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SSP economic growth projections: Major changes of key drivers in integrated assessment modelling

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ABSTRACT

GDP scenarios are major drivers of climate change and climate change mitigation assessment studies. In this paper, a major update of the SSP GDP projections is presented. By using the most recent economic data and short-term projections by the World Bank and International Monetary Fund, the update captures changes in the system of national accounting and purchasing power parities, as well as the impact of the Covid 19 pandemic. Harmonization between the data and the original end-of-the century SSP projections was carried out in terms of GDP per capita in order to preserve the underlying narrative of income convergence. The result is a set of projections compatible with the most recent data and the SSP narratives. A comparison of DICE models calibrated to the original and updated SSP2 GDP per capita projections illustrates how significant the impact of an update of income data on integrated assessment results can be. The estimated global social costs of carbon in 2015 and 2030 rose by almost 30%.

1. Introduction

The Shared Socio-economic Pathways (SSPs) are a set of 5 scenarios developed by the climate change research community with the intent to facilitate integrated research and promote consistency across the scientific literature (O'Neill et al., 2014; Riahi et al., 2017). Each scenario comprises narratives and quantifications of a possible future, including economic, demographic and emissions trajectories. Together they provide a basis for exploring climate-change related challenges in different socio-economic environments, see Fig. 1.

In a recent review of scenario and SSP-based literature, O'Neill et al. (2020) find that the SSPs have been widely adopted (>1370 papers) and conclude that they have been successful in addressing the immediate needs of the research community. The SSP population (K. C., S, and Lutz, 2017) and GDP projections (Cuaresma, 2017; Dellink et al., 2017; Leimbach et al., 2017) are especially likely to been drawn upon in the studies (>890 and > 780 papers respectively). These projections are basic elements of the SSP framework and are important drivers to many Integrated Assessment Models (IAMs) on climate change (e.g. Baumstark et al. (2021); Krey et al. (2020)), Multisector Dynamics Models (MSDs) and other climate change and environmental assessment models. As such, changes in the economic growth projections can have a large impact on results. After reviewing the changes of his seminal DICE (Dynamic Integrated model of Climate and the Economy) model (Nordhaus, 1992a) over time, Nordhaus found that the upward revisions of GDP and other economic parameters accounted for the most significant changes in results, leading him to conclude that the projections of economic activity are the"least precise parts of IAMs" and that they"-deserve much greater study than has been the case up to now" (Nordhaus, 2017a).

In their review O'Neill et al. (2020) also identify needs and opportunities for improvement of the SSP framework. One need, they highlight, is the necessity to keep the scenarios up to date: since their first publication in 2013, the official SSP population scenarios have received minor updates, while the GDP scenarios have not. O'Neill et al. (2020) acknowledge the inherent tension between update-frequency and stability of the scenarios but call for an immediate update nonetheless, and further recommend that the quantitative drivers of the SSPs such as population and GDP be updated every 5 years, while the overall narratives and framework remain more stable. Research applications focused on the near-term would benefit in particular from projections that are consistent with the most recent data.

In practice, the SSP GDP and population scenarios, that span the years from 2010 to 2100, are harmonized with historical data from national accounts or other secondary sources to construct continuous GDP and population pathways from, e.g. 1980, to 2100. These harmonized pathways are then used as model-drivers. It is important for the credibility of model results, that the underlying population and GDP

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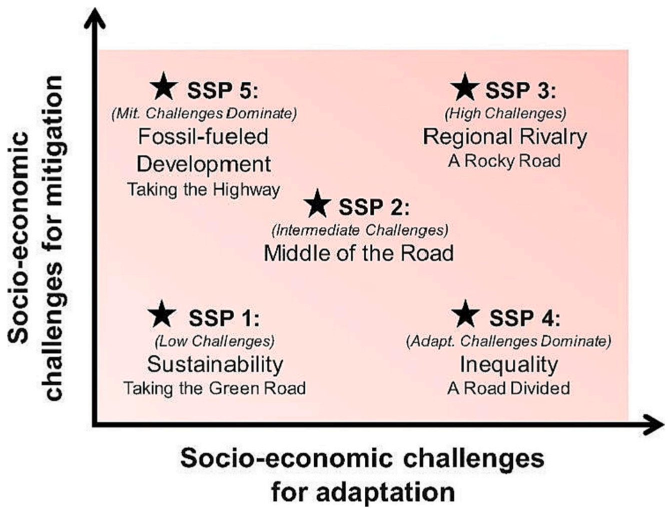

Fig. 1. Overview of the five SSPs as defined by the challenges for mitigation and adaption that their narratives entail (O'Neill et al., 2017; O'Neill et al., 2014).

pathways are consistent with the most recent historical data. Any inconsistency with historical data will call into question the plausibility of future projections.

