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Can we project well-being? Towards integral well-being projections in climate models and beyond

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Scientists have proposed many "Beyond-GDP" indicators to replace the Gross Domestic Product (GDP) in order to quantify genuine societal development. While GDP is regularly projected, research on future trajectories of Beyond-GDP indicators is lacking, failing to meet policymakers' needs. Focusing on the Human Development Index (HDI), this paper attempts to calculate one of the first global well-being projections for 161 countries by 2100 using the shared socioeconomic pathways (SSPs), the socioeconomic inputs underlying global climate change scenarios. The results indicate a potential global well-being improvement from medium to very high level, depending on the SSPs, with most countries reaching high human development under SSPs 1&5. While serving as an initial step in well-being projection, the results highlight a crucial gap in existing climate change models which are used by the IPCC —they inadequately account for the feedback effects of climate change on well-being. This oversight results in counterintuitive or potentially misleading well-being projections. Therefore, we propose steps to improve this situation. By synthesizing climate change feedback effects on HDI determinants, this assessment delves into their implications for well-being and further underscores the necessity for interdisciplinary collaborations among well-being researchers, climate scientists and policy modelers to achieve sound integral well-being projections.

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Introduction

What will the future of humanity look like? Human society has experienced rapid population, economic, and technological development since the early 20th century, leading to rapid, and even irreversible, exploitation of natural resources and environmental threats such as climate change and biodiversity loss (Cardinale et al., 2012; Masson-Delmotte et al., 2021). Given these trends, do we expect the quality of life to keep growing, or will well-being gradually stagnate or even decline?

In science and policy circles, the research on projections of Gross Domestic Product (GDP), a summary statistic of economic activity, is abundant. The GDP is the most influential indicator and is widely seen as a measure of the "success" and "development" of countries. Its history goes back centuries, but it became an international standard after the Second World War (Coyle, 2017). GDP is projected for both the short and long-term time scales by organizations including the International Monetary Fund (IMF), Organization for Economic Cooperation and Development (OECD), and many other institutes and scholars (OECD, 2020). However, although GDP is dominant in forecasting and policy making, it is known for only accounting for market activities and material well-being, i.e., not measuring overall well-being and neglecting inequalities and sustainability (van den Bergh, 2009; Fioramonti, 2013; Fleurbaey, 2009; Stiglitz et al., 2009).

Many organizations and scholars have developed beyond-GDP indicators and indexes to replace GDP and to measure sustainability, well-being, and inequalities. Well-known examples include the Human Development Index (HDI) (UNDP, 2020), Genuine Progress Indicator (GPI) (Cobb et al., 1995), U-index (Krueger et al., 2009), Subjective Well-being (Kahneman and Krueger, 2006; OECD, 2013), Comprehensive Wealth (World Bank, 2021), Ecological Footprint (Rees, 1992; Wackernagel, 1994; Wackernagel and Rees, 1998), Sustainable Development Goals (Griggs et al., 2013), and Planetary Boundaries (Rockström et al., 2009; Steffen et al., 2015). However, the dominance of GDP is still maintained (Berik, 2018; Hoekstra, 2019). While there are various reasons for the lack of a breakthrough, one crucial point is that most Beyond-GDP studies focus only on retrospective statistics with very few forward-looking projections (Kwatra et al., 2020). The knowledge gap significantly constrains the policy relevance of Beyond-GDP indicators because decision-makers want to understand how things might develop in the future, not just what happened in the past.

A few studies showed the possibility of projecting Beyond-GDP indicators and presented novel findings. For example, we learned that better educational attainment substantially improves HDI values in developing countries with modest emission increases (O'Neill et al., 2020). In addition, based on the Inclusive Wealth Index, a city-level projection in China showed that building up human and produced capital is crucial for resource-dependent cities to prevent the impending sustainability declines in adaptation and mitigation (Cheng et al., 2022). Empirical understanding is growing on the synergies and trade-offs between key variables underlying climate change, population, the economy and well-being (Cuaresma and Lutz, 2015). The shared socioeconomic pathways (SSPs) are proposed as a sound framework for projecting the HDI and assessing climate change's mitigation and adaptation challenges. However, integrating feedback from environmental changes in long-term well-being projections remains a main challenge with only preliminary investigations (Lutz et al., 2021).

Here, we aim to present long-term trajectories of humanity's future by projecting countries' HDIs and exploring the impact of climate change on well-being. HDI was chosen as it is one of the most popular and institutionalized Beyond-GDP indicators for well-being. It is an aggregate of three well-being dimensions: health (a long and healthy life), education (knowledge level and accessibility), and GDP (a respectable level of living). We base our projections on the SSPs, developed in the context of the Intergovernmental Panel on Climate Change (IPCC) (Riahi et al., 2017); available SSP variables provide essential inputs for the HDI projections up to 2100 (Samir and Lutz, 2017). As such, we first calculate and plot global and country-level well-being developments with HDI projections under five SSPs from 1970 to 2100, with a novel decomposition analysis to highlight the primary drivers for the next decades of well-being development. Notably, the results that the highest level of human development is to be achieved under SSP5, i.e., "Fossil-Fueled Development" with high population growth, rapid economic expansion, and high GHG emissions (Kemp et al., 2022). This observation points to the absence of climate change feedback in the initial well-being projections. In response to these gaps, we further synthesize critical climate change feedback effects on HDI determinants and re-assess the future well-being trajectories with crucial feedback effects of climate change impacts. Our study indicates that different SSPs could potentially lead to distinct human development trajectories and global well-being outcomes over the century and shed light on the possibilities and remaining challenges for future well-being projections. All calculation steps, data sources, and assumptions are available in "Methods."

