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Underestimating demographic uncertainties in the synthesis process of the IPCC

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In this work, we systematically analyse the population projections used in the emissions scenario ensembles reviewed by the Working Group III in the latest three reports of the Intergovernmental Panel on Climate Change (IPCC). We show that emissions scenarios span smaller demographic uncertainties than alternative estimates both for the world and for critical regions, such as South-East Asia, Sub-Saharan Africa, and China. Furthermore, the range of demographic projections has consistently shrunk over subsequent reports, exposing a problematic convergence towards a single socio-economic pathway: the “middle path” or SSP2. We argue that the undersampling of population uncertainties limits the range of future emission trajectories and has implications for climate transition scenarios. Emissions scenarios with a wider set of assumptions about future population should be submitted to the IPCC. The methods utilised in this study inform the development of independent audit methods for the assessment of relevant uncertainty sources in IPCC databases.

Emissions scenario ensembles reviewed in the IPCC assessment process are designed to highlight the high uncertainty about how the future may evolve[1], providing “plausible representations of the future development of emissions of substances that are potentially radiatively active”, such as greenhouse gases (GHG)[2]. However, since the scope of scenarios in the IPCC is broader than the sole emissions scenarios, as it includes climate as well as Impact, Adaptation, and Vulnerability scenarios, unless stated differently, in this analysis, “scenarios” are meant exclusively as “emissions scenarios”. They are generated by Integrated Assessment Models (IAMs) or other coupled numerical models, which answer an open call for scenarios of the IPCC. In these emissions scenarios, the selection of which demographic data to be incorporated is critical[3,4]. Not only do population size, age composition, and educational attainment directly affect GHG emissions through various channels, such as food and energy demand[5,6] but they also influence patterns of decarbonisation through different income trajectories[7]. Furthermore, as projections approach 2100, properly representing the complex dynamics between population size, education, and wealth becomes paramount. For instance, while fertility rates are likely to reduce locally due to rising female education[8], longevity is likely to increase locally due to greater wealth[9]. In addition, the assumptions on heterogeneity in population greatly affect the evaluation of future vulnerability and adaptation options. For instance, while urbanisation is likely to expose more people to the climate change-induced extreme events, such as heatwaves and floods[10], increased educational attainments are associated with reduced vulnerability and enhanced adaptive capacity[11,12]. While population-related factors are of crucial importance for Impact, Adaptation, and Vulnerability, the population ranges used in this work are applicable exclusively to the emissions scenarios.

In the IPCC assessment process, these complex dynamics are handled with an increased level of sophistication in the emissions scenario generation. Emissions scenarios have evolved considerably[13–15]. As quantitative extensions of four exploratory world narratives, the Special Report on Emissions Scenarios (SRES) adopted a total of 40 emissions scenarios[16], which escalated to 380 scenarios assessed in the Third Assessment Report, and was later integrated with the inclusion of climate policies in the so-called post-SRES scenarios for a total of 750 scenarios assessed in the Fourth Assessment Report. As in the SRES emissions scenarios alternative combinations of driving forces could lead to similar levels and structures of energy and land use[17], an approach to scenario generation was later developed where the focus was rather on spanning the multiple options of radiative forcing target level in 2100. This approach generated the Representative Concentration Pathways (RCPs), which informed the Fifth IPCC

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cycle[18]. RCPs countenance a variety of GHG concentration futures, from a rising radiative forcing pathway leading to 8.5 W/m^2 (RCP8.5) to a "peak and decline" pathway, reaching 2.6 W/m^2 by 2100 (RCP2.6). To highlight how mitigation and adaptation challenges may vary as the result of economic, technological, demographic, or institutional factors, RCPs can be combined with the Shared Socio-economic Pathways (SSPs), a framework comprising five storylines: a "sustainable development" path (SSP1), a "middle- of-the-road" path (SSP2), a "regional rivalry" path (SSP3), an "inequality" path (SSP4), and a "fossil-fuel development" path (SSP5)[19].

Population trends, both in SRES and SSPs, are based on a set of assumptions regarding fertility, mortality, and migration which are consistent with the framework of the scenarios in terms of economic development and education attainments. However, SRES scenarios, which were characterised by a value of global population varying in 2100, between 7 and 15 billion, explicitly anchored their population projections to selected sources of demographic trajectories[16]. Differently, population and economic development assumptions in the SSPs were designed to account for challenges to adaptation and mitigation to climate change[20].

Despite the variety of the social-economic pathways of current SSPs, concerns about the representativeness and diversification of current emissions scenario ensembles remain, particularly with regards to the prominence of "middle-of-the-road" pathways[21], inadequate account of policy-relevant knowledge gaps[22], and insufficient focus on exposing policy vulnerabilities[23].

In this work, we combine different lines of evidence to offer a critical analysis of the representativeness and diversity of the population assumptions used in the emissions scenarios submitted to support evidence-based knowledge on climate change mitigation as part of the activities of the Working Group III of the IPCC assessment cycles. Among the reports released by the IPCC, here we focus on those having a supporting database of model-based climate change mitigation scenarios, forming the backbone of the Working Group III of IPCC. Since the Fifth Assessment Report (AR5), emissions scenarios were made available publicly, thus making the latest three IPCC reports, AR5, SR 1.5, and AR6, mark a step-change in the climate change literature assessment conducted by the IPCC. We perform a statistical analysis of the IPCC databases against authoritative multi-national databases, such as that of the United Nations' population projections (UN), finding evidence of undersampling of population uncertainties. Furthermore, we analyse the temporal evolution of all emissions scenarios submitted to the IPCC, regardless of the "vetting" process outcome, finding evidence of excessive convergence towards the population projections of a single SSP, namely "middle-of-the-road". In addition, the illustrative pathways, the selected scenarios chosen in AR6 to rep- resent a range of possible options for mitigation, are primarily based on the SSP2 storyline. The findings in terms of undersampling of uncertainty ranges and convergence towards SSP2 of the emissions scenario ensembles are robust at a global level (as shown in the sections "IPCC population scenario ensemble uncertainty across the reports" and "Comparing IPCC AR6 with UN projections") as well as at a regional level (as shown in the sections "Regional analysis of IPCC AR6"). The methods proposed in this article can find further applications as part of an audit methodology[24] to bring out both the strong aspects and the areas needing refinement within the IPCC review and synthesis processes. Through a continued and meticulous examination, scientists and stakeholders can help ensure that IPCC's assessments continue to be reliable and adaptable to the demands of policy.

An overview of the latest assessment reports and their focus is given in the Supplementary Material.

Results

Comparing global projections under the SSPs with alternative projection methods and assumptions

Currently, available global population projections are varied, diversified, and specific to the purpose for which they have been developed, as this affects structural and parametric decisions of the modelling. Beyond their use in climate policies, population projections made available by international offices of statistics, such as the European Commission and the United Nations, serve multi-national policy formulation on socioeconomic and sustainable development goal achievement. In addition, several databases are developed at a national scale, conceived to plan national policies, serve infrastructure investments in social services, and assess sustainability goal fulfilment. In this section, we provide an overview of the key methods used for demographic projections. The databases reported in Fig. 1 are relevant applications of different projection methods: deterministic, probabilistic, probabilistic integrated with expert elicitation, statistical models, and expert elicitation).

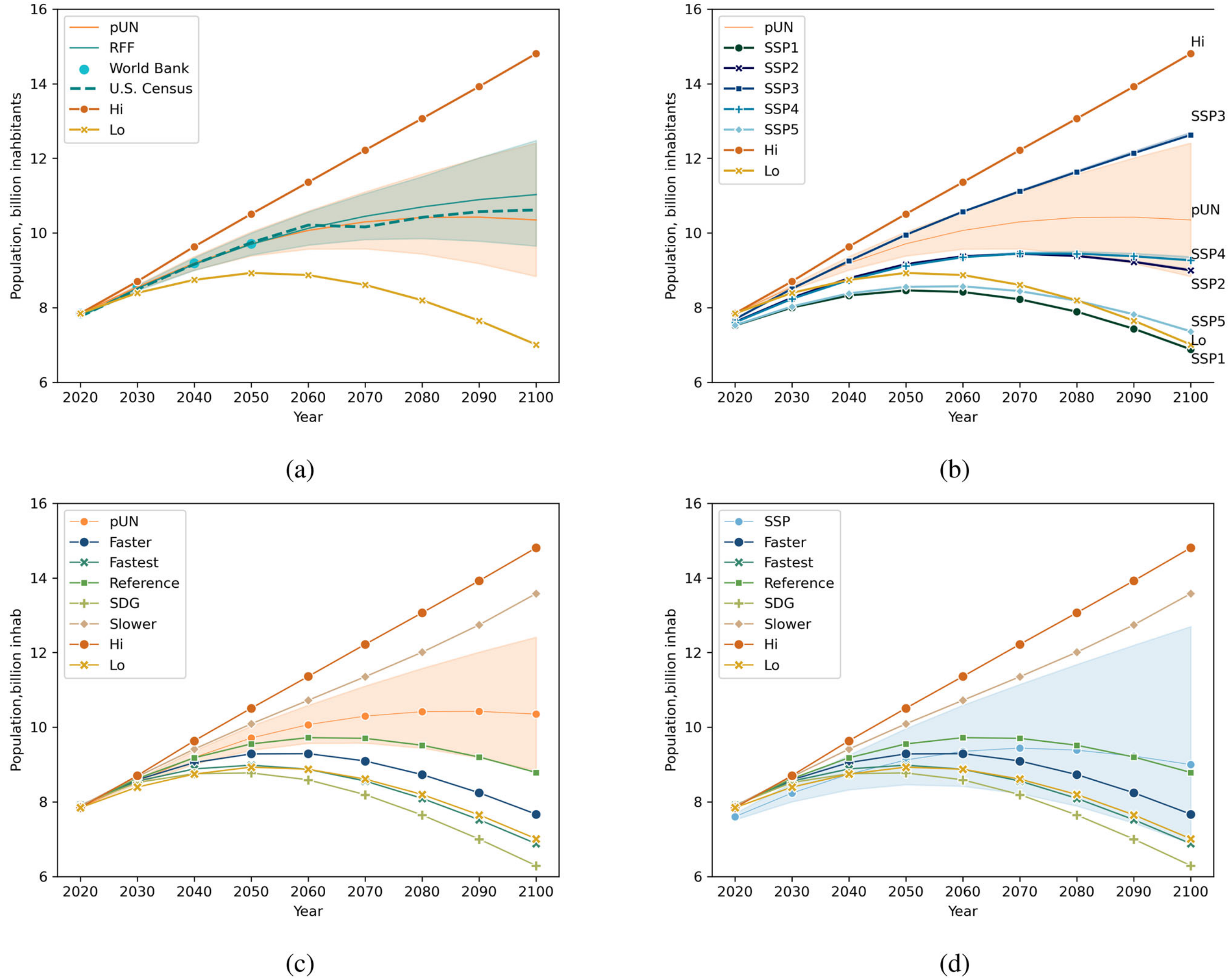
Deterministic methods have been used since 1950 by the United Nations for population projections. Their main feature relies on resolving key parametric uncertainties using expected realisation of fertility and mortality distribution[25]. By applying sensitivity analysis, alongside a central projection, the United Nations provides a set of scenarios where parameters are set to systematically vary to explore the sources of uncertainty on the future of population. For example, Fig. 1 shows two extreme projections obtained by UN varying assumptions on fertility from a baseline. Adopting either more or less conservative assumptions on fertility, they obtain, respectively the lowest (the "Low variant" variant, "Lo" in the chart) or the highest projection (the "High variant" variant, "Hi" in the chart). Deterministic methods are also at the foundation of most national database as well as other multi-national/global databases with a country-level granularity: Eurostat[26], World Bank[27], and the International Database[28].

Differently from the deterministic methods, other approaches (probabilistic methods) sample distributions of their key parameters, to handle uncertainty on fertility, mortality, and migration. Originally, probabilistic projections of population were developed at the International Institute for Applied Systems Analysis (IIASA)[29,30]. Later, in 2015, the United Nations started developing probabilistic projections, in addition to the deterministic ones[31]. These methods use a hierarchical Bayesian approach to support the model parameterisation.

Recent probabilistic population projection methods include expert elicitation. The Resources for the Future (RFF) study[32] is an example of such an approach, and although adopting a similar method, shows notable divergences from the probabilistic projections of the UN. The inclusion of comments from experts (i.e. addition of a variance component to the total fertility rate, the inclusion of an age-adjusted probabilistic migration rate, and the inclusion of an upper limit on population that depends on both population density and geographic area[33]), leads the RFF 5*th*–95*th* percentiles cover a narrower space in the low-fertility area (Fig. 1, top left panel).

Further approaches implement statistical methods for population projection using auto-regressive error propagation on uncertainty[34], such as the population projections of the Institute for Health Metrics and Evaluation (IHME), which is based on fertility, migration, and mortality rate estimates of the Global Burden of Disease Study. Figure 1 shows IHME scenarios overlaid with the UN distribution and SSPs, respectively in bottom left and bottom right panel. The IHME projections propose a reference scenario as well as four alternative scenarios that reflect faster or slower trajectories for two key drivers of fertility rates, namely the education of females and access to modern reproductive health services, which are measured using contraceptive met need ("Faster Met Need and Education", "Fastest Met Need and Education", "SDG Met Need and Education", "Slower Met Need and Education").