This consistency issue of the GDP projections has further been put into the spotlight by the Covid 19 pandemic and the economic crisis that it brought about. The global drop in GDP in 2020 and its probable recovery are not covered by the original SSP projections, and while one can assume that the pandemic will have little to no impact in the long-run, its impact in the near term is non-negligible (for early analyses of the impact of COVID on GDP see Asian Development Bank et al. (2020), Beckman et al. (2021) and Maliszewska et al. (2020), and see Moyer et al. (2022) for an analysis of long-term impacts).

In this paper, an update of the SSP GDP pathways is presented and its impact on integrated assessment results analyzed. By using the most recent economic data and short-term projections by the World Bank (WB) and the International Monetary Fund (IMF), the update captures recent changes in national accounts and Purchasing Power Parities (PPPs): a new System of National Accounts (SNA) has been adopted (van de Ven, 2015), and a new International Comparison Program report (World Bank, 2020) has been published, since the SSPs were first developed. In using this data, the update also captures the impact of the Covid 19 pandemic. Finally, in using a harmonization method that operates on a GDP per capita basis, the update takes the latest population projections developed at the Wittgenstein Center (K. C., S, 2020; Lutz et al., 2018) into account.

It should be noted that the updated scenarios presented in this paper are not the result of an overhaul of the overall SSP framework or narratives, nor do they stem from new model-based projections built upon updated production functions and model-parametrization. “Bottom-up” types of updates such as these are being discussed and prepared by the community but require time before becoming available. Instead, the scenarios presented in this paper are the result of more “top-down” approach built upon an extensive harmonization exercise, for which the intricacies lie in handling the changes in national accounting and denominations.

This paper answers a clear call by the community to revisit the basic SSP quantifications. And while other recent studies have expanded upon the SSP projections, e.g. Kikstra et al. (2021), who extend SSP GDP per capita and population projections until the year 2300 in order to quantify the effect of long-term economic feedbacks on the social cost of carbon dioxide, Murakami and Yamagata (2019) who downscale them into a 0.5-degree global grid, Wear and Prestemon (2019) who downscale them to create within-country income distributions for the US, and Geiger (2018) who uses them to create harmonized GDP time-series from 1850 to 2100 for a wide range of countries, there exist, to the best of the author's knowledge, none that have answered the call for an update. It is the authors' hope that the provided scenarios[1] serve as such.

2. Methodology

The original GDP and populations scenarios cover 194 countries and span the years from 2010 to 2100 in 5-year time steps. The GDP scenarios were created by a modelling team at the OECD (Dellink et al., 2017) and are labelled as such in the public database managed by the International Institute for Applied Systems Analysis (IIASA).[2]

The updated GDP scenarios have the same spatial resolution, yet a finer temporal resolution in the near-term: 1-year time steps between 2010 and 2026 and 5-year time steps thereafter, starting in 2030. They are constructed on a per capita basis, by harmonizing the long-term GDP per capita levels with the most recent data and short-term projections of GDP per capita growth.[3]

2.1. Data sources

The GDP per capita data used in the harmonization process of the updated scenarios, comes from the World Bank's World Development Indicator Database (World Bank, 2021a) and the International Monetary Fund's World Economic Outlook of October 2021 (International Monetary Fund, 2021).[4] The choice of these data sources was the result of a comprehensive comparison exercise of available and applicable databases, see Appendix A. In the end, the WDI and WEO were chosen as reference historical data sources due to their high coverage in recent years, the reputation of their backing institutions, their wide-spread use in the community and their update-frequency, i.e., quarterly for the WDI and twice yearly (April and October) for the WEO.