Methods

Our methodology is composed of two parts: a calculation based on the current SSPs scenario database followed by a critical reflection based on scientific literature. We first project the HDI over an extended time series based on GDP, education, and life expectancy projections under SSPs 1–5. We employ the GINI index to quantify global inter-country inequality in human development and a decomposition analysis to assess the contributions of HDI's three components. Based on the calculated results, we then adopt a systematic snowballing literature review method to synthesize the influencing mechanisms of climate change on various dimensions of well-being. Subsequently, we present a preliminary effort to integrate environmental impact in the well-being projections. These tentative findings are aimed to provide a basis for future work on well-being projections.

HDI projection and analysis

Quantifying the past and future HDI time series by country. HDI is a widely used measure of human development based on three crucial dimensions: a long and healthy life, knowledge, and decent living (UNDP, 2020). For any country i, we estimate its HDI in the past year t (1970–2010) or project the HDI in a future year t (2015–2100) by the five baseline SSP scenarios in three steps. First, we quantify a country's development level in each of the three HDI dimensions through an HDI indicator (Table 1), using the historical estimate of the indicator or its projected value under five SSPs. Then, we perform a min–max normalization of the indicator values to obtain three HDI Dimension indexes ranging from 0 to 1 (Table 1 and Eqs. 1–3). Finally, we calculate the HDI as the geometric mean of the normalized indexes ranging from 0 to 1 (Eq. 4). The literature categorizes four tiers of human development level based on the HDI values: very high (0.800–1.000), high (0.700–0.799), medium (0.550–0.699), and low (0.000–0.549). In addition, to track the global achievement of human development in year t, we obtain the population-weighted

Table 1 An overview of the HDI indicators and indexes (1970–2100).		
HDI dimension	**HDI indicator (unit; min.–max.)**	**HDI Dimension index**
Long and healthy life	Life expectancy at birth (years; 20–110)	Life expectancy index (0–1)
Knowledge	Mean years of schooling (years; 0–17)	Education index (0–1)
A decent standard of living	GDP per capita (2005 International $; 100–402,000)	Income index (0–1)

HDI from the country-level HDI estimates (Eq. 5).

$$I_{\text{Health},i,t} = \frac{\text{Life expectamcy at birth}_{i,t} - 20}{110 - 20} \quad (1)$$

$$I_{\text{Education},i,t} = \frac{\text{Mean years of schooling}_{i,t}}{17 - 0} \quad (2)$$

$$I_{\text{Income},i,t} = \frac{\ln\left(\text{GDP per capita}_{i,t}\right) - \ln(100)}{\ln(402,000) - \ln(100)} \quad (3)$$

$$\text{HDI}_{i,t} = \sqrt[13]{I_{\text{Health},i,t} \cdot I_{\text{Education},i,t} \cdot I_{\text{Income},i,t}} \quad (4)$$

$$\text{HDI}_{\text{global},t} = \frac{\sum_i \text{Population}_{i,t} * \text{HDI}_{i,t}}{\sum_i \text{Population}_{i,t}} \quad (5)$$

Of note, we made two critical modifications to the HDI method employed by the United Nations Development Programme (UNDP) (Sen and Anand, 1994). First, to create projections that are comparable across countries and scenarios, we define the maximum reference points of all three HDI indicators in our dataset that covers past and future time series of 130 years (see Table 1), which exceed those adopted by the UNDP and other studies that focused on past HDI measurements. As such, the pre-2015 HDI estimates in our analysis should appear lower than previously reported HDIs, resulting in a conservative interpretation of the development level by the conventional numerical criteria. Secondly, to satisfy the data requirement for HDI projections under the SSPs, we chose to use similar but also the exact HDI indicators adopted by the UNDP. Specifically, because long-term projections of the two UNDP education indicators ("Expected years of schooling" and "Mean years of schooling") are unavailable, we use "Mean years of schooling by broad age (15+)" to measure development in the education dimension. For the same reason, we use GDP per capita instead of gross national income (GNI) to track development in the income dimension.

Combining SSPs. To project human development under designed future scenarios, we refer to the five SSP baseline scenarios that define global developments over the twenty-first century without additional climate policies. The scenarios differ by main socioeconomic factors, such as population, and technological and economic growth, which directly relate to the three HDI dimensions. For example, SSP1 ("Sustainability") and SSP5 ("Fossil-fueled Development") achieve optimistic human development with substantial investments in education and health, and rapid economic growth, through increasingly sustainable practices and fossil-based development that can effectively manage social and ecological systems (e.g., by geoengineering), respectively. SSP2 is the "Middle of the Road" scenario where trends broadly follow their historical patterns. SSP3 ("Regional Rivalry) and SSP4 ("Inequality") are less optimistic than the other SSPs in economic and social development, with little investment in education or health in developing countries. Among the five SSPs, SSP3 projects the lowest global GDP growth and the highest global population growth. Even without new climate policies, the

SSP projections could lead to a wide range of emission outcomes (i.e., global warming of 3.1–5.1 °C above the pre-industrial level by 2100) (Riahi et al., 2017). However, the socioeconomic projections neglect the feedback from climate change and other environmental impacts. Furthermore, the baseline SSP projections of population, education, and the economy are essential inputs to the Integrated Assessment Models (IAMs) to simulate potential energy use and emissions with or without new climate policies (Samir and Lutz, 2017).

