in the transition to clean energy, are also critical policy levers that could counter the effects of increasing wealth on emissions. A fully integrated approach that includes slowing population growth will allow humanity to most effectively mitigate and adapt to climate change.

7. Conclusion and research recommendations

Limiting climate disruption and its impacts will require systematic change. This should include transitioning away from fossil fuels, reducing unsustainable energy and material consumption, as well as slowing and ideally ending global population growth (Ripple et al., 2019). Policies that accelerate fertility reduction will contribute to emission reductions and increase adaptive capacity, thereby limiting climate disruption and reducing human exposure to climate risk. In concert with technological advancements and policies that end fossil fuel use, we recommend expansion of family planning programs, improved education, and other rights-based policies that lower fertility as part of an integrated climate change response.

In order to create the most effective policies, more basic and applied research in population-related fields is needed. For instance, Tamburino et al. (2020) documented the increased neglect of the impact of population in food security research over a 50 year period (1969–2018). Papers on population decreased during the period, while production (technology-focused) papers increased strongly. This is concerning because analyses of the efficacy of national population-related policies in the context of climate impacts, like food security, are especially important. For example, a pilot study in Ethiopia identified the 2050 contraceptive prevalence rate trajectory needed to lower fertility to a rate that would eliminate the food gap expected from climate effects (Moreland and Smith, 2012). This kind of research should be pursued for other climate impacts, with cross sectoral collaboration with family planning and reproductive health professionals to determine the appropriate methods and response. The family planning and reproductive health community should also do more to document the vulnerability-reduction benefits that come with greater access to family planning (Hardee et al., 2018).

Lastly, most studies that examine the effects of population change on mitigation or adaptation efforts use exogenous projections that are not subject to biosphere feedbacks. This not only hinders the evaluation of population-related policies, it is likely to miss important environmental responses (Lawson and Spears, 2018). These approaches are inadequate for the detailed mitigation and adaptation planning necessary to limit climate disruption and its impacts (Asefi-Najafabady et al., 2018; Motesharrei et al., 2017). More studies are needed that not only include actions to lower fertility, but also couple human and natural systems. To facilitate this, there should be more collaboration between social scientists experienced in reproductive health and population policy and climate scientists.

Rights-based policy interventions could decrease fertility rates to levels consistent with low population pathways. Lower global population pathways will contribute to emission reductions, reduce human vulnerability and exposure through increased adaptive capacity, as well as provide co-benefits for human development such as health improvements, poverty reduction and women's empowerment (Stephenson et al., 2010). Slowing and eventually ending population growth will also slow the degradation of ecosystems and help avert the extinction of species that provide irreplaceable environmental services humans and other species need to survive (Cinner et al., 2018; Crist et al., 2017; Marques et al., 2019). We urge scientists, policy analysts and politicians not to overlook population growth in the global response to climate change.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.141346.

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