2.2. GDP per capita units

The GDP per capita data from the WB and IMF is given in constant 2017 international dollars at purchasing power parity (short notation: 2017$PPP), with the base year, 2017, corresponding to the year of the most recent International Comparison Program (ICP) report that provides the PPP estimates.[5] The original GDP per capita SSP projections, on the other hand, are given in 2005$PPP. In order to harmonize the

[1] The updated scenarios are available at https://doi.org/10.5281/zenodo.7523033.

[2] The OECD scenarios are available at (https://tntcat.iiasa.ac.at/SspDb/) along side other GDP scenarios based on alternative modelling approaches (Cuaresma, 2017; Leimbach et al., 2017).

[3] The temporal resolution of the updated scenarios is controlled by the temporal resolution of the data sources. In this case, the chosen data sources for historical data and short-term projections (see section 2.1) provide yearly data from 1980 until 2026, i.e. 6 years into the future. The sources are updated every year, therefore the projections can be as well. The R-package mrdrivers, created specifically for scenario construction, updates the scenarios automatically as new data becomes available, see https://github.com/pik-piam/mrdrivers#readme.

[4] The exact series-codes of the GDP per capita data used are”NY.GDP.MKTP.PP.KD” and”NGDPRPPPPC”, for the WDI and WEO respectively.

[5] The ICP's main objectives – namely the creation of PPPs, and the conversion of national GDPs into a common currency while controlling for differences in price levels – make it one of the most significant statistical initiatives in the world. Since 1970, the ICP has published 9 reports, continuously expanding the number of participating economies, from 10 in 1970 to 173 in 2017. Between comparison cycles, the ICP may update its PPP computation methods, and adapt for any changes in systems of national accounting, consumer basket compositions and reference year. The ICP is managed by the World Bank and United Nations Statistical Commission (UNSC), and as the sole, widely recognized source for global PPPs, its reports and findings are used by economic institutions worldwide.

projections with the data a common unit is required; either the data is converted into 2005\$PPP or the projections are expressed in 2017\$PPP.

2.2.1. Option 1: Converting the data

Converting the data into 2005\$PPP can be accomplished using the WDI's country-specific GDP deflators and PPPs in the years 2017 and 2005:

$$x_{2005}(c,t) = x_{2017}(c,t)\frac{ppp(c,t=2017)}{ppp(c,t=2005)}def_{2017}(c,t=2005) \tag{1}$$

where, $x_{2005}(c,t)$ is the GDP per capita in 2005\$PPP of country c in year t, $x_{2017}(c,t)$ the GDP per capita in 2017\$PPP, $ppp(c,t)$ the PPP conversion factor in local currency units (LCU) per international \$ and $def_{2017}(c,t=2005)$ the GDP deflator base 2017 in year 2005 in 2005LCU per 2017LCU.[6]

However, constructing scenarios based on a conversion of the data into 2005\$PPP still requires a significant harmonization effort in order to smoothen the transition between new data and old projections. That is because the GDP per capita values of the original SSP projections differ from the newly converted data values *even in the historic time period*. These differences stem from changes in GDP accounting methods and PPP conversion factors: since the original SSPs were developed in 2013, a new System of National Accounts (SNA) has been adopted (van de Ven, 2015), and a new International Comparison Program (ICP) report (World Bank, 2020) has been published.

The changeover from the SNA 1993 to the new SNA 2008 was endorsed by the United Nations Statistical Commission already in 2009, but implementation took a while longer, with most OECD countries adopting the new SNA between 2014 and 2016. As a result, GDP levels in 2010 increased by 3.8 percentage points on average for the OECD. The conceptual change between SNAs with the largest impact on GDP levels was the reclassification of Research and Development purchases as investments instead of intermediate goods. However, GDP levels were also impacted by the inclusion of new or expanded data sources and general improvements of accounting methods, which countries took the opportunity to implement alongside the changeover of the accounting standards. In some cases, these so-called statistical benchmark revisions had a larger impact on GDP levels than the changeover of standards.[7]

The publishing of the latest ICP report also had an impact on GDP levels, when accounted in PPP. On the one hand, the 2017 ICP cycle was the first to adopt the definition of GDP provided by SNA 2008 as its framework for the common ICP expenditure classification. On the other hand, simply the availability of the report has changed historic PPP levels in certain databases and institutions. The yearly PPPs in the WDI, for example, are the result of an inter- and extrapolation exercise between and from the two most recent ICP benchmark years. With the 2017 report published, these are 2017 and 2011, which meant that the PPPs for all years before 2011 were revised.