Assessing global well-being inequalities using the Gini coefficient. We employ the Gini coefficient to assess the evolution of global well-being distribution between countries from the past decades (1970–2010) to the projected future under five SSP scenarios (2015–2100). The Gini coefficient, calculated as half of the relative mean absolute difference of all pairs of country samples in each year, varies from 0 (complete equality) to 1 (complete inequality) (Farris, 2010). With i and j representing two countries from a total of n countries, we quantified the Gini coefficient for global well-being in year t in Eq. 6.

$$G_t = \frac{\sum_{i=1}^n \sum_{j=1}^n \left| \text{HDI}_{i,t} - \text{HDI}_{j,t} \right|}{2n \sum_{j=1}^n \text{HDI}_{j,t}} \quad (6)$$

Quantifying the well-being impact of the HDI indicators over time. We employed decomposition analysis (Sun, 1998) to quantify how development in each HDI dimension contributes to changes in HDI during three 40-year periods: the past (1970–2010), the near future (2015–2055), and the far future (2060–2100). Since HDI is equal to the geometric mean of the three normalized HDI Dimension indexes (i.e., Eq. 4), we calculated the contribution of health, education, and income development to HDI development in each period as below:

$$H_{\text{effect}} = E^0 I^0 \Delta H + \frac{1}{2}\Delta H\left(I^0 \Delta E + E^0 \Delta I\right) + \frac{1}{3}\Delta H \Delta E \Delta I \quad (7)$$

$$E_{\text{effect}} = H^0 I^0 \Delta E + \frac{1}{2}\Delta E\left(I^0 \Delta H + H^0 \Delta I\right) + \frac{1}{3}\Delta H \Delta E \Delta I \quad (8)$$

$$I_{\text{effect}} = H^0 E^0 \Delta I + \frac{1}{2}\Delta I\left(H^0 \Delta E + E^0 \Delta H\right) + \frac{1}{3}\Delta H \Delta E \Delta I \quad (9)$$

where H^0, E^0, and I^0 represent the value of the health, education, and income indexes at the start year of the 40-year periods, respectively; ΔH, ΔE, and ΔI measure the difference of the three HDI Dimension indexes between the start and the end year, i.e., $\Delta H = H^t - H^0$, $\Delta E = E^t - E^0$, and $\Delta I = I^t - I^0$ (H^t, E^t, and I^t represent the end-year values).

Assess environmental impacts on well-being. We employ a systematic snowballing literature review method to synthesize how air pollution and climate change affect health, education, and income, i.e., the three HDI dimensions (see a detailed review table in Table S1). We include studies that not only articulated the potential impacts but also quantified such impacts. Then, we integrate the knowledge of the identified mechanisms into our initial HDI projection results for a preliminary re-assessment. Crucially, the qualitative assessment is informed by representative

IAM-SSP baseline runs showing current and future trends of three air pollutants (black carbon, SO_2, and NO_2) and global mean temperature (IIASA, 2018) (see Table S2). To assess the neglected well-being impacts due to air pollution and warming under different SSPs, we compare the pollution and temperature levels in 2010 and 2100, For instance, increased (decreased) black carbon concentration or global mean temperature from 2010 to 2100 suggest downward (upward) adjustment on the initially-projected HDI levels. The magnitude of the pollution or temperature changes among the SSPs indicates the potential trend of the neglected well-being impacts.

Data sources. Our analysis covers 161 countries, representing 96% of the global population and 93% of the global GDP in 2010 (for example, we excluded countries with missing historical data of mean years of schooling). We obtained the data of population (all, male and female), life expectancy at birth (male and female), and mean years of schooling by broad age (15+) in the past (1970–2010) and future (2015–2100) from the Wittgenstein Centre (WIC) for Demography and Global Human Capital (Lutz et al., 2018, 2017). While estimates of life expectancy at birth are available every five years, we interpret them as the measurements for the later year (e.g., life expectancy at birth in 2020–2025 would indicate life expectancy at birth in 2025). Historical GDP per capita data are from income projection under SSPs (Cuaresma, 2017) and we applied OLS regression extrapolation to estimate the missing data for 25 countries with missing data. The projection data of air pollution and global mean temperature for Table S2 is from https://tntcat.iiasa.ac.at/SspDb.

Results

Three distinct global well-being trajectories under five SSPs.
Following a steady improvement since 1970, the current HDI values indicate that global well-being remains at a low level on average but is close to reaching the medium level (i.e., the HDI threshold of 0.55, see "Methods" and "Data"). Although all five SSPs suggest further well-being improvement in the future, the varying well-being growth rates result in diverging global well-being outcomes by the end of the century (Fig. 1A). Following SSP1 and SSP5, the world is on the way to achieve a very high well-being level on average by 2100 ($HDI_{global,2100} > 0.80$). In particular, the fossil fuel-led development in SSP5 presents the most significant global well-being improvement, with $HDI_{global,2100}$ reaching 0.84, a level only the most developed countries today (e.g., Luxembourg) could reach in 2050 in the same scenario. In contrast, SSP3 and SSP4 indicate a slowly growing global well-being that nearly stagnates in the later decades. The SSP3 and SSP4 worlds only reach medium well-being on average by 2100 (i.e., $HDI_{global,2100} < 0.6$), as opposed to achieving high well-being ($HDI_{global,2100} = 0.74$) by following historical trends under SSP2.