Most scenarios submitted to the latest IPCC report cycles, use the population assumptions of the Shared Socioeconomic Pathways (Fig. 1, top right panel). The framework is based on expert elicitation, a broad effort of the demographic community to overcome the limitations of an exclusive statistical approach. This approach involved experts' views and insights on drivers of population change with a focus on how socioeconomic development such as healthcare, education, technology and various policies influence demographic behaviour[8]. Rather than adopting a probabilistic view assigning lower or higher likelihood, the five SSP narratives display the widest possible range of socio-economic paths, moving from a sustainable path (SSP1, with the future global population projected to be the smallest,



(a) (b) (c) (d)

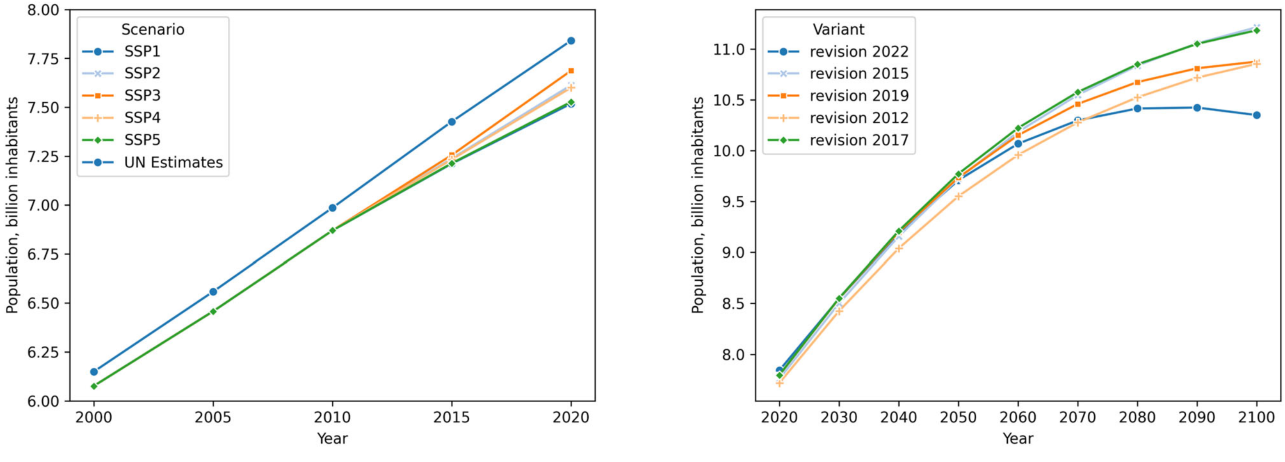
Fig. 1 | Population projections from global databases. Panel (**a**) shows the global population projections developed by UN, the United Nations, (pUN) (a faded orange area represents the 5th to 95th percentile range and a bold orange line depicts the median[25]); the U.S. Census projection (International Database), shown with a blue continuous line; the World Bank estimates shown in blue circles; the 5th to 95th percentile range of the probabilistic distribution developed by Resources for the Future (RFF)[32] in green; the highest and lowest deterministic scenarios developed by UN (dUN) (the "High variant" and the "Low variant", named "Hi" and "Lo" scenarios, shown respectively in orange and in gold[25]). Panel (**b**) shows the United Nation Population Prospects (pUN)[25]; the highest and lowest deterministic scenarios developed by UN (dUN), "Hi" and "Lo"[25]; and the SSPs, the Shared Socioeconomic Pathways (SSP1, SSP2, SSP3, SSP4, and SSP5) developed by IIASA[8]. Panel (**c**) overlays the pUN distribution, with the highest and lowest deterministic scenarios developed by UN (dUN) ("Hi" and "Lo"), and the scenarios developed by IHME (Institute for Health Metrics and Evaluation) which projected scenarios of faster or slower achievement of education and Sustainable Development Goals (SDG) ("Faster Met Need and Education" ("Faster"), "Fastest Met Need and Education" ("Fastest"), "Reference", "SDG Met Need and Education" ("SDG"), "Slower Met Need and Education" ("Slower")[34]). Panel (**d**) overlays the SSP range, with the "Hi" and "Lo" scenarios, and with the IHME scenarios.

reaching 6.8 billion in 2100) to a regional rivalry case (SSP3, with the future global population projected to be the highest, reaching 12.6 billion in 2100)[19].

With the exception of a few datasets (highest UN and RFF percentiles, "Hi", SSP3, IDB, and "Slower"), most forecasts peak and decline or stabilise. The earliest peak is forecasted in the range 8.4–8.9 billion by 2050 in the most sustainable scenarios (SSP1, "Lo", and "SDG"). Scenarios conceived to represent medium trends vary considerably: "Reference" (IHME) and SSP2 are forecasted to peak either in 2060 (9.7 billion) or 2070 (9.4 billion), whereas the UN median reaches its maximum of 10.4 billion in 2090. This wide variability is due to the diversity of the input assumptions, in particular the effectiveness of policies on the achievement of sustainable development goals which could impact education attainment, the key factor determining fertility[35].

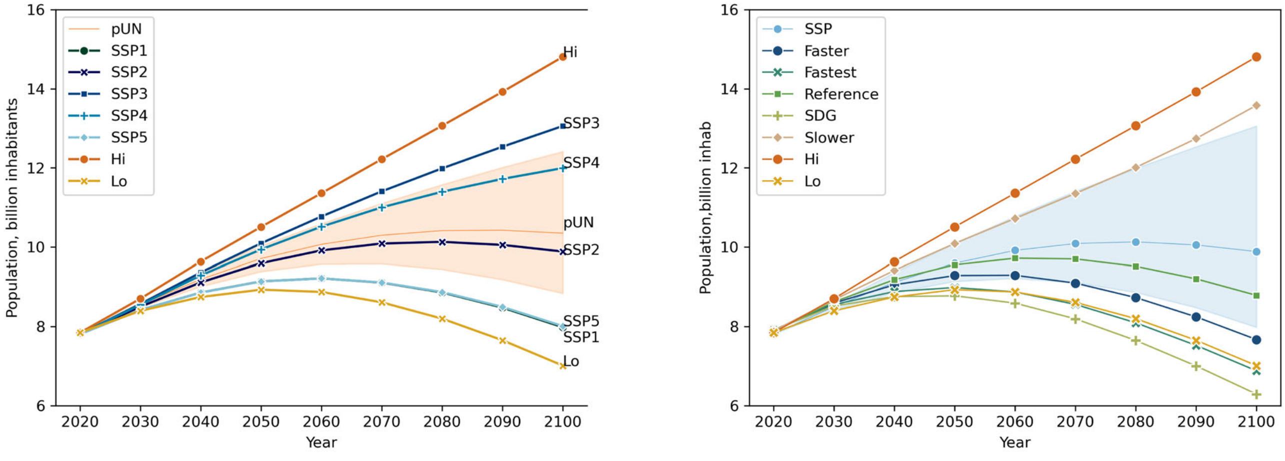
Comparing the probabilistic projections against the SSPs, it is clear that the 5 scenarios span well the projected population ranges, although more represented in the lower population levels. However, it appears that the central SSP2 would correspond to the lower probability rank, as about 5% of cumulative probability would be close to this future realisation. Conversely, higher probabilities would correspond to SSP3, as about 95% of cumulative probability would be close to this pathway. This behaviour is also confirmed by historical trends of population, showing records nearer to SSP3 compared to alternative SSPs (Fig. 2, left panel). Furthermore, in the section "Weighting probabilistic projections on SSPs", we apply a linear combination of the SSPs to determine the UN and RFF probabilistic and show that SSP3 would represent the biggest component. Though the scenario community opposes assigning probabilities to different scenarios, the fact that the SSP2 is the central one lends itself to being considered the most likely or at least the most plausible.

Whilst comparing SSPs against alternative literature, deviations can be seen in historical data, as the version 2.0 of the SSPs (SSPs 2.0), was last updated in 2018 (see Fig. 2). Such deviations are not present in the updated version of the SSPs (version 3.0), available in the SSP 3.0 database (see Fig. 3).



(a) (b)

Fig. 2 | Historical global population: SSPs and UN. Panel (**a**) shows historical data of global population for the years 2000–2020[25], and the SSPs, developed by IIASA[8]. Panel (**b**) shows the projections of global population estimated by the United Nations in the 2012[45], 2015[31], 2017[46], 2019[44], and 2022 revisions[25].



(a) (b)

Fig. 3 | Global projections as in the new SSP release. Panel (**a**) shows the United Nation Population Prospects (pUN)[25]; the highest and lowest deterministic scenarios developed by UN (dUN), "Hi" and "Lo"[25]; and the SSPs 3.0 (SSP1, SSP2, SSP3, SSP4, and SSP5) developed by IIASA, available in the SSP 3.0 database. Panel (**b**) overlays the range of the SSPs 3.0 (available in the SSP 3.0 database), with the "Hi" and "Lo" scenarios, and with the IHME scenarios.

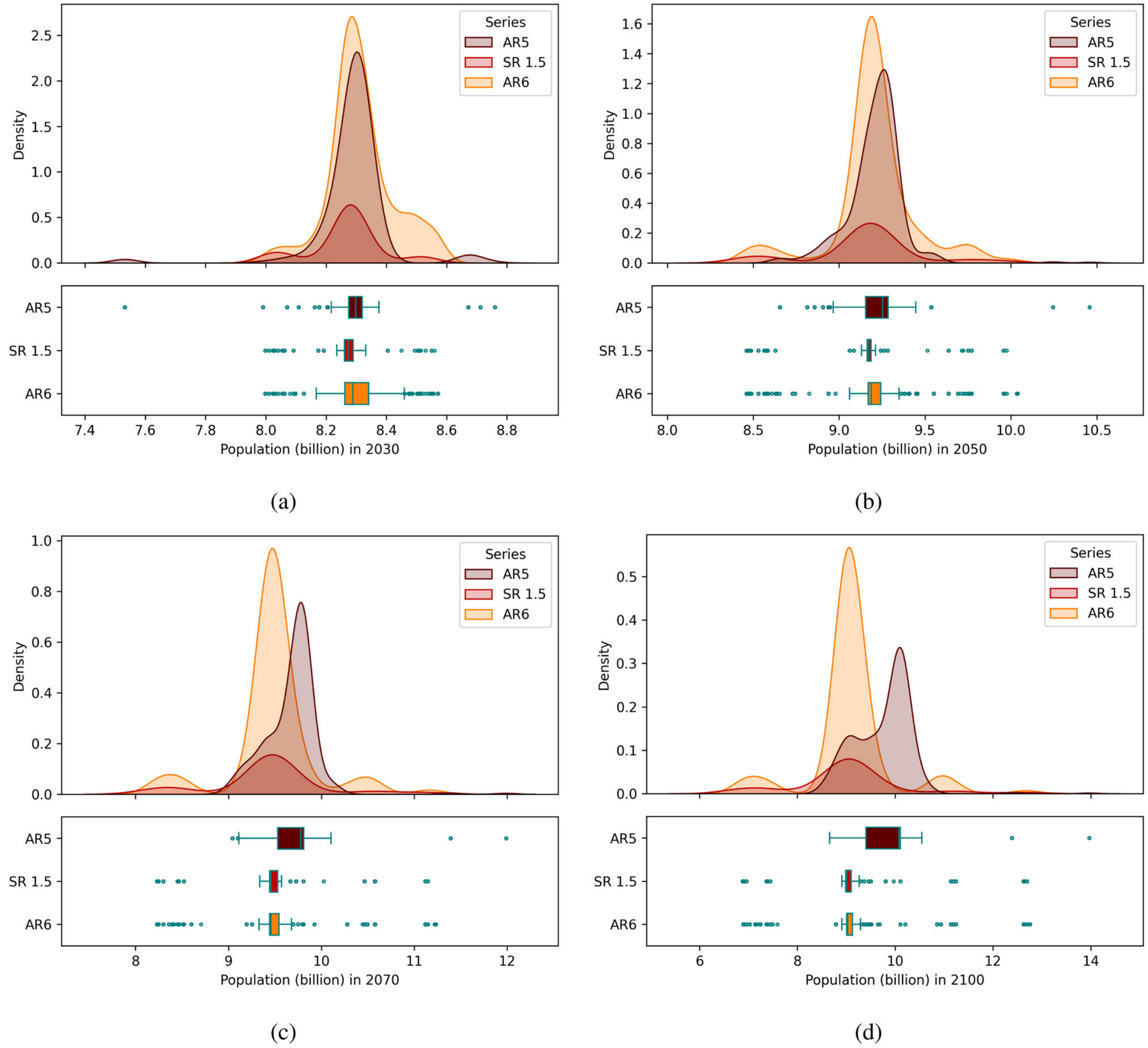
Since the SSPs 2.0 were the main reference for the former IPCC cycles, they are used in the remainder of the analysis for developing the comparison against the scenarios submitted to the Working Group III focusing on the mitigation of climate change.