Taking into account the SNA changeover, the statistical benchmark revisions and the revised PPP factors in 2005, conversion of recently published GDP per capita levels from 2017\$PPP to 2005\$PPP will not lead to the same value as GDP per capita data published years before. Fig. 2 illustrates the resulting difference between database versions. It shows GDP per capita over time for 12 world regions[8] from different database versions. The differences between the same databases published in different years is more clearly apparent in regions like Sub-Saharan Africa (SSA) and Middle Eastern Asia (MEA), where GDP per capita levels, in absolute terms, have not increased much between 1980 and 2020, but the differences are present in all regions.

2.2.2. Option 2: transforming the projections

Alternatively to converting the data, the original projections can be expressed in 2017\$PPP. This option comes with its own challenges of holding the original SSP story-line of"convergence-to-the-frontier" intact. The original SSP GDP per capita projections were constructed with an underlying narrative of a catch-up by developing countries to the GDP per capita of countries at the frontier. Converting the original projections from 2005\$PPP to 2017\$PPP does not guarantee to keep the behavior of countries' GDP per capita trajectories *relative* to that of the frontier the same.[9] In fact, due to country-specific GDP deflators and different PPP conversion factors, the relation of GDP per capita to that of the United States can be very different depending on the unit (see Fig. 3). In this figure, the original SSP GDP per capita values for the Unites States (the representative frontier economy), Ghana and Guyana are shown. The left panels show the GDP per capita in 2005\$PPP and the right in 2017\$PPP. It becomes apparent that conversion distorts the countries' GDP per capita relative to that of the United States. While when expressed in 2005\$PPP the SSP5 GDP per capita in 2100 of both developing countries is approximately 50% lower than that of the United States, it is almost 10% and 110% higher when expressed in 2017 \$PPP, for Ghana and Guyana respectively. This distortion is most significant for SSP5, but applies to all SSPs.

In order to nevertheless construct comparable SSP projections in 2017\$PPP, the following approach was chosen. For the year 2100, the assumption was made that the ratio between country's GDP per capita to that of the United States would be equal to those of the original SSPs in 2005\$PPP. With $ppp(c=\text{USA},t)=1$ for all t, GDP per capita in 2017\$PPP in 2100 for all countries can be calculated as:

$$x_{2017}(c,t=2100) = x_{2005}(c,t=2100)def_{2005}(c=USA,t=2017) \tag{2}$$

Once the GDP per capita in 2100 is known, a transition (see Section 2.3.2) from historical data in 2017\$PPP to the 2100 values can be constructed, thereby creating SSP projections in 2017\$PPP that preserve the narrative of income convergence.

Both the conversion to 2005\$PPP and the transformation into 2017 \$PPP are valid options, and updated projections have been constructed with both.

2.3. Scenario construction

The updated GDP scenarios are are constructed on a per capita basis so that the SSP income-convergence narrative is preserved. If the harmonization were to take place on the level of GDP, the introduction of new population projections would lead to GDP per capita trajectories out of line with the SSP storylines.

2.3.1. GDP per capita harmonization method

Harmonization is required to create a smooth transition between the data and the projections, no matter whether GDP per capita is in 2005 \$PPP or 2017\$PPP. It is described in the following points (see Appendix B for the equations):

- Until the year 2020, the updated scenarios match the data from WDI.
- Between 2020 and 2026 they follow the WEO's short-term estimates of GDP per capita growth, covering the growth impacts of the Corona shock.
- Between 2026 and 2100, the scenarios follow a path that, by 2100, leads them back to the same GDP per capita relative to that of the

[6] The R-package GDPuc was created to facilitate GDP conversion, see https://github.com/pik-piam/GDPuc#readme

[7] See Fig. 2 of van de Ven (2015) for a decomposition of the total impact on GDP into impacts from the changeover of standards and impacts from the statistical benchmark revisions, and the entire report for more details on the SNA changeover.

[8] See Appendix C for the country-to-region mapping.