While the projected global well-being development is consistent with the SSP storylines, our decomposition analysis sheds light on the underlying driving forces and temporal dynamics (Fig. 1B). SSP1's and SSP5's significant well-being improvements align with their optimistic outlook of economic and social development (i.e., substantial worldwide investment in education and health and rapid GDP growth). In both SSP1 and SSP5, the primary global well-being driver is education improvement in the earlier decades (2015–2055) and health advances in the later decades (2060–2100). While SSPs 3&4's shared outlook that developing countries continue to lag in education, health, and economic growth explains the projected global well-being lags, our results highlight the critical role of education development. Global education improvement is the primary driver of global

well-being improvement in SSP3 and SSP4 during 2015–2055—its significant halt in 2060–2100 is the main culprit for stagnating global well-being. Further, across all five SSPs, global health development becomes an increasingly crucial source of global well-being improvement over time.

SSPs suggest opposite trends in global well-being inequality.
Our country-level HDI estimates suggest a steadily declining global well-being inequality since 1970. However, the SSPs present significantly different future patterns (Fig. 2A). The between-country well-being inequality continues to improve under SSP2, i.e., following the historical development, and the inequality declines at an accelerated and nearly identical rate under SSP1 and SSP5. Moreover, the inequality improvements under SSP1, SSP2, and SSP5 come from all three HDI domains (Fig. 2B). Note that the Gini coefficient of health and education in SSP1 and SSP5 are almost identical among the time trend so they would overlap and SSP1 is covered. Under SSP3 and SSP4, however, the between-country well-being inequality improvements are more modest than the historical trend would imply, and potentially reverse the historically declining trends in the health and income domain. Several factors drove this reversal. Chief among them was the continuing slow economic and education development in relatively poor and populous countries. The slowdown of converging among developed countries also contributes to the increasing income inequality among countries. The high education inequality among countries is also of note under SSP3 and SSP4: by 2100, the mean years of schooling still range from a minimum of 2 years to a maximum of 16 years.

Our results show well-being improvement in all countries by 2100, yet to different extents across the SSPs (Fig. 2C). The well-being development differences are particularly crucial for countries at low well-being levels today, which include most countries in Africa and many in Asia and South America. Under SSP1 and SSP5, those countries are on the way to reaching high well-being levels by 2100. Some of the most populous developing countries, such as China, Iran, and Russia, would join the OECD countries in reaching a very high well-being level by 2100. However, under SSP3 and SSP4, one-quarter of the world population and most African countries remain at low well-being levels and a third at medium well-being levels. Only a few of the most developed countries today, such as New Zealand, Ireland, Japan, Norway, and Luxembourg, would reach very high levels of well-being amid the high global inequality.

Air pollution and climate change affect well-being projections.
The SSPs exhibit substantial variations in global mean temperature rises, air pollution levels, and the impacts of climate change impacts. These differences arise from their significant variations in how the global energy system transits from conventional fossil fuels to low-carbon alternatives, without new climate policies. According to the representative runs of IAMs, by 2100, the global mean temperature increases from pre-industrial levels range from 3.0 °C in SSP1 to 5.1 °C in SSP5; black carbon emissions (BC) range from 2.0 Mt/year in SSP1 to 5.8 Mt/year in SSP3.

Ample literature suggests that air pollution and climate change impacts (e.g., more frequent heat waves and other natural hazards) could have sizable socioeconomic and well-being implications.