Relevant multi-national databases are compared in Table 2; their underlined assumptions are further discussed in the section "Database types and applications".

IPCC population scenario ensemble uncertainty across the reports

We analyse the density of distribution and inter-quartile ranges for the databases built for the Fifth cycle (contributing to the Fifth Assessment Report, AR5), for the Special Report on 1.5 °C (SR 1.5), and for the Sixth Cycle (contributing to the Sixth Assessment Report, AR6). These latest reports are characterised by an increasing number of emissions scenarios[36]. For instance, AR6 used 1686 vetted scenarios over a total of 2266 submitted scenarios, compared to the 1184 scenarios submitted for AR5 (see the section "Comparing previous IPCC databases with other lines of evidence: global scale"). The increasing number of reviewed scenarios reflects the growing scientific community and interest in climate mitigation pathways. In principle, it can ensure that future uncertainties are correctly represented.

We find evidence of the contrary. As shown in Fig. 4, the database peaks give evidence of the higher number of scenarios submitted for AR6, resulting in higher densities compared to alternative report databases. Moving towards the end of the century, areas surrounding peaks are accommodated in bigger ranges of population (8.0–8.2 billion inhabitants in 2030, compared to 8.5–11 billion inhabitants in 2100); a behaviour linked with the more visible bimodal distribution of the scenarios submitted for AR5. Still referring to Fig. 4, boxplots show a trend in the ranges of population in the second part of the century. Both in the low bounds and the high bounds, population scenarios used in AR6 and SR 1.5 contain values of lower magnitude than those shown in AR5. The interquartile ranges of population scenarios also reduce, meaning that, despite the growing number of scenarios, the database entries concentrate in a smaller area in the database built for AR6 compared to the one for AR5.



(a) (b)

(c) (d)

Fig. 4 | Distribution of global population in IPCC databases. The figure shows the distribution of global population (in billion inhabitants) of the scenario databases used in the AR5, SR 1.5, and AR6 reports, in four panels, each of which represents a specific year: 2030 (**a**), 2050 (**b**), 2070 (**c**), and 2100 (**d**). Each panel has the density of probability at the top and a boxplot of the population scenarios at the bottom: the first shows the density of scenarios across the population ranges, the second accounts for the population ranges displayed in the scenarios.

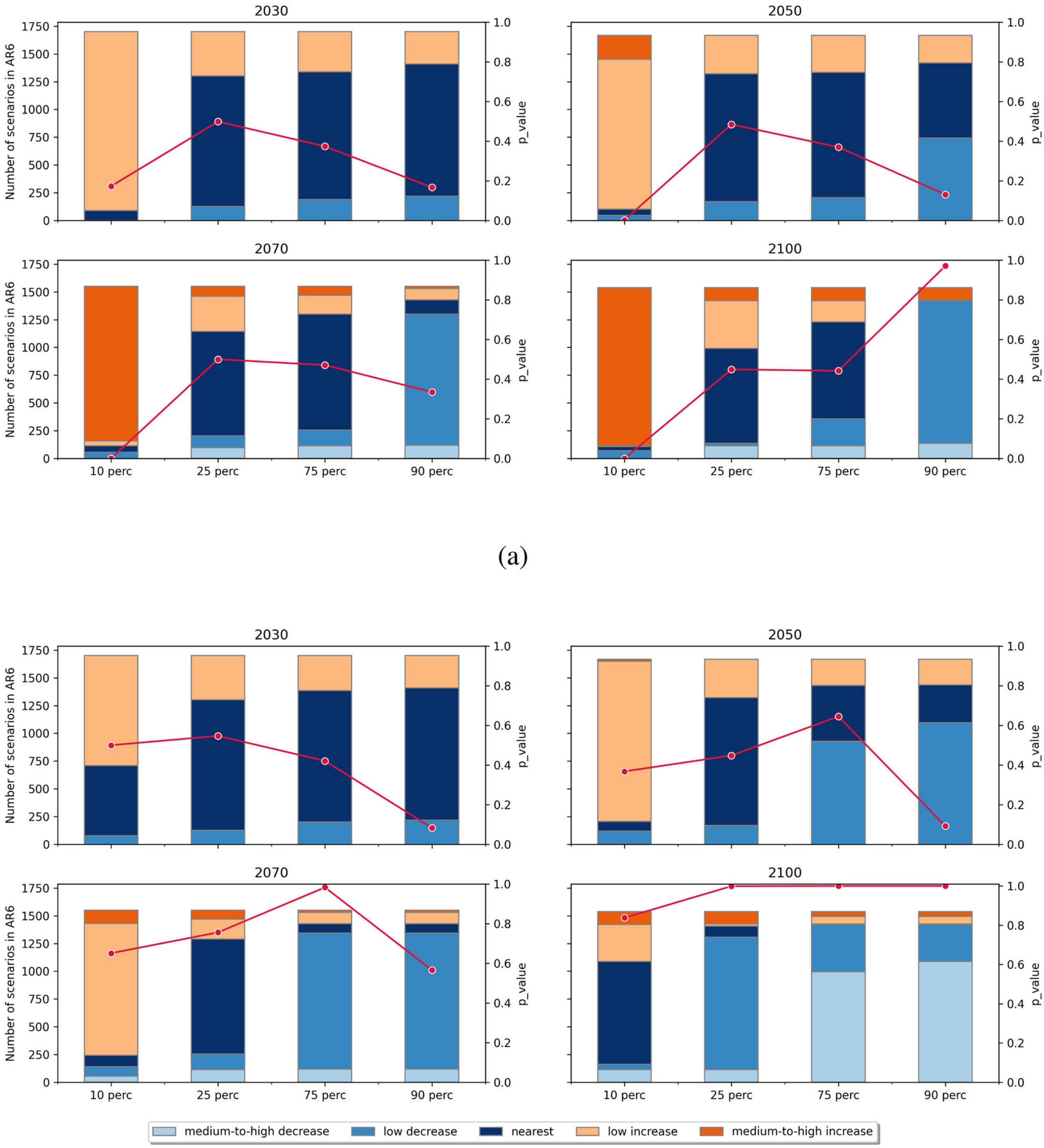
We quantify the distribution of deviations of AR6 in comparison with AR5 and SR 1.5. In Fig. 5 we estimate the distribution of scenarios in AR6 having a statistical summary (such as the median) deviating by a certain percentage from the equivalent statistical summary calculated in an alternative report database and apply a one-tailed Welch *t* test to each decade, using a 5% confidence, and for a set of percentiles (10th, 50th, 75th, 90th). The Welch *t* test had these null hypotheses: "a selected statistical population measure of a scenario sample in a certain decade in the database built for AR6 is lower than the corresponding statistical population measure of a scenario sample in the database built for AR5 (or SR 1.5) for the same decade".

While for central percentiles, AR6 and AR5 display slight differences for most scenarios and in all years analysed, positive and negative deviations are more relevant, respectively, in the low and high tails of the distribution. The trend shows that both in the low tail and in the high tail, scenarios submitted for AR6 cover smaller ranges than those in the AR5.

In comparison with SR 1.5, most scenarios have a (positive or negative) deviation smaller than 10% until 2070 for all the calculated percentiles, with negative deviations becoming dominant (meaning that scenarios submitted for AR6 are be- ing smaller than those in SR 1.5). However, in 2100, most scenarios submitted for AR6 had a significant negative deviation (bigger than 10%) compared to SR 1.5 for the high tails of the distribution. This suggests that the two databases had reasonably close underlined assumptions on global population until 2070, after which diverged with AR6 using scenarios with more limiting assumptions on global population growth.

Inspecting the AR6 database

In the remainder of the paper, we focus on AR6 and provide a detailed analysis of the population scenarios at a global and regional level. The two levels of regional aggregation in the analysis are necessary because of the different population distribution of these emissions scenario ensembles.



(a)

(b)

Fig. 5 | Distributions of deviations from AR6 database. The figure shows distributional deviations of population of AR6 from AR5 (**a**) and from SR 1.5 (**b**) in years: 2030 (top left), 2050 (top right), 2070 (bottom left), and 2100 (bottom right). For each year, population scenarios are aggregated in stacked bars, where each bar shows a selected population statistics: the 10th, 25th, 75th, 90th percentiles. The bins in each bar represent a number of scenarios in the AR6 database with a statistics departing by a certain amount from the same statistics calculated in the AR5 (or the SR 1.5) database. For example, "nearest", indicates the number scenarios in AR6 comprised between—1% and 1% of a selected statistics in the AR5 (or the SR 1.5) database (such as 10th). Each bin is allocated a range of the difference between the AR6 and AR5 (or the SR 1.5) databases. The bins are: "medium-to-high decrease" (smaller than −10%), "low decrease" (between −10% lower and −1%), "nearest" (between -1% and 1%), "low increase" (between 1% and 10%), "medium-to-high increase" (bigger than 10%). The line is the p-value of the Welch-t test performed at the selected decades.

This analysis gives further evidence of undersampling and SSP family convergence in the regional emissions scenario ensemble.

Comparing IPCC AR6 with UN projections. We use the UN projections for the historical comparison with the scenarios reported in the IPCC AR6 databases, as they have the best track record of accuracy in their median projections at the global level of population[37]. The section "Comparing previous IPCC databases with other lines of evidence: global scale" reports the same analysis for AR5 and SR 1.5.

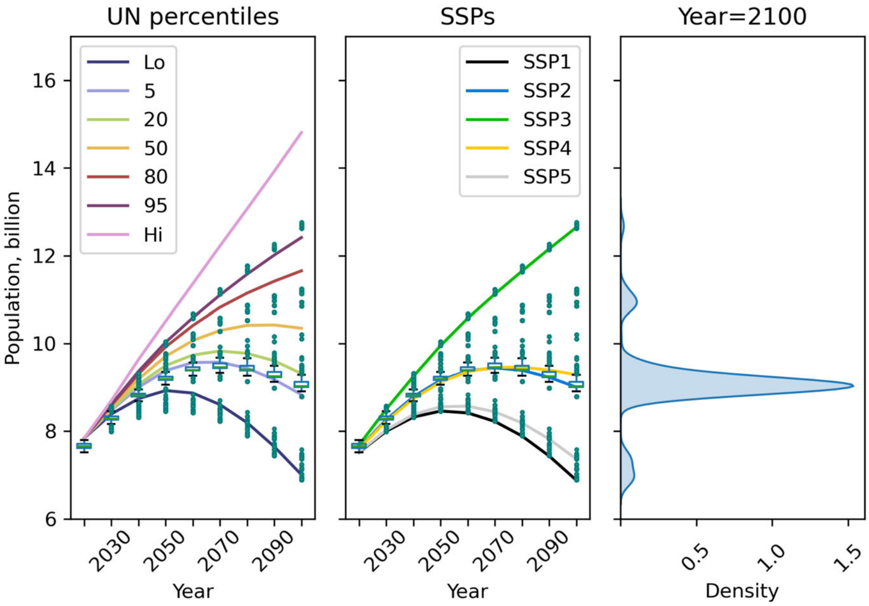


Fig. 6 | Global population in the database used by IPCC in AR6 and in alternative lines of evidence. The figure shows the population scenarios in the database used in AR6. In the panel on the left, the population scenario ensemble is represented in boxplots, overlaid by continuous lines showing the 2022 revision of the UN Population prospects[25] (the 5th, 20th, 50th, 80th, 95th percentiles (pUN) and two extreme fertility scenarios "Lo", Low variant, and "Hi", "High variant"). In the central panel, the population scenario ensemble is represented in boxplots, overlaid by continuous lines representing the SSPs[8]. In these two panels, the boxes show the quantiles, and the whiskers extend to the rest of the distribution excluding the outliers. Outliers are shown in dots beyond the whiskers. The panel on the right shows a density plot of the population scenario ensemble, taking as representative the 2100 milestone year.

Table 1 | The table gives an overview of illustrative pathways, providing their extended name, narrative category (Cur-Pol, Mod-Act, Neg, LD, Ren, SP, GS), and the corresponding warming level reached in 2100

Pathway name	Narrative	Warming in 2100 (°C)
NGFS 2 *CurrentPolicies*	Cur-Pol	Below 4
*EN INDCi*2030 3000 *f*	Mod-Act	Below 3
*EN NPi*2020 900 *f*	Neg	Below 2
*EN NPi*2020 400 *f lowBECCS*	Neg	Below 1.5 with high overshoot
LowEnergyDemand 1.3 *IPCC*	LD	Below 1.5 °C with no or limited overshoot
*S S P*2 *openres lc* 50	Ren	Below 2
S usDev S DP – *PkBudg*1000	SP	Below 1.5 °C with no or limited overshoot
*DeepElec S S P*2 *HighRE Budg*900	Ren	Below 1.5 °C with no or limited overshoot
CO Bridge	GS	likely below 2

The inter-quartile global population values of AR6 lies between the 5th and 20th percentile of the UN distribution (Fig. 6, bottom panel, left side). Although we note that a downward amendment in the future population has also occurred during the revisions over time of the UN projections[25] (Fig. 2b), we observe a growing trend which, starting with SR 1.5, showed a smaller interquartile interval. This is the result of a strong concentration of the scenarios submitted to the IPCC to the SSP2 pathway (Fig. 6) and is confirmed by the frequency of the SSP2 family, covering more than 80% of the total scenarios recorded in the metadata. To further support this conclusion, the frequencies of the SSP family have been cross-checked with those calculated from the metadata for the scenario ensembles, obtaining 3.7%, 82%, 2.4%, 1.5%, 2.1 and 9%, respectively, for SSP1, SSP2, SSP3, SSP4, SSP5, and other storylines.