[9] A similar effect can be observed if the scenario construction were based on new data points combined with the original GDP per capita growth rates

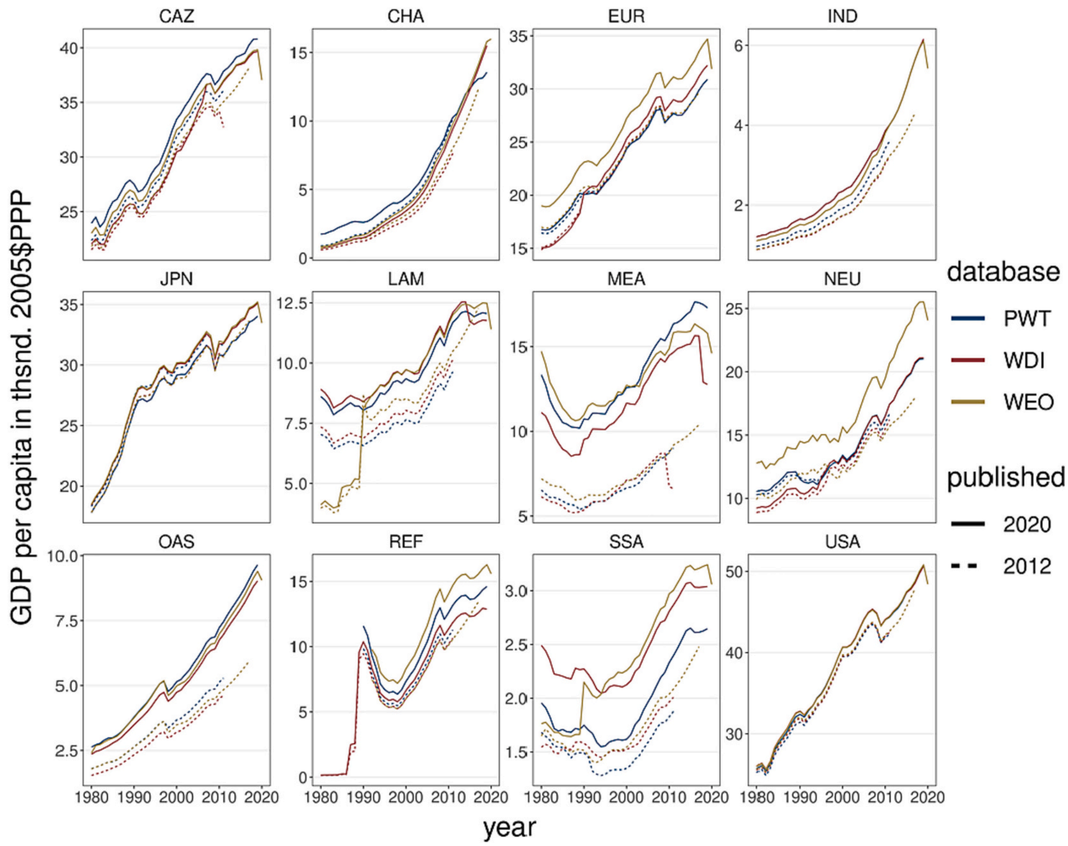

Fig. 2. GDP per capita in 2005$PPP from different versions of existing databases for 12 world regions (region mapping in Appendix C).

USA, as in the original scenarios.[10] Depending on whether the GDP per capita in 2026 of the updated scenarios is higher or lower than that of the original SSP projections, the convergence back to the same GDP per capita relative to that of the USA is either accelerated or prolonged. In the case of lower GDP per capita, SSP1 and SSP5 start converging right away, SSP2 starts 5 years later, and SSP3 and SSP4 10 years later by 2036. In the case of higher GDP per capita, the convergence behavior is reversed: SSP3 and SSP4 start converging right away, SSP2 by 2031, and SSP1 and SSP5 by 2036. Until convergence is commenced, the absolute difference between the updated values and the original SSPs is kept constant to the difference computed in 2026 (see Appendix B for an illustration). This SSP specific convergence behavior was implemented following the underlying SSP storylines[11]: in SSP1 and SSP5, high GDP per capita growth is expected, therefore faster catch-up (or slower slow-down) is a reasonable assumption. The opposite is true for SSP3 and SSP4.