Health. Globally, people's health and survival are under threat due to climate change. Forecasts indicate that these dangers might rise dramatically if we do not react (Lee et al., 2018; Romanello et al., 2023). Studies have extensively examined the various pathways through which climate change affects health, primarily attributing these impacts to meteorological changes
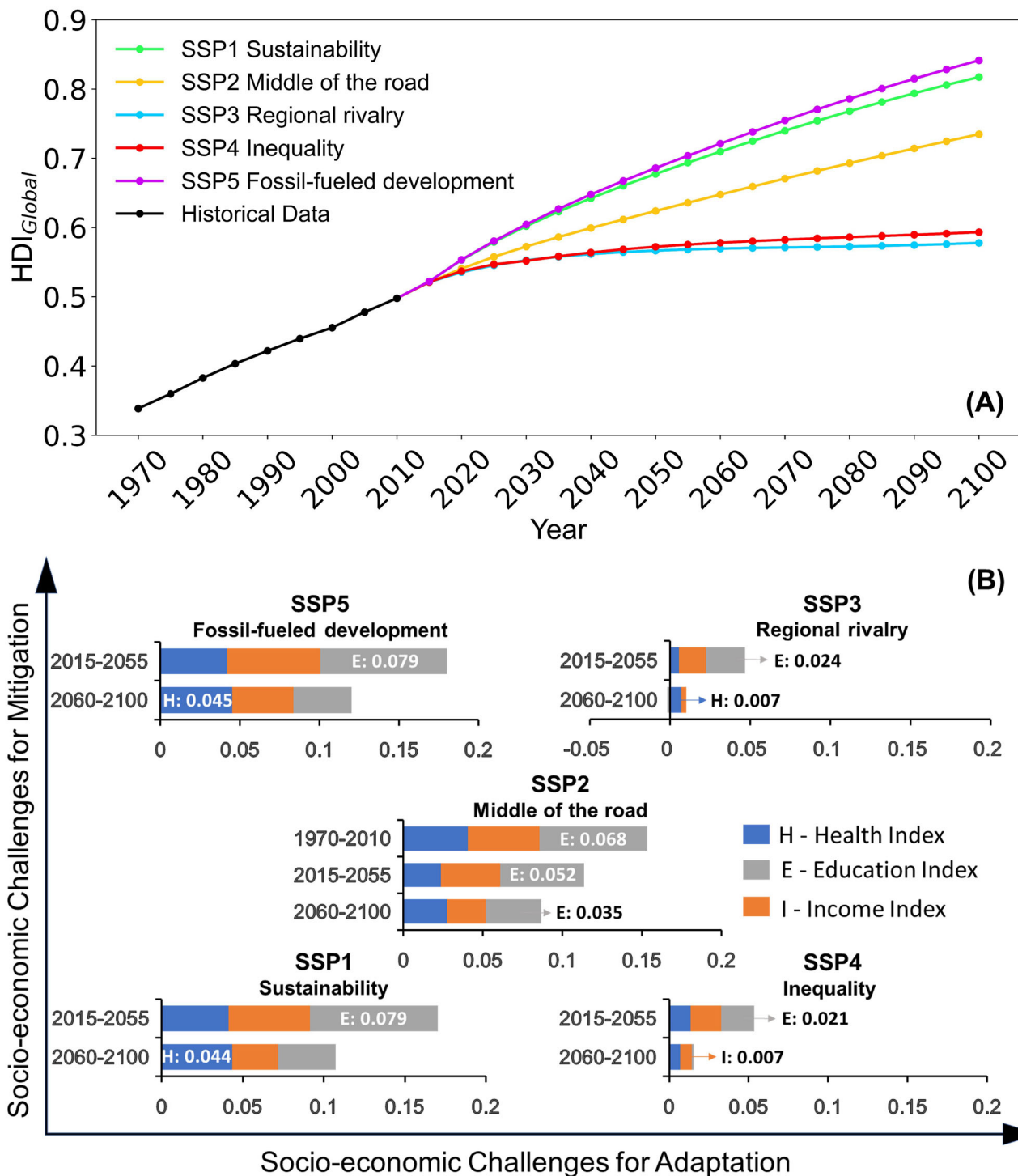
Fig. 1 Trends and drivers of global well-being development (1970–2100). A Global population-weighted HDIs of the past (1970–2010) and projected under the five SSPs (2015–2100). **B** The three HDI dimensions' contributions to global well-being change during three periods: past (1970–2015), near future (2020–2055), and far future (2050-210). Each SSP name is followed by its narrative title. Different challenges to mitigation and adaptation faced by each SSPs are illustrated with x- and y-axis (O'Neill et al., 2017).

and extreme weather events. The ensuing consequences typically manifest in three predominant domains including the proliferation of infectious diseases, increased mortality rates, and adverse respiratory, cardiovascular, or neurological outcomes (Rocque et al., 2021). Among them, air pollution has long been proven to lead to increased mortality and hospital admission due to respiratory and cardiovascular disease. Climate change policies play a crucial role in pollution control and adaptation,