We also note that the same trend is shown in the illustrative pathways, selected scenarios chosen to illustrate archetypal transitions. They belong to three categories. One is compatible with limiting warming to 1.5 °C with "no or limited overshoot", which include "shifting development pathways" (SP), low demand (LD), and high renewables (Ren). Other illustrative pathways are compatible with a below 2 °C transitions and the remainder implement policies leading to warming beyond 2 °C[38].

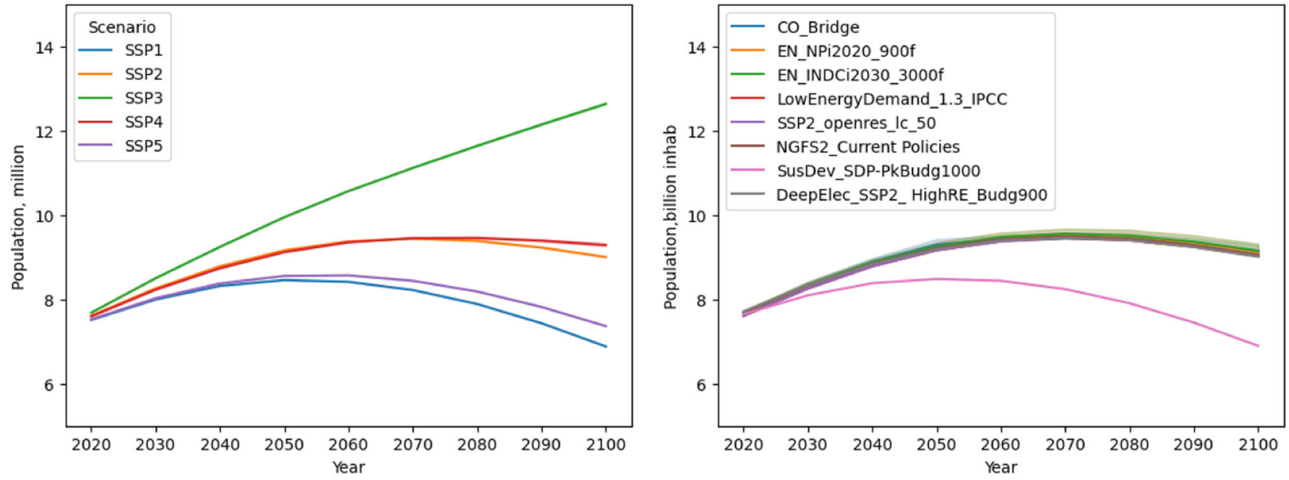
Table 1 gives an overview of pathways, their narrative, and the corresponding level of warming.

The development of illustrative pathways shows a bias in the choice of the SSP. In fact, most of them but one, are based on SSP2. Only the SP pathway is based on SSP1. None of the illustrative pathways uses population projections compatible with SSP3 (Fig. 7).

Regional analysis of IPCC AR6. AR6 is the first IPCC report to show, in addition to socio-economic, emission, and energy projections at a regional level for 10 regions in addition to a granularity including 5 and 6 regions. The list of regions is reported in the section "Comparing AR6 with other lines of evidence at regional scale: estimation of regional aggregation errors".

Regional projections show wider ranges of variability than the global scale, especially for a 10-region breakdown. However, this variability is more likely related to aggregation routines rather than being representative of an actual diversity in the scenario narrative. Region aggregation (Fig. 8) Despite this variability, strong similarities can be found in the trends between the regional and the global scale. Using 5 regions, results collapse on one single trajectory, which is between SSP2 and SSP4, with SSP2 being the preferred modelled pathways for most developing regions (see Fig. 8).

Scenarios have inter-quartile ranges bigger for a 10-region granularity than for a 6-region aggregation (Fig. 9). The comparative analysis between the AR6 database (with a 10-region granularity) and UN is based on the approach described in the section "Comparing AR6 with other lines of evidence: regional scale". The discussion focuses on Africa, China, India, and Latin America and the Caribbeans, where a direct correspondence can be made between the two sources, IPCC and UN. From Fig. 9, we can see that most of the time the IPCC database is lower than the UN median. For regions deemed as crucial for the future population growth, such as China, Africa, and India, the population magnitude appears underestimated in comparison with the UN probabilistic projections. For example, the projections for China and India in AR6 are located just below the UN median but those for Africa appear even far from the lowest UN percentiles. Notably, the values reported in the scenario ensemble for the region corresponding to Africa may be skewed by the potential inclusion of the Middle East countries (the



(a) (b)

Fig. 7 | Global population in SSPs and illustrative pathways. The figure compares SSPs in panel (**a**) and illustrative pathways (**b**). Cur-Pol: current policies; Mod-Act: 2030 climate policies and limited additional climate actions, GS: gradual strengthening of current policies, LD: low demand, Neg: net-ngative, Ren: high renewables.

"R10MIDDLE_EAST" IPCC region). Regional aggregation errors are discussed in the section "Comparing AR6 with other lines of evidence at regional scale: estimation of regional aggregation errors".

Overall the regional analysis in the 10-region granularity is inherently difficult because of the high noise in the regional aggregation which does not allow us to dive into a deep analysis except for acknowledging that a ten-region aggregation does not seem an ideal format for the result representation.

Subregional analysis of IPCC AR6. Due to its low geographical granularity, the emissions scenario ensemble used in AR6 cannot be used directly to draw conclusions on comprehensiveness and diversity of the uncertainty space for demography in selected multi-country groups with specific challenges to reach a sustainable development. These groups refer to Small Island Developing States (SIDS), Least Developed Countries (LDCs), and Landlocked Developing Countries (LLDCs). However, mapping the deterministic and probabilistic projections developed by the UN on the SSPs (see Fig. 10) similar trends as those observed at a global scale can be seen (as shown in Fig. 1). Specifically, SSPs may come close to the 80th percentile of the UN distribution. Conversely, SSPs span an area wider than the one provided by the UN in the lower bound. This happens in all the subregions, except for the SIDS areas when compared to the SSP 3.0, despite notable calibration problems. The narrative of the SSPs scenarios seems to align with a partial or full realisation of the sustainable development goals in slowing down population growth.

Concerning the diversity of the emissions scenarios submitted to the IPCC database, the over-representation of SSP2 observed for the main IPCC regions, (see Fig. 10), is likely extendable to these special groups of countries. Such a limited coverage of only a few of the possible demographic outcomes unveils knowledge gaps on climate change implications, especially important for more vulnerable countries.

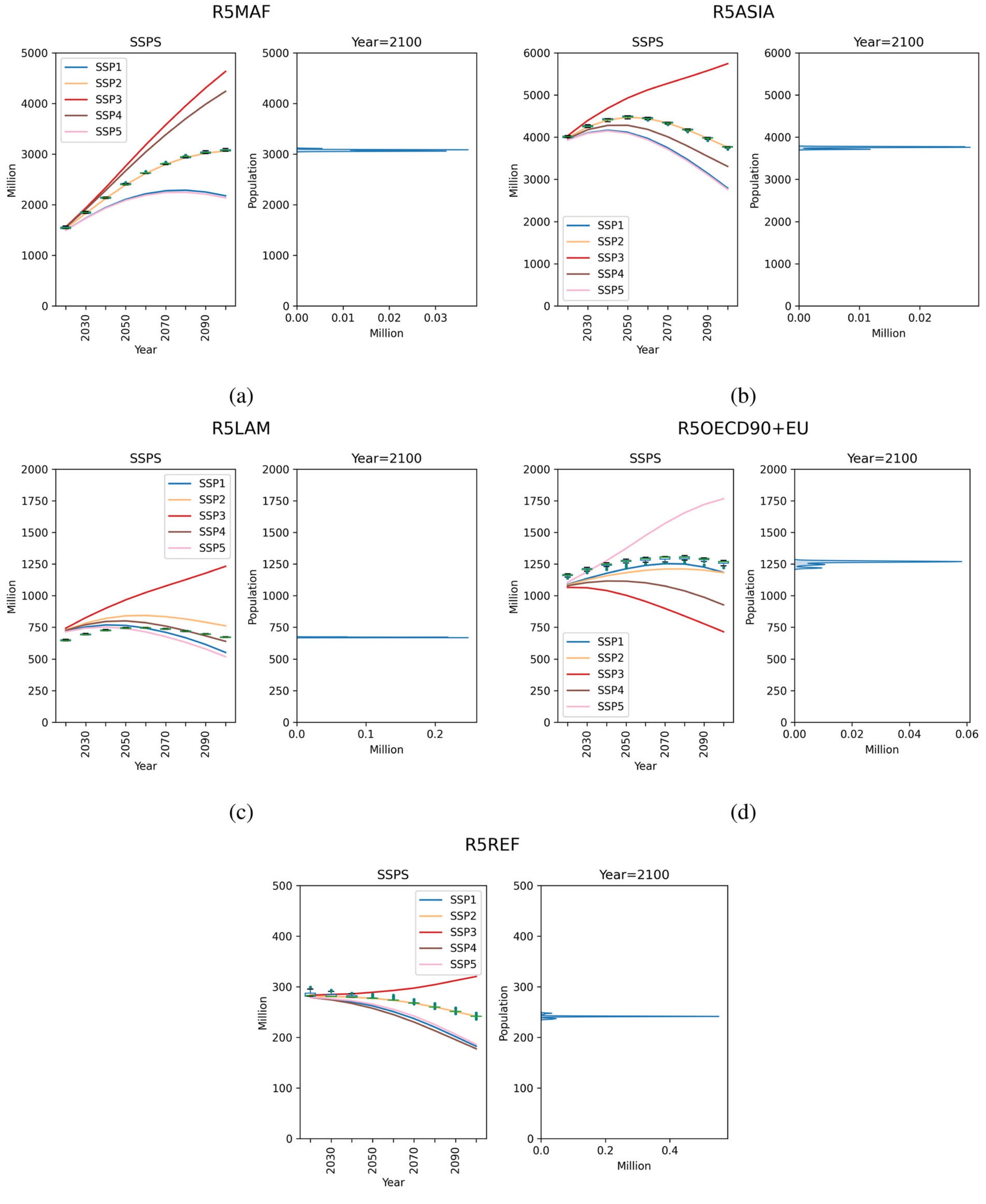
Discussion

This paper proposes a historical analysis of the representation of the global population, focusing on the variability of population size across the latest IPCC assessment reports. The analysis draws on a review of alternative population databases to question whether the variability of the database used by the IPCC is sufficient to embed uncertainty about future projections.

Most emissions scenarios submitted to the database curated by the IPCC, use the underlying assumptions of the Shared Socioeconomic Pathways, where the population of each country is projected on the basis of a series of narratives, each of which contains hypotheses on fertility, mortality, and migration. The historical analysis of the global human population in the emissions scenarios of the latest IPCC reports, highlights a decrease in the range of the population variability, demonstrated by a reduction in the variance of the population and of the sample means. The existing method to create the IPCC database leads to an over- representation of the SSP2 narrative. It is apparent, for instance, while moving from AR5 to AR6, that most of the emissions scenarios submitted belong to the "Middle of the Road" scenario. Conversely, observations from statistical approaches proposed by alternative literature reveal that SSP2 may cover only a few of the future possible outcomes. In fact, SSP2 appears to be less than the 5th percentile of the global population in 2050 (according to both UN and RFF) and to be less than the 5th or 20th percentile (according to RFF and UN, respectively) in 2100. Weighting methods, where alternative storylines can be numerically combined, can be used to alleviate the problem of reconciling certain deviations from scenarios and reality, as implemented in the section "Weighting probabilistic projections on SSPs". Nevertheless, there is still a need to expand future databases towards targeting also different SSPs from SSP2. In particular, future research involving the use of population projections associated with the SSP3 storyline would be relevant.