2.3.2. *GDP and population scenarios*

The updated SSP GDP scenarios, $X_u(c,t,s)$, are the product of the updated SSP GDP per capita scenarios and harmonized SSP population scenarios, $P_h(c,t,s)$:

$$X_u(c,t,s) = x_u(c,t,s)P_h(c,t,s) \tag{3}$$

The population scenarios P_h are the result of a harmonization process of recently updated SSP population projections (K. C., S, 2020; Lutz et al., 2018) with WB data. This harmonization step was performed to keep GDP scenarios as consistent as possible with the GDP per capita scenarios. This way, not only do the GDP per capita values of the SSP updates match WDI data in historic years and the near-term future, but so do the GDP values.

The harmonization method for the population scenarios is somewhat more straightforward than that of the GDP per capita scenarios. Until 2020 the scenarios match WDI data (World Bank, 2021a), between 2020 and 2026 the scenarios follow short-term WB population growth estimates from the Population Estimates and Projections (PEAP) database[12] (World Bank, 2021b), and between 2026 and 2100, the scenarios use the updated SSP population growth rates (see Appendix B for the equations).

3. Results

This section presents the results of the scenario update and compares the updated scenarios with the originals. They are presented first on a global level and then for the same countries as in the results section of Dellink et al. (2017). These countries are USA, China, India and Tanzania, i.e. examples of a high-income economy, middle-income emerging economy, a low-income emerging economy, and a low-income developing economy, respectively.

3.1. *Global projections*

Fig. 4 depicts the updated and original global projections of GDP per

[10] For the USA itself, the scenarios in 2005$PPP converge to the original US GDP per capita levels, and the scenarios in 2017$PPP back to the inflation adjusted value, see equation 2.

[11] The SSP scenario-specific assumptions and quantifications for TFP-related growth drivers are shown in Table B1 in Appendix B.

[12] The World Bank's PEAP data is sourced from the United Nations World Population Prospects data, for which the latest revision at the time of writing was the 2019 report (United Nations, 2019), available at https://population.un.org/wpp/Download/Archive/Standard/. Therefore, the population estimates provided by the World Bank and used in this paper do not account for any impacts the COVID pandemic may have had on population.