thereby improving life expectancy through climate change mitigation (Lee and Greenstone, 2021; Lucas et al., 2019). Regarding the climate change impacts, non-optimal temperature and extreme weather events affect health through pathways such as heat exposure, water and food security, and undernourishment (Costello et al., 2009). The World Health Organization (WHO) calls climate change the single biggest health threat in the twenty-first century and associates it with 250,000
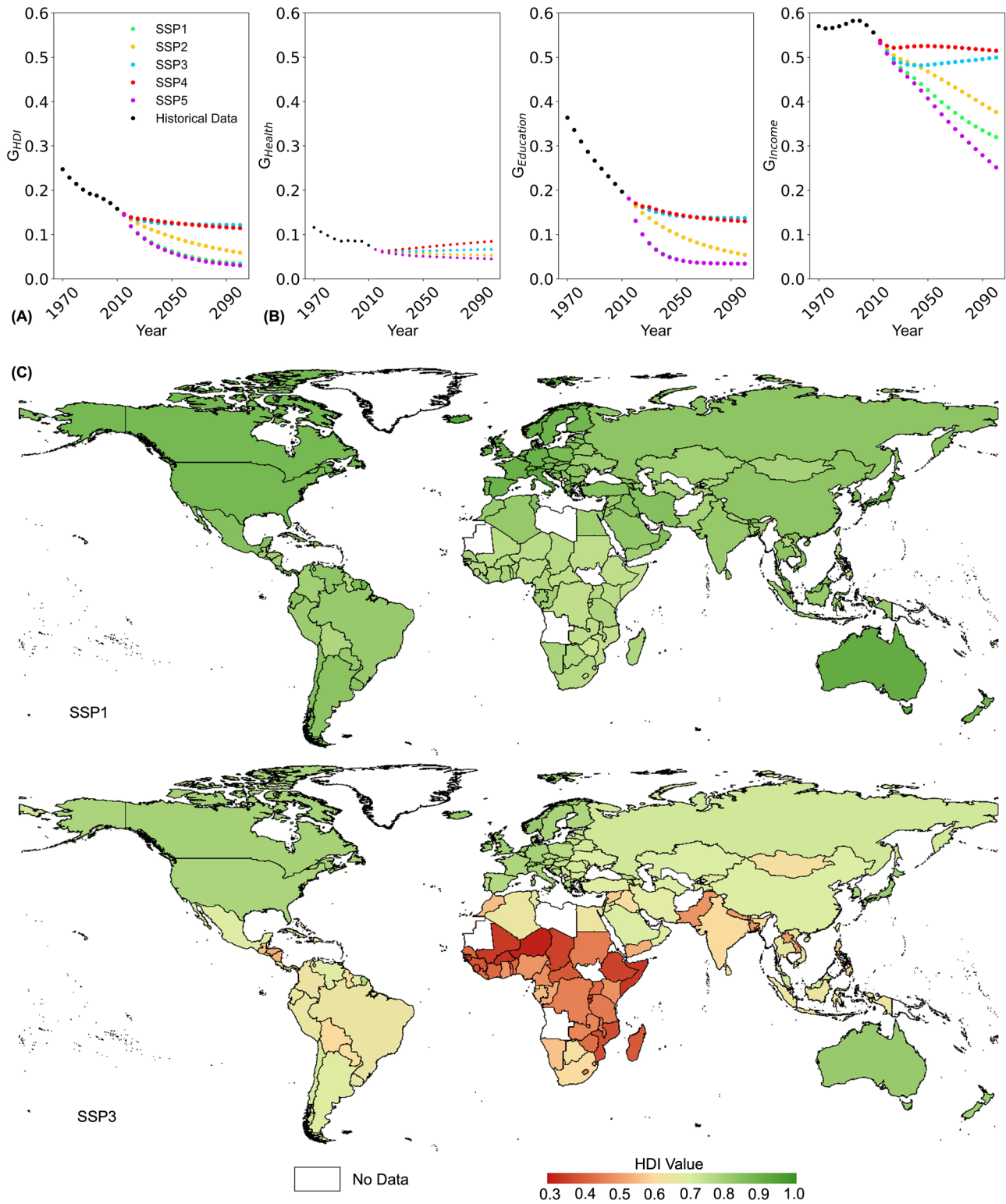
Fig. 2 Trends of between-country well-being inequality (1970–2100). A Gini coefficients of the past (1970–2010) and projected (2015–2100, under five SSPs) HDI between countries (G_{HDI}). **B** The same as (**A**) except showing Gini coefficients of the three HDI indicators, respectively (G_{Health}, $G_{Education}$, and G_{Income}). Note that because the income indicator's plausible range is much broader than that of the health, the values of the three Gini coefficients are incomparable. In addition, the Gini coefficients we presented here are based on between-country differences and neglect the within-country differences. **C** A contrast of the potential well-being outcomes of the 161 countries in 2100 under a "best" scenario (SSP1, top) and a "worst" scenario (SSP3, bottom).

additional annual deaths in 2030–2050 (WHO, 2021). Climate-induced natural disasters, such as flooding and droughts, can also threaten the lives and health of people and thus induce health damages (Hauer and Santos-Lozada, 2021). As climate impacts increase, its effect on health also aggravates. A recent study found that mortality increased by 1.8% under a lower-emissions scenario and 6.2% in a high-emissions scenario (Bressler et al., 2021).

In addition to the heightened risk posed by climate change on physical health, a growing body of evidence suggests that mental health is also susceptible to negative impacts stemming from heatwaves, extreme weather events, and suboptimal temperatures (Huang et al., 2011; Lawrance et al., 2022; Patel et al., 2018). Studies have indicated an elevated risk of suicide and other mental disorders in correlation with increasing local temperatures. Notably, a projection by Burke et al. in 2018 suggests that unmitigated climate change (RCP8.5) could potentially lead to a collective increase of 89–40 thousand additional suicides (95% CI) across the United States and Mexico by the year 2050. Moreover, the health impacts of climate change are not equally distributed: people in poorer and warmer places are impacted more than those living in cooler and richer places (Gasparrini et al., 2017).

Education. Studies on the relationship between climate change and education are relatively scarce (UNICEF, 2019). Climate change can affect education through extreme weather events like heat waves, floods, hurricanes, and droughts that influence children's mental and physical well-being and lower education attendance (Sheffield et al., 2017). Studies also show that students who are schooled in a higher temperature tend to have poorer academic performance: higher temperature could negatively impact education performance by up to 13% of a standard deviation, where further impaired human capital is followed (Park, 2022; Park et al., 2021). In addition, some populations will be affected more than others due to a lower capacity for climate change adaptation (e.g., to afford heating and air conditioning) (Park et al., 2020). Moreover, if parents work in sectors that are affected by climate impacts, they might be financially compelled to send their children to work rather than to school (Kousky, 2016). Air pollution exposure has also been found to impair the education outcomes by aggravating or increasing the risk of respiratory and other health aspects of children (Gartland et al., 2022; Miller and Vela, 2013).