On a regional scale, the analysis shows a double layer of geographical granularity biases. On the one hand, IAMs participating in the IPCC process reduce the complexity of a country-level representation aggregating country-level information into native regions. On the other side, the IPCC regions are aggregated results from the IAMs native regions. With the term "native regions" we indicate the regional aggregation generated as a primary output from IAMs. This double layer of aggregation makes a rigorous comparison difficult to make. On a regional scale, it appears not possible to investigate trends for regions, such as R10REST_ASIA, which contains countries excluded from bigger Asian regions) where high discrepancies can be found even with SSP aggregation. However, certain conclusions can be made for crucial areas, such as Africa,

China, and India which shows lower discrepancies between AR6 and aggregations made on either the SSPs or the UN databases. First, these countries / regions show in the AR6 database an over-representation of SSP2, and, second, the same are under-estimated in the way population may grow in comparison with the UN data. Although, this should not suggest any inherent error in the assumptions made, it would reveal that the approach is somehow biased towards a representation of an exclusive specific pathway. In this regards, it emerges a question around the



(a)

(b)

(c)

(d)

(e)

Fig. 8 | Distribution of regional population in the database used by IPCC. The figure shows the population distribution for the 5 IPCC regions, R5MAF, R5ASIA, R5LAM, R5OECD + EU, R5REF (**a**, **b**, **c**, **d**, **e**). Each panel displays on the left the boxplot of the distribution per milestone year: each box represents the quantiles, the whiskers extend to the rest of the distribution (except for the outliers), and the continuous lines correspond to the SSPs[20]. Each panel displays in the chart on the right the density plot for the demographics for a representative year, 2100. Values are in million inhabitants.

representativeness of the storylines embedded in the SSPs. The literature suggests that it could be convenient to shift storylines covering more extreme scenarios[39]. Especially, scenarios adopting storylines more challenging with respect to climate change mitigation and adaptation can be prepared due to their inherent higher difficulty in reaching mitigation targets.

In view of the next IPCC cycles, some groups have proposed changes to the submission process. First, an open process of submission

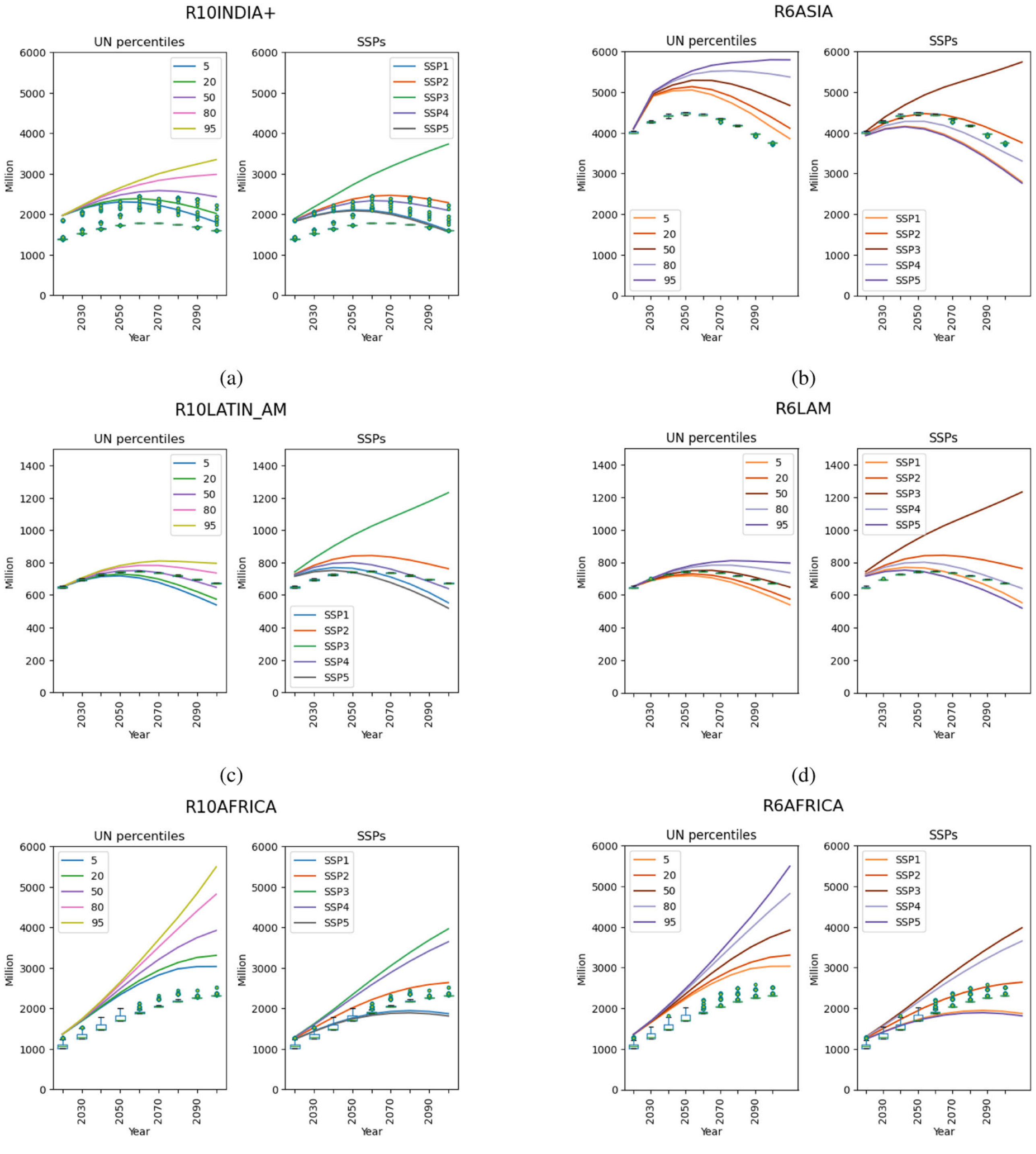
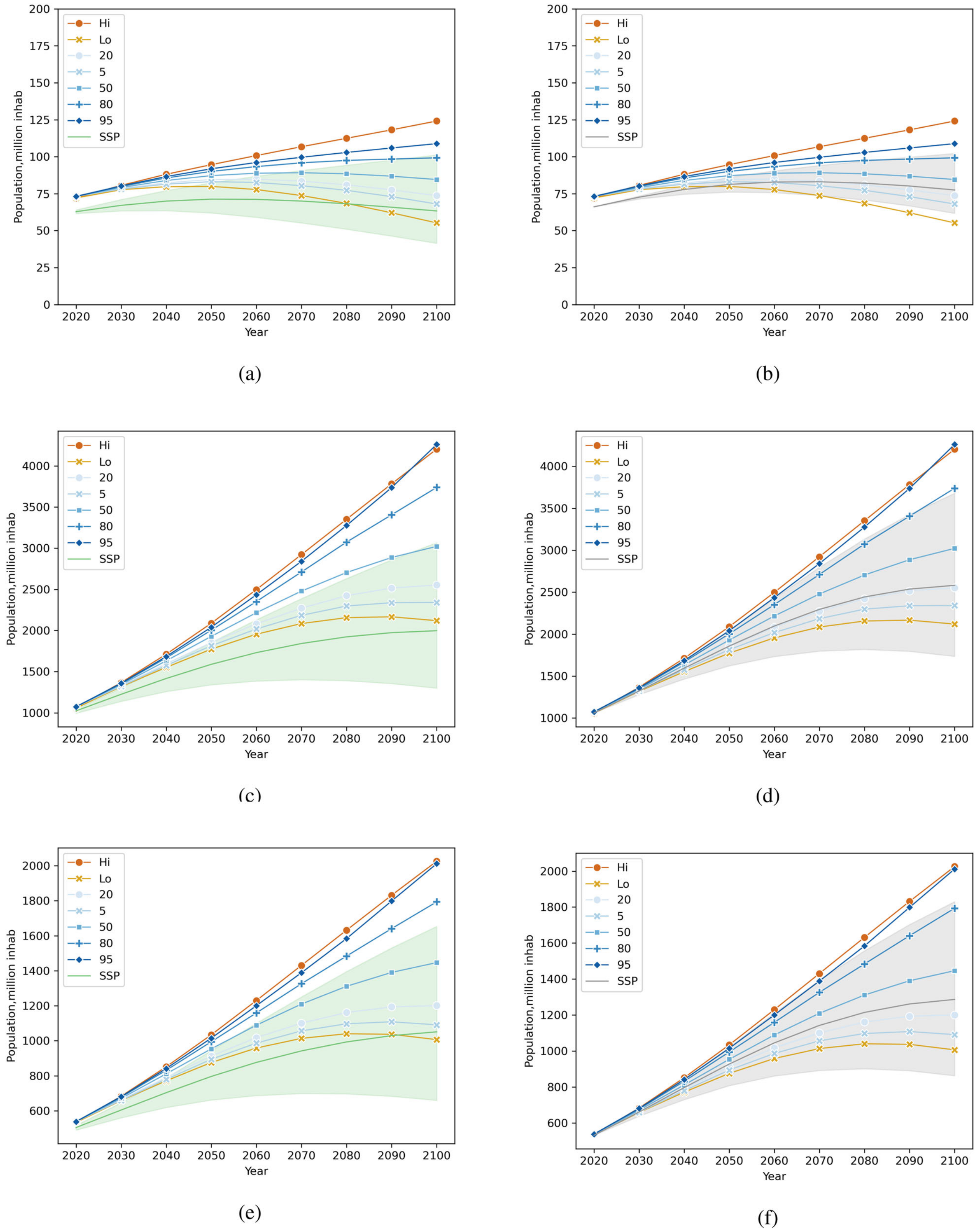


Fig. 9 | Distributions of regional population in the database used by IPCC in AR6. The figure projects the population for a 10- (**a**, **c**, **e**), and for a 6-region granularity (**b**, **d**, **f**). The boxes in each panel show the quantiles, and the whiskers extend to the rest of the distribution, excluding the outliers. The continuous lines represent the 2022 UN revision[25] (left) and the SSP[20] (right).

where the assumptions used in the research studies generating results for the IPCC database are publicly available, could ascertain the robustness of the emissions scenarios themselves[22]. Second, higher statistical meaning to the scenario database would be obtained if there were bigger diversity in the models submitting their research outputs, extending the procedures of Coupled Model Intercomparison Projects used by the IPCC Working Group I and II communities[22]. Furthermore, we argue that, in addition to ascertain the quality of a single scenario, a revision of the scenario ensemble as a whole should be performed. Important database attributes to be explored would include comprehensiveness at representing the uncertainty space, diversity of the scenarios hypotheses, and assessment of the relevance of scenarios to fill policy gaps[40]. Finally, to capture the growing uncertainty of future population, we claim that auditing techniques, such as those shown here for population, could be used to ascertain the quality of the database as it is being built. Notably, auditing would allow a critical assessment of the database



(a) (b)

(c) (d)

(e) (f)

Fig. 10 | Population projections for special regions in the UN and the SSP databases. The UN projections are shown for the Small Islands Developing States, the Least Developed Countries, and the Landlocked Developing Countries in the top, mid, and bottom panels. The lines are the 2022 revision[25] (the 5th, 20th, 50th, 80th, 95th percentiles and two extreme fertility scenarios ("Lo" and "Hi", "Low" and "High variant"). The shaded area represents the SSPs, version 2.0[8] and version 3.0 on the left and right side.

against alternative lines of evidence. For instance, divergences in the population futures have been amplified in the literature using probabilistic approaches, where more powerful parameterisation of time-dependent correlations are implemented, compared to storytelling ones. Since probabilistic methods have the advantage of assigning a probability to each population trajectory, they could be used to inform the database in a complimentary way to storytelling approaches based on the SSPs.

Methods

The methods section is organised as follows:

- overview of the modelling approaches used in the literature for estimating population projections (section "Approaches for population projections ")
- overview of the major multi-national databases (section "Database types and applications ")
- estimation of similarity between probabilistic projections and SSPs through the use of weighting methods (section "Weighting probabilistic projections on SSPs")
- statistical methods applied to the population ensemble of the previous IPCC reports, AR5 and SR 1.5 (section "Comparing previous IPCC databases with other lines of evidence: global scale")
- estimation of deviations of regional aggregation between the population ensembles of the IPCC reports and other lines of evidence (UN and SSPs) (section "Comparing AR6 with other lines of evidence at regional scale: estimation of regional aggregation errors")
- comparison of AR6 demographic projections with alternative lines of evidence at a regional scale (section " Comparing AR6 with other lines of evidence: regional scale")
- description of the acronyms used in the paper (section "Acronyms")

Among the scenarios submitted, the assessment of climate change science conducted by the IPCC pertains only those passing the "vetting", which have emissions and energy data that are within reasonable historical ranges. However, in this analysis, all the statistical analysis presented here uses the scenario databases including scenarios passing and non-passing the vetting process. The inter-percentile range for the global statistics is between 0.5 and 99.5%, to exclude out-of range samples. The inter-percentile for the regional statistics is between 25 and 75% to compensate regional aggregation problems.

Approaches for population projections

National and multi-national databases are obtained primarily from the implementation of deterministic methods. More recently, probabilistic frameworks and expert elicitation approaches have been proposed.

Table 2 shows the geographical and time coverage as well as modelling approach of the major databases available.

Table 2 | Multi-national databases of population projections, grouped into those applying deterministic or probabilistic methods, expert elicitation, and statistical models

Database	Geography	Time	Source
Deterministic			
EUROSTAT	EU27 & EFTA	2022–2100	EUROSTAT[26]
OECD	46 countries	2021–2030	OECD
World Bank	Global	2022–2050	World Bank[27]
US Census	Global	2022–2100	US Census[28]
Probabilistic			
UN	Global	2022–2100	UN DESA[25]
Expert elicitation			
IIASA	Global	2010–2100	IIASA[8]
Expert elicitation & probabilistic			
RFF	Global	2010–2300	RFF[32]
Statistical models			
CCF50	Global	2018–2100	The Lancet[34]

OECD (Organization for Economic Cooperation and Development) covers 34 OECD member countries, 6 EU countries not belonging to the OECD, and Brazil, Colombia, India, Indonesia, China, Russia and South Africa. Expert elicitation methods can be used to generate deterministic projections, such as those from IIASA, or to integrate probabilistic methods such as those used in the projections by Resources for the Future (RFF). CCF50 represents the "completed cohort fertility at age 50" model.