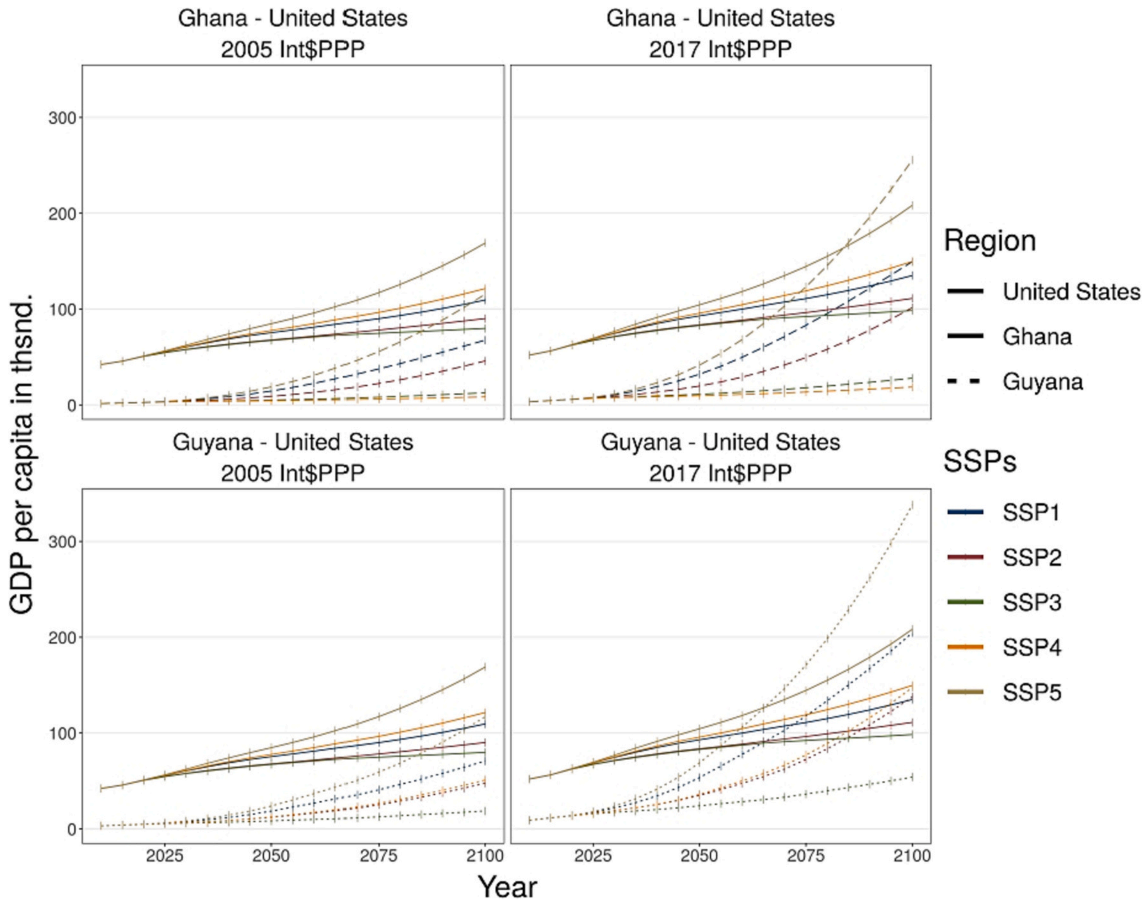

Fig. 3. Original SSP GDP per capita projections in 2005$PPP and 2017$PPP.

capita, GDP and population[13] (levels on the left and growth rates on the right).

Overall, updated GDP per capita levels are very close to the original. They show the same wide spread between SSPs, with the updated SSPs having a marginally narrower spread in 2100 than the originals. This proximity of the projections is by construction: on the country level, updated GDP per capita projections in 2100 match the originals exactly. On a global level, deviations result from different population projections used as weights in the aggregation. The updated population levels show substantial changes to the originals. Across SSPs global population is projected to be higher for all SSPs, for the entire century, with the exception being SSP5. For SSP5, end-of century population is the same as in the original. This is in part because SSP5 now follows the SSP1 trajectory, and not a distinct trajectory as in the original (see Lutz et al. (2018) and K. C., S (2020) for more information).

The updated global GDP levels are the product of the updated GDP per capita and population levels, and thus reflect the overall increase in population: GDP levels are higher for SSPs1–4, with the largest increase being in SSP3. For SSP5, GDP levels are slightly lower by the end of the century.

The near-term growth rates for GDP per capita and GDP differ from the originals considerably, with the most striking difference being in 2020 and 2021. These reflect the impact of the Covid-19 pandemic on economic growth as estimated by the IMF. Since by construction the updated SSPs all follow the same pathway until 2025, the Covid shock and the estimated recovery until 2025 is the same for all SSPs. Only after 2025 do growth rates start to differ amongst SSPs. In the long-term growth rates converge close to the originals.

Global population growth rates are also, by construction, the same across SSPs until 2025. After that they equal the growth rates of the updated Wittgenstein Center growth rates, which differ from the originals.

It is interesting to note, that the relatively large difference in global GDP per capita between the updated and original scenarios in 2015 (approximately 13% see Table 1, almost disappears by 2020. The upwards correction in 2015 is negated in 2020 by the Covid shock, leading to very small GDP per capita differences in the periods thereafter. On a global scale, the difference due to the change of GDP accounting method and PPPs is incidentally, yet effectively canceled out by the Covid shock.

3.2. *Country-level projections*

Fig. 5 depicts updated and original GDP per capita levels for China, India, Tanzania and the United States.[14]

The near-term panels on the left clearly illustrate the effect that changes in the national accounts and PPP conversion factors have on historical income data. The 2015 values differ for all four countries, see Table 1. The relative difference is highest for Tanzania, where GDP per capita has been corrected upwards by almost 45%.

The near-term panels also depict the impacts of the Covid shock: there is a decline in GDP per capita in 2020 for 3 of the 4 countries, with

[13] A clear distinction was made In the previous section between the updated SSP population scenarios from Lutz et al., and the harmonized SSP population scenarios P_h used in the GDP scenario construction. However, in order to use the same qualifier for the GDP per capita, GDP and population scenarios shown here, we will use"updated" to refer to the harmonized SSP population scenarios.