Income. Climate change effects could negatively affect current and future global income, primarily through reduced labor productivity and crop yields (Burke et al., 2015a; Lesk et al., 2016). High temperature and humidity in the working environment reduce labor productivity and work hours (Kjellstrom et al., 2009). Under high emission pathways, work capacity loss can reach 11–28% in tropical countries, leading to significant GDP losses (Kjellstrom et al., 2016). Health impacts, as discussed earlier, could also reduce GDP by lowering human capital stocks. In addition, increases in health costs will cause a further drag on the economy—in high-emission scenarios, the health cost from climate change-induced malnutrition amounts to 0.4% of global GDP (Hasegawa et al., 2016). Agriculture is especially vulnerable to climate change-induced natural hazards like droughts and floods, and there is significant heterogeneity between countries and different types of crops (Deryng et al., 2014; Schlenker and Roberts, 2009). Moreover, climate change will lead to capital losses from natural disasters or real estate damages due to sea level rise; existing estimates range from $9.7 trillion to $591.7 trillion, depending on the emission scenarios, estimation periods, and other factors (Hsiang and Jina, 2014; Warren et al., 2021). The impact of climate change varies based on location and income levels. Workers in low and middle-income tropical and subtropical countries, particularly those in labor-intensive jobs conducted outdoors, are particularly vulnerable. These individuals face heightened exposure to solar radiation, increasing their susceptibility to the effects of climate change (Habibi et al., 2021).

Assessing the magnitude of the neglected well-being impacts. Based on the literature review above and the projected air pollution and global mean temperature trends under the SSPs (see "Methods"), we assess the potential direction and rank the significance of the environmental feedback effects on our initial well-being projections in Table 2. For example, dark green indicates that we think that one well-being determinant (health, education and income) will improve in future projections compared to the 2010 level, hence well-being outcomes will be adjusted upwards significantly. Note that the coloring scheme only allows for column-wise comparison between different SSPs on the impacts from certain category. For row-wise, different mechanisms of air pollution category or temperature are not directly comparable in their impacts on well-being. For example, a light green shown in SO_2 category in SSP4 does not mean that it will necessarily lead to a less upward effect in Health and Education than the dark green of NO_2 category in SSP4.

Nevertheless, our analysis highlights the importance of climate and health mechanisms because they could further influence well-being by affecting education and income outcomes. Therefore, health seems to be a logical starting point in future model development towards including the environmental feedback effects. Moreover, temperature plays a part in the mechanisms that underlie all three well-being aspects, not only because we use it as the sole indicator of climate change-induced natural disasters and global warming effects but also owing to its impact on education and economic outcomes through health mechanisms.

Table 2 also indicates that the well-being impacts vary significantly per SSP, and some results might seem counter-intuitive. For example, the high-fossil fuel scenario SSP5 shows the best SO_2 air pollution improvements. This is because the storyline of SSP5 also features a high deployment of pollution mitigation technologies. In this sense, SSP5 would have two conflicting feedback effects on health: highly positive impacts due to better air quality but substantial negative impacts due to worst global warming and related extreme weather events. On the other hand, SSP1 would be least affected because the global warming impacts on health, education, and income are lowest among all five SSPs, and there is a significant improvement in air quality. Although it is impossible to weigh the positive impact of air quality improvement against the negative impacts of global warming, considering the feedback effects may lead to even higher HDI values in SSP1 than the initial projections suggest. In contrast, SSP3 is likely to have lower HDI values because of the strong negative effect of global warming and mild improvement or even deterioration in air quality.

Discussion and conclusion
Integral well-being projections in climate models and beyond. Global systematic projections of well-being are crucial but currently absent. Here, we explored the potential to project well-being with HDI, one of the main Beyond-GDP indicators. The calculations are based on the SSPs which are employed by the IAMs as part of the IPCC's work on global greenhouse gas scenarios. Our research highlights that the well-being view is generally lacking in climate change research, specifically omitting concrete and comprehensive feedback loops from climate change impacts.

The HDI results provide various indications of future well-being about potential trends, drivers and distribution, yet the projections for SSP1 and SSP5 reveal a paradox. Despite starkly different narratives—one centered on sustainability (SSP1) and the other on fossil-fueled development (SSP5)—both pathways exhibit a surprisingly similar HDI trajectory. The empirical results thus would not suggest a robust projection reflecting genuine future well-being, as climate change impacts are ignored. To enhance the reliability and accuracy of well-being projections,

Table 2 Potential air pollution and climate change impact on initial well-being projections under the SSPs.

	Health				Education				Income
	Air pollution			Climate change impact	Air pollution			Climate change impact	Climate change impact
Mechanisms[a]	(i)			(ii)	(iii)			(iv)	(v), (vi), (vii)
Indicator	BC	SO₂	NO₂	Global mean temperature	BC	SO₂	NO₂	Global mean temperature	Global mean temperature
SSP1									
SSP2									
SSP3									
SSP4									
SSP5									

Colors indicate the potential direction of the impacts (green: well-being benefit; red: well-being damage; based on the known mechanisms and a comparison of current and future SSP estimates); color shades indicate the possible significance of the impacts (light to dark: low to high well-being impacts by ranking the numerical estimates for the SSPs in 2100).