Deterministic methods. Deterministic methods, the standard approach to projecting population since 1940, use the cohort-component method of population projection, meaning that they balance over a time period the three components underlying population dynamics: the number of births (fertility rate), deaths (mortality rate), and migration flows by region. Most national population projections define one likely path of the future population (central projection); in this case the numbers of births and deaths are taken equal to the expectations of their distributions[41]. In some cases, multi-national and global databases with a country-level granularity include a high and low variant of population projection, in addition to the medium (or central) projection[25]. Eurostat and United Nations are examples of relevant multi-national databases, in addition to the International Database (by the U.S. Census), and the World Bank. As each model is developed for a certain purpose, the underlying model assumptions may substantially differ from one database to another, causing them to diverge quite substantially. For example, while the Eurostat projections have been developed originally to ground EU policies since 2000, the UN has, among its many objectives, the assessment of the implications of population change on different aspects of international interest, such as food security and climate change.

Probabilistic methods. Probabilistic methods are designed to take into account the degree of uncertainty in past data and how this may affect future projections of fertility, mortality, and migration as these quantities vary with time in a stochastic manner[42]. The UN has been releasing probabilistic projections since 2015. In the latest UN Population Prospects[25], population projections for each country were constructed from a set of trajectories of future outcomes of total fertility rate and life expectancy at birth, whereas one central projection for migration was applied to each set of future fertility and mortality outcomes. The method used a Bayesian hierarchical model for filling gaps in parameter estimation and generating posterior probabil- ity distributions, which were then sampled with a Markov Chain Monte Carlo (MCMC) algorithm.

Expert elicitation: shared socioeconomic pathways. An important example of expert elicitation approach is represented by the Shared Socioeconomic Pathways (SSP) projections, which have been developed as expert opinion-based futures as a research community effort, which in 2014 led to the identification of a set of five SSP storylines/narratives[43]. While the narratives describe the main characteristics of the SSP future development, the quantification of these storylines includes estimates of factors like population, economic development, land use, and energy use[20]. Among the five hypothetical futures, SSP narratives include a world of sustainability-focused growth and equality (SSP1), a "middle of the road" world where trends broadly follow their historical patterns (SSP2), a fragmented world of "resurgent nationalism" (SSP3), a world of ever-increasing inequality (SSP4); and a world of rapid and unconstrained growth in economic output and energy use (SSP5)[20]. The methodology and estimation of the population projections of the SSPs are explained in detail in alternative source[8]. From the SSP database, population projections can be found as developed by the International Institute for Applied Systems Analysis (IIASA), the National Center for Atmospheric Research (NCAR), and OECD (Organization for Economic Co-operation and Development).

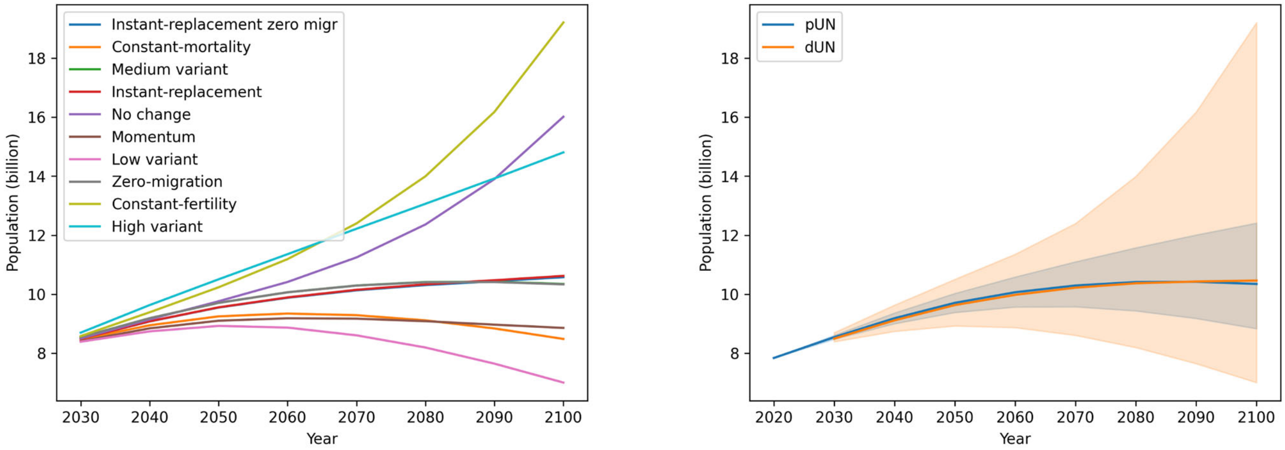
Probabilistic methods and expert elicitation. Finally, expert elicitation can be used to inform probabilistic methods in long-term projections covering a wider time frame than 2100[33]. The authors used an MCMC-sampled statistical model, similar to the probabilistic one used by UN, extended for projecting to 2100 to 2300, which was modified later with the inclusions of selected demographers' comments[32,33].

Statistical models. Statistical models were developed for completed cohort fertility models at age 50 years (CCF50)[34]. Completed cohort fertility measures the total fertility rate at 50 years of age. The model uses time-series random walk functions of educational attainment and contraceptive met need. It includes age-specific fertility rates and age-specific mortality to 2100, and net migration as a function of the Sociodemographic Index, crude population growth rate, and deaths from war and natural disasters.

Database types and applications

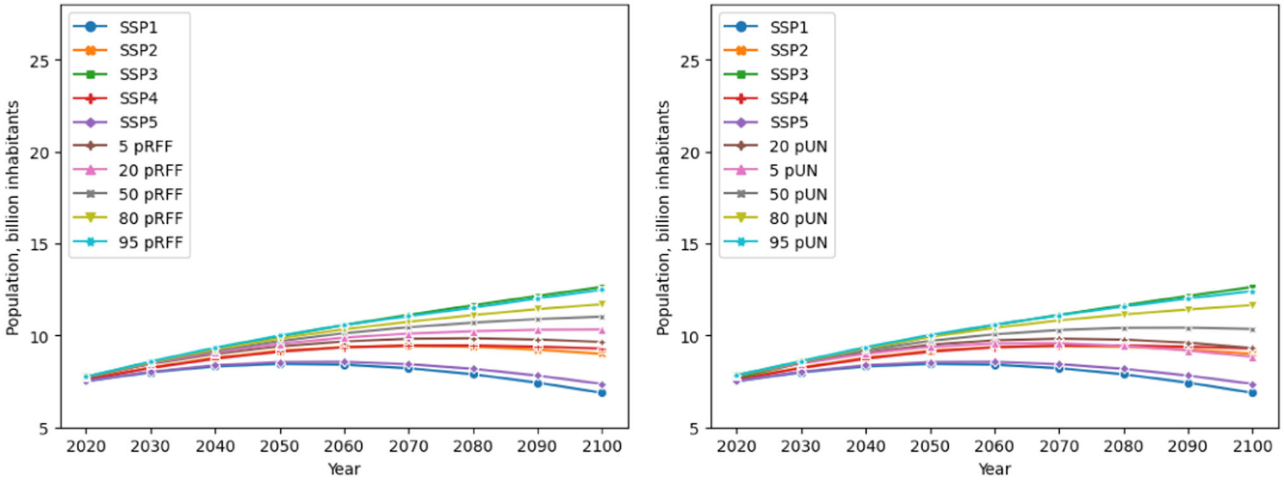
There are several multi-national databases of population projections using deterministic methods.

- the International Database, published by the U.S. Census Bureau since 1996, which includes total population, population by age and sex, and demographic characteristics usually derived from census data, such as fertility, mortality, and migration from a base (initial) year through 2100 for 228 countries.
- Eurostat projections of population (the latest one being the EUROPOP- 2023). These populations are meant as 'what-if scenarios' that aim to show, for a long-time period, the hypothetical developments of the population size and its structure at a country level up to 2100[26].
- The UN Population Projections, the official United Nations population estimates and projections prepared by the Population Division of the Depart- ment of Economic and Social Affairs of the United Nations Secretariat. Past projections of population published after 2010 covered up until 2100. Since 1978 they have been updated every two years, with the inclusion of updated national censuses from 237 countries. UN assessments have provided projections by age and sex for a medium scenario and



(a) (b)

Fig. 11 | Global population from the deterministic projections of UN. Panel (**a**) shows the deterministic scenarios proposed by the United Nations (dUN) where each scenario is represented individually ("High Variant", "Medium Variant", "Low Variant", "Constant-fertility", "Instant-Replacement", "Instant-Replacement zero migration", "Zero migration", "Momentum", "Constant-mortality", "No change"). Panel (**b**) shows the deterministic scenarios (dUN) as an orange areas overlaid by the population distribution projections for the percentiles 5th, 20th, 50th, 80th, and 95th of the probabilistic distribution developed by UN (**b**)[25].



(a) (b)

Fig. 12 | Global population from probabilistic projections of RFF and UN (pUN). The figure shows the global population projections for the percentiles 5th, 20th, 50th, 80th, and 95th of the probabilistic distribution developed by RFF (**a**)[32] alongside the SSPs (SSP1, SSP2, SSP3, SSP4, and SSP5) developed by IIASA[8]. Panel (**b**) displays the projections developed by UN for the percentiles 5th, 20th, 50th, 80th, and 95th (pUN)[25] alongside the SSPs.

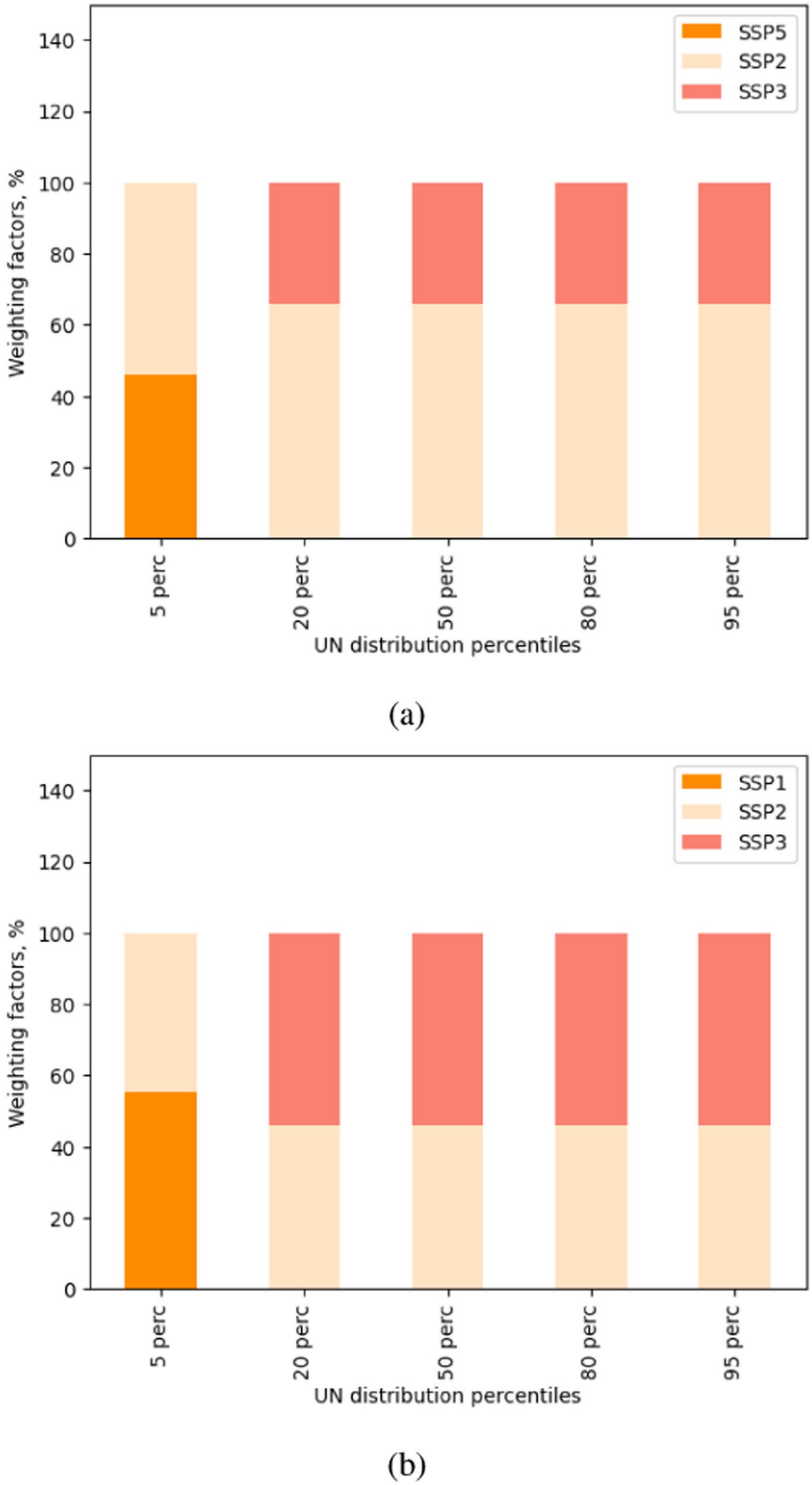
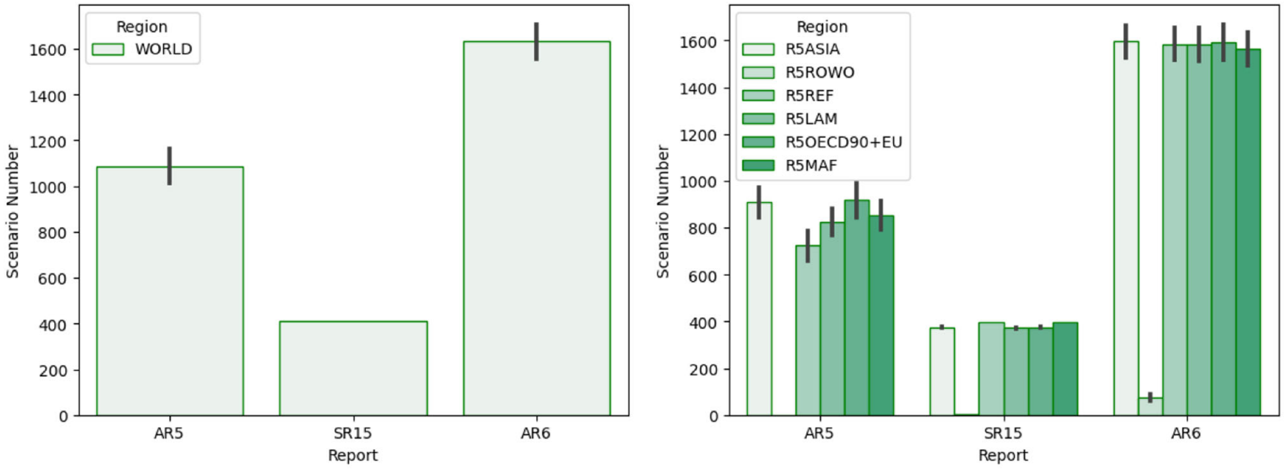


Fig. 13 | Weights of SSPs to generate UN population in 2100. The figure shows the weighting factors in percentages of SSPs, determined to match the population distribution projections for the percentiles 5th, 20th, 50th, 80th, and 95th of the selected probabilistic projections in 2100. Panel (**a**) shows the linear combination of the SSPs leading to each quantile of the population projections estimated by RFF[32]. Panel (**b**) shows the values of the weighting factors giving a selected quantile of the population projections estimated by UN[25].

alternative scenarios based on variations of fertility, mortality, and migration assumptions. Among the deterministic projections, five scenarios differ with respect to the level of fertility: medium-fertility, low-fertility, high-fertility, constant-fertility and instant-replacement-fertility. In the high-fertility scenario, total fertility for each population is projected to be 0.5 births higher than the medium scenario. Similarly, in the low-fertility scenario, total fertility is projected to be 0.5 births below the level assumed for the medium scenario. In the constant-fertility scenario, total fertility remains equal to 2022 levels. In the instant-replacement scenario, fertility for each country is set to ensure a net reproduction rate of 1.0 from 2022. Other scenarios



(a)

(b)

Fig. 14 | Numbers of scenarios in the database used by IPCC in AR6. Number of scenarios reporting the population variable for the world (**a**) and for the reported 5 regions (**b**) in IPCC AR5, SR 1.5, and AR6: R5ASIA (Asia), R5ROWO (Rest of the World), R5REF (Re- forming Economies), R5LAM (Latin America), R5OECD + EU (OECD), R5MAF (Middle East and Africa). The bars report the average number of scenarios between the years 2050 and 2100; the error bars show the difference in scenario number between the highest number of scenarios (for 2050) and the lowest number of scenarios (2100). 2050 and 2100 are chosen years among the milestone years reported in AR databases, which typically have 1-, 5- or 10-year steps.

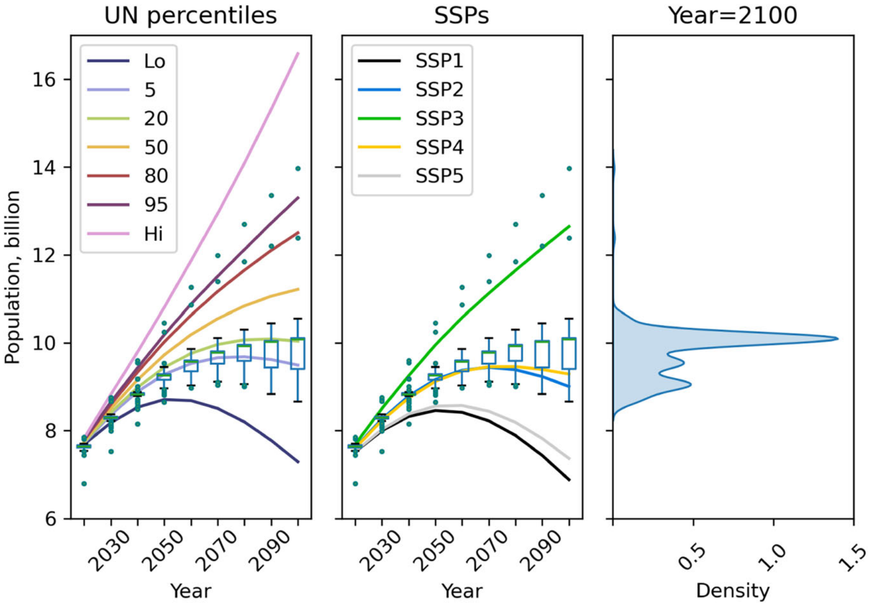


Fig. 15 | Distribution of population scenarios of the database used in AR5. The figure shows the population scenarios in the database used in AR5. In the panel on the left, the population scenario ensemble is represented in boxplots, overlaid by continuous lines showing the 2015 revision of the UN Population prospects[31] (the 5th, 20th, 50th, 80th, 95th percentiles (pUN) and two extreme fertility scenarios "Lo", Low variant, and "Hi", "High variant"). In the central panel, the population scenario ensemble is represented in boxplots, overlaid by continuous lines representing the SSPs[8]. In these two panels, the boxes show the quantiles, and the whiskers extend to the rest of the distributions excluding the outliers. Outliers are shown in dots beyond the whiskers. The panel on the right shows a density plot of the population scenario ensemble, taking as representative the 2100 milestone year.

include a momentum scenario, a constant-mortality scenario, a zero-migration scenario, and a "no change" scenario, in which both fertility and mortality are kept constant.

- the World Bank release of country-level population projections for the world to 2050, now based on UN and other multinational bodies projections[27]. In the past, the World Bank projections were independent population projections, which between 1984 and 1955, were revised approximately every 2 years and published as one updated variant published with a long time horizon to 2150.

The UN's population forecasting track record has been notably good on a global level. For example, the UN's 1958 forecast of the world population in 2000 was accurate to within 4%, despite some accuracy loss in the projected total fertility and life expectancy for selected regions, such as Asia[37].

In addition to the deterministic projections, the UN provide probabilistic projections[25]. Figure 11 represents the probabilistic prediction intervals and the deterministic scenarios. For clarity, only the extreme ones, falling beyond the prediction intervals, are represented: a low-fertility and a high variant ("Low Variant" and a "High Variant"). During the estimation of the lowest and highest population projection, the "Constant fertility" and the "Instant replacement" trends have been removed, since they are mathematical exercises and are not grounded on realistic assumptions. Consequently, the top and the bottom projections become the "High fertility" and the "Low fertility" scenarios.

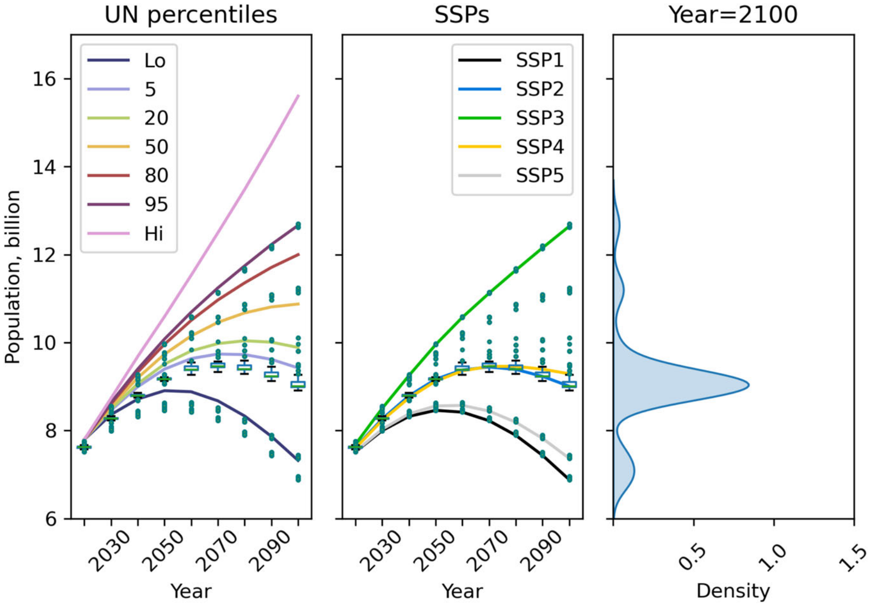


Fig. 16 | Distribution of population scenarios of the database used in SR 1.5. The figure shows the population scenarios in the database used in SR 1.5. In the panel on the left, the population scenario ensemble is represented in boxplots, overlaid by continuous lines showing the 2019 revision of the UN Population prospects[44] (the 5, 20, 50, 80, 95th percentiles (pUN) and two extreme fertility scenarios "Lo", Low variant, and "Hi", "High variant"). In the central panel, the population scenario ensemble is represented in boxplots, overlaid by continuous lines representing the SSPs[8]. In these two panels, the boxes show the quantiles, and the whiskers extend to the irest of the distributions excluding the outliers. Outliers are shown in dots beyond the whiskers. The panel on the right shows a density plot of the population scenario ensemble, taking as representative the 2100 milestone year.

Weighting probabilistic projections on SSPs

Here we map the RFF and the UN probabilistic projections on the SSPs applying a weighting approach. After extracting the relevant percentiles (5th, 20th, 50th, 80th, and 95th) from each probabilistic distribution, the method selects first a couple of the SSP pathways being the upper and the lower bound to a selected distribution percentile. In a second step, once the two SSP pathways lying around each percentile are defined, we use an optimisation algorithm to calculate the percentage of the relevant SSPs contributing to the projected percentile of each external source.

Figure 12 shows how each SSP is located with respect to the percentiles estimated from the alternative literature sources.

Then the weighting methodology was applied for two milestone years (2050 and 2100). Here, we present the results for 2100 only.

For example, when the method is applied to RFF and UN in 2100, we use a linear combination of SSP2 and SSP3 for all the percentiles as SSP2 and SSP3 were the SSPs within which all percentiles were contained in 2100. These SSPs were weighted to become equal to a selected percentile of the RFF, first, and of the UN distribution, afterwards. Figure 13 shows that while the projection at the lowest percentile (5th) has a bigger proportion of SSP2, most of the UN populations percentiles of distribution are the combination of larger SSPs in terms of population magnitude. Certain percentiles lie beyond SSP3 or SSP2, such as the 5th percentile of the UN distribution. Although results are not shown here, the percentile 95th in 2050 fell beyond the SSP3.

Comparing previous IPCC databases with other lines of evidence: global scale

The increasingly higher number of population scenarios belonging to the scenario ensemble analysed in AR6, compared to AR5 and SR 1.5 is apparent (Fig. 14).

In search of evidence of representativeness and diversity of the former scenario ensembles, this section extends the statistical analysis proposed in the section "Comparing IPCC AR6 with UN projections" for AR6, to the AR5 and SR 1.5.

AR5 database. With the exception of a few outliers, the AR5 database population size lies below the 50th of the UN distribution, 2015 release, the closest in time to the AR5 publication[31] (Fig. 15). Although at the time of AR5, SSPs had not been developed yet, we map SSPs on top of the AR5 database scenarios to ease the comparative assessment with subsequent databases. Most of the scenarios in AR5 are not constrained to follow the SSP2 pathway and the inter-quartile distribution covers a considerable area beyond it (Fig. 15).

SR 1.5 database. The SR 1.5 database in terms of global population values shrinks compared to AR5, thus the population size is found primarily below the 5th percentile of the UN distribution, 2019 release, the closest to the SR 1.5 publication[44] (Fig. 16). Putting the SR 1.5 distribution in the perspective of the SSP characterisation, the inter-quartile distribution represents the SSP2 only, with just a few outliers moving towards the remaining intra-SSP space.