The potential trend/significance of the impacts (from left to right: +5 to −5):

[a]Mechanisms: (i) Energy transition → Air pollution → Mortality; (ii) Climate change → Temperature → Mortality; (iii) Energy transition → Air pollution → Health → Education performance; (iv) Temperature → Extreme weather events (e.g. floods) → Education attendance; (v) Temperature → Agriculture yield → Income; (vi) Temperature → Labor productivity → Income; (vii) Temperature → Extreme weather events → Economy burden & damage → income.

it is imperative to integrate the climate change feedbacks on well-being into future scenarios.

This paper has explored some tentative steps by presenting the possible trends under each SSPs projection of climate change's air pollution and warming effect on our well-being projection. We found that the well-being projection in SSP1 will be adjusted positively for lowered air pollution and slightly negatively owing to global warming, compared to other SSPs. Hence, our study emphasizes the necessity of incorporating climate change feedback mechanisms for more accurate and nuanced well-being projections. Health emerges as a crucial factor, influencing human behavior through various mechanisms, offering a starting point for modeling the feedback loops between climate, the economy, health, and education. Additionally, given that temperature represents global warming and influences well-being through extreme weather events, it emerges as a pivotal factor for initiating the integration of feedback loops.

Limitations and implications for future studies. While the HDI encompasses critical aspects of well-being through health, education, and income dimensions, it has limitations in achieving comprehensive coverage (Liu et al., 2023). Beyond its primary dimensions, climate change exerts multifaceted impacts on social well-being, contributing to heightened conflict and potential adverse effects on mental health (Marshall Burke et al., 2015b; Hsiang et al., 2013; Lawrance et al., 2022). Recognizing the varied vulnerability and impact of climate change across demographic groups underscores the necessity of integrating climate justice considerations into well-being assessments (Hertel et al., 2010; Schlosberg, 2012; Thomas and Warner, 2019), crucial for addressing resultant poverty and economic inequality. Moreover, Global warming may have contributed to a 25% increase in population-weighted between-country inequality over the past half-century (Diffenbaugh and Burke, 2019). Expanding our

investigation to include other Beyond-GDP metrics, such as measurements of sustainability like Inclusive/Comprehensive Wealth and Planetary Boundaries, offers a more nuanced understanding of the broader implications. This exploration might not only contribute insights into the current climate models and scenarios but also guide considerations for future expansions.

The next generation of SSPs could explore how social and environmental policies affect well-being. This should include policies that affect the level of economic activity, such as working from home or shifting to a 4-day work week. It is also crucial to formulate more detailed development pathway scenarios that align with national or even sub-national (regional) contexts (Lehtonen et al., 2021). The adaptation towards sustainable development faces uncertainty and challenges entwined with social processing, which could not be captured in models simply but is essential to consider (Scoones and Stirling, 2020). An upgrade in more comprehensive scenarios will help politicians, media and the general public to visualize the policies that will shape the remainder of this century and bring human society to move forward to a better future.

There is a growing emphasis on integrating well-being considerations into modeling practices. Models like Earth4All focus on well-being projections until 2050 but lack a clear theoretical basis for their indices (Randers and Collste, 2023). The iSDG model (Arquitt, 2020) projects indicators for all 17 SDGs until 2050 but is tailored to specific countries rather than global. Other established models such as FUND, PAGE, and DICE, while influential, have limitations in incorporating well-being only as a side factor (Anthoff and Tol, 2014, 2013; Hope, 2013; Nordhaus, 2018, 2008). IAMs also start to incorporate well-being as components or outcomes partially and preliminary climate-well-being feedbacks. However, most are still economics-centered, lacking sufficient coverage of ecological and well-being processes, and often oversimplify and underestimate climate change damages

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due to methodological issues, such as assuming 90% of GDP remains unaffected because it takes place indoors (Harfoot et al., 2014; Keen, 2021). While the IMAGE GISMO module focuses on human development, and the International Futures model integrates various submodules from environment to governance to heath, specific feedback from climate to well-being is limited to mortality from malaria suitability and crop yield changes and respiratory diseases due to indoor solid fuel burning (Hughes, 2019; Vuuren and Stehfest, 2021). Hence, this field is in its early stages, highlighting a critical need for more explicit and effective feedback loops as evidence of climate change's impact on well-being becomes clearer. Breakthroughs in modeling are crucial for achieving a genuine and holistic well-being projection.

Data availability
The population (all, male, and female), life expectancy at birth (male and female), and mean years of schooling by broad age (15+) in the past (1970–2010) and future (2015–2100) of SSP1-3 are from the Wittgenstein Centre (WIC) for Demography and Global Human Capital (http://dataexplorer.wittgensteincentre.org/wcde-v2/). We requested the data for SSP4–5 from IIASA. GDP per capita data are requested from Jesus Crespo Cuaresma. All the data and code processed in this study are available at https://github.com/kkedliu/HDI-projection.

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Conceptualization: KL, RW and RH; literature review: KL, RW, IS, and RH; methodology: KL, RW, and RH; data collection and processing: KL; analysis: KL, RW and RH; supervision: RW and RH. Original draft: KL, RW, and RH; review and editing: KL, RW, IS, and RH. All authors have read and agreed on final manuscript and submission.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

Informed consent

This study does not need any consent from other parties than authors.

Competing interests

The authors declare no competing interests.

Additional information

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