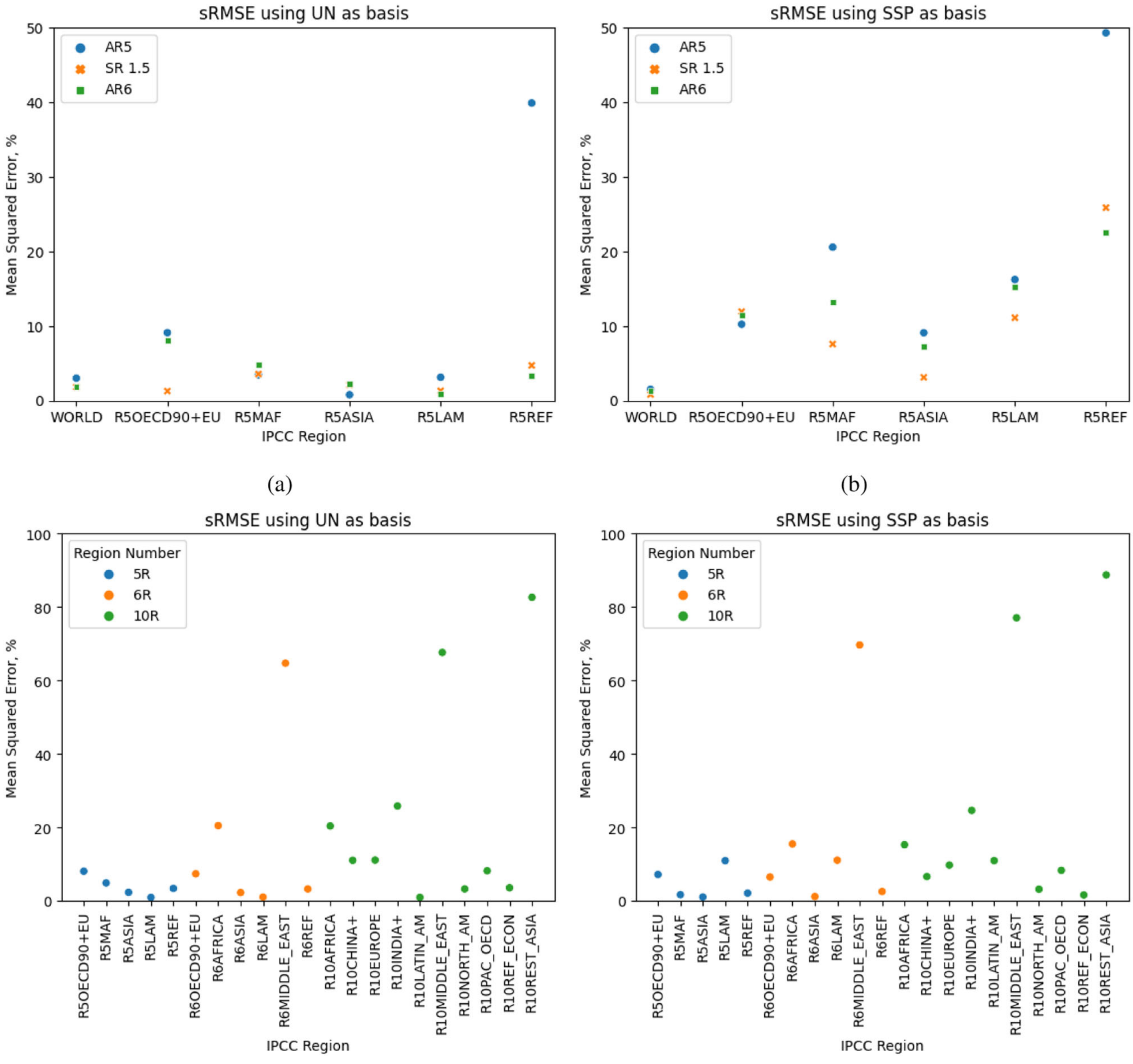
Comparing AR6 with other lines of evidence at regional scale: estimation of regional aggregation errors

In the AR6 database, the 5-region granularity includes "R5MAF" (Northern Africa and Middle East), "R5LAM" (Latin America), "R5ASIA" (Asia), "R5OECD90 + EU" (OECD countries), "R5REF" (Reforming Economies). The 6- region granularity separates Middle East from "R5MAF" to make a dedicated region; thus it includes "R5AFRICA", "R6LAM", "R6ASIA","R6MIDDLE EAST", "R6OECD90 + EU", "R6REF". The 10-region granularity separates: OECD into Europe, North America, and Pacific Asia; Asia into China, India, and Rest of Asia; and includes "R10AFRICA", "R10CHINA+ ", "R10EUROPE", "R10INDIA+ ", "R10LATIN_AM", "R10MIDDLE_EAST", "R10NORTH_AM", "R10PAC_OECD", "R10REF_ECON", "R10REST_ASIA".

Moving to assess the projected population on a regional basis, we estimate the sample variability, calculating the scaled root mean squared error (sRMSE) for global and regional population values across the latest IPCC databases.

We use the year 2020 to calculate the difference between 1) the reported values in the IPCC and the UN statistics, 2) the reported values in the IPCC and the SSP values using the IPCC regional definition. For doing so, the 2020 country values of population from the UN database, are aggregated to form the IPCC reporting regions. The deviations were calculated in terms of ratioed mean squared error, which means that the error is normalised using the regional UN value (see Fig. 17).

The milestone year 2020 is chosen as a reference to estimate the aggregation errors. In fact, the year 2020 is deemed to have the lowest variability across the model scenarios, being more dependent on the



(a) (b)

(c) (d)

Fig. 17 | Error between values of the IPCC databases and alternative lines of evidence. The figure shows on the left panel, the scaled Root Mean Squared Error (sRMSE) for scenario ensembles used for AR5, SR 1.5, and AR6, expressed in percentage over the reference used to calculate the error. Panel (**a**) displays the error on a global and a 5-region level using the UN database as a reference, panel (**b**) displays the error using the SSP database as reference. Panels (**c**) and (**d**) show the error for regional values from the scenario ensemble used in AR6 according to the R5, R6, and R10 aggregation using respectively UN and SSPs as a reference.

quality of the calibration in the latest IPCC report. Calibration to more up-to-date statistics can explain why deviations from SSP appear most of the time bigger than those with UN. For this reason, the discussion here will focus on the deviation compared to the UN database.

Due to the noise in the original database, calculations on regional values only include the range between the 25th and 57th percentile.

$$sRMSE = \sqrt{\frac{(x_i - \mu)^2}{(n-1)\mu^2}} \quad (1)$$

As shown in Eq. (1), the sRMSE is calculated between the database observations (x_i), where each observation i represents a scenario output in year 2020 for a selected region, and the UN (SSP) reference value for the same year and region (μ). The obtained value is divided over the sample size of the database (n) and then scaled over the UN (SSP).

The sRMSE shows historically a reduction in the error value moving from AR5 to AR6 and the deviations from 2020 UN data are larger at a regional level rather than at a global level (Fig. 17). Regarding the 5-region aggregation, there is a reduction in the sRMSE error between AR5 and SR 1.5, most likely due to the availability of more up-to-date statistics as the scenario submission time got closer to 2020. Moving to AR6, the sRMSE in the AR6 database for R5OECD90+EU, R5ASIA, R5MAF, and R5LAM, although being most of the time lower than the AR5 database, increases compared to the SR 1.5 report; possibly, this is the result of the bigger variability introduced by a larger number of scenarios which characterises AR6. The OECD region, R5OECD90 +EU is the only region where the sRMSE estimated for AR6 is not lower than the corresponding value for AR5, but the deviations are negligible. The sRMSE values for a 5-region

Table 3 | The table gives an overview of the approach followed for matching the aggregated UN regions with the IPCC ones

UN region	IPCC Region	Major caveat in UN correspondence
AFRICA	R10AFRICA	
China	R10CHINA+	only China included
EUROPE	R10EUROPE	Russia included
Southern Asia	R10INDIA+	
LATIN AMER- ICA AND THE CARIBBEAN	R10LATIN AM	
Western Asia	R10MIDDLE EAST	Iran not included
NORTHERN AMER- ICA	R10NORTH AM	
Japan	R10PAC OECD	Oceania and South Ko- rea not included
Russian Federation	R10REF ECON	Ukraine not included
South-Eastern Asia	R10REST ASIA	

granularity shows deviations lower than 5% for all the regions with the exception of R5REF, which deviates more than 10%. These values mean that a 5-region granularity can be considered acceptable in terms of accuracy.

A 6-region granularity, which is available in AR6, produces an improved sRMSE for all the regions, except for R6AFRICA and R6MIDDLE_EAST. Discrepancies across models originate primarily from the attribution of North Africa to either Africa or Middle East.

A 10-region granularity, which is also available in AR6, offers to separate Africa and the OECD countries. However, higher errors can be found on average in the R10 database, with the highest errors being with R10MIDDLE_EAST, R10REST_ASIA, R10EUROPE. Several reasons could lead to this behaviour. Above all, there is an inherent difficulty in matching exactly the definition of the IPCC regions from the native regions in each IAM contributing to an IPCC cycle. In particular, the native regions follow specific rules for the aggregation which depend on the model focus. Greater deviations from statistics may come from regions with younger track records on data collection (for example the Re- forming economies), although errors appear more evident when the definition of the IPCC region is not bound to an institutionally defined area, such as the rest of Asia (R10MIDDLE EAST). Finally, some regions, despite being characterised by good quality databases available (such as R10EUROPE), have the most varied sub-regional definitions in terms of country allocation across models; in partic- ular, the inclusion of Turkey in the region definition is an important source of variability across models.

For research and policy recommendations, the choice of the regional granularity in the IPCC database must come primarily from the scope of the study and data availability. However, from the deviations observed from the UN, the use of the five-region granularity seems a good compromise for balancing reporting errors. The use of the six-region aggregation can be also convenient, but users should consider the large deviations found for the Middle East. The use of the 10-region granularity can be convenient as it separates out selected regions, which can be critical for observing emerging trends.

Comparing AR6 with other lines of evidence: regional scale

To assess how the regional trends from the IPCC database, compared with alternative databases, we use the R10 granularity in the AR6 with the probabilistic projections from UN. Direct country-level summation cannot be performed on the UN probabilistic projections, unless weighting factors are applied. To propose a fair comparison between the IPCC regions and the UN regions, we use the closest aggregated regions available in the UN database to match the IPCC regions, as shown in Table 3. Table 3 shows the divergences in the regional definition during the assignments of the IPCC regions against the corresponding *replica* in UN. The closest representations can be found in Africa, China, India, Latina America and the Caribbeans, and Northern America.

Table 4 | Acronym list

Acronym	Definition
AR	IPCC Assessment Report
EFTA	European Free Trade Association
CCF50	Completed cohort fertility at age 50 Model
Cur-Pol	Current Policies
GHG	GreenHouse Gases
GS	Gradual Strengthening of current policies
IAM	Integrated Assessment Models
IHME	Institute for Health Metrics and Evaluation
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
LD	Low Demand
LDCs	Least Developed Countries
LLDCs	Landlocked Developing Countries
MCMC	Markov Chain Monte Carlo
Mod-Act	Modified Action
NCAR	National Center for Atmospheric Research
OECD	The Organization for Economic Cooperation and Development
Ren	High Renewables Pathways
RFF	Resources for the Future
SDG	Sustainable Development Goals
SIDS	Small Islands Developing States
SRES	Special Report on Emissions Scenarios
sRMSE	scaled Root Mean Square Error
SP	Shifting Development Pathways
SSP	Shared Socioeconomic Pathways
UN	United Nations
US	US United States

Acronyms

Acronym list (Table 4).

Data availability

The data used in this research were all available from public sources. AR5 data were downloaded from the IIASA AR5 database. SR 1.5 data were downloaded from IAMC 1.5 °C—Global and five-regional timeseries data snapshot release 2.0 IAMC explorer. AR6 data were downloaded from the IIASA AR6 database. SSPs 2.0 (2018 release) were downloaded from the SSP 2.0 database SSPs 3.0 (2024 release) were downloaded from the SSP 3.0 database. The UN Population estimate and standard projections released in 2022 were downloaded from the UN standard projections (2022 revision). The UN Population probabilistic projections released in 2022 were downloaded from the UN probabilistic projections (2022 revision). The UN Population probabilistic projections released in 2015, 2017, and in 2019 were downloaded from the UN probabilistic projection (older revisions). The UN Population Estimate standard projections released in 2012, 2015, 2017, and in 2019 were downloaded from the UN standard projection (older revisions). The World Bank data were downloaded from the World Bank website. The International Database data on population were downloaded from the US Census website. The data from the Institute of Health Metrics and Evaluation were downloaded from the IHME website The Resources For the Future data on population were downloaded from the RFF repository. The data used in this paper can be found in the Climate Scenario Data Science data repository.

Code availability

The code for data processing can be found at the Climate Scenario Data Science software repository.

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Author contributions

The authors confirm their contribution to the paper as follows: study conception and design: S.G.; data collection: S.G.; analysis and interpretation of results: S.G., L.C., L.D., G.M., F.N., R.M., M.T.; draft manuscript preparation: S.G., F.N., M.T. All authors reviewed the results and approved the final version of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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