[14] A plot comparing updated and original GDP per capita levels for 183 countries is shown in Appendix D.

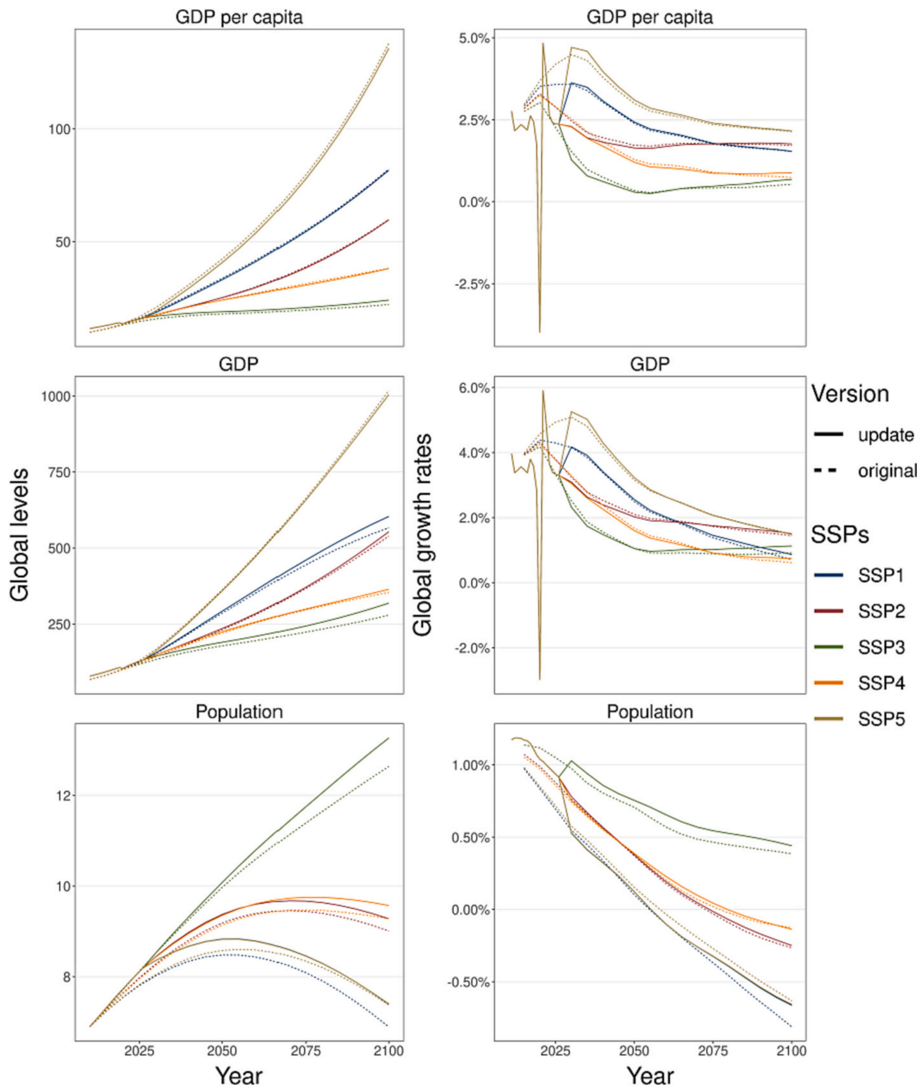

Fig. 4. Updated and original SSP scenarios for GDP per capita, GDP and population, aggregated to a global level. The left-hand panels comprise the scenario levels and the righthand panels the associated annual growth rates. The GDP per capita levels are in thsnd. 2005$PPP, the GDP levels in tril. 2005$PPP and the population levels in billions. The growth rates are in %/year.

Table 1
Relative % difference in GDP per capita between the updated and original SSP2 scenario for the historic years and near future (region mapping in Appendix C).

	2015	2020	2025	2030	2035
Example countries					
China	18.09	5.23	4.02	3.50	2.82
India	29.63	10.85	18.13	15.65	12.16
Tanzania	44.91	32.23	16.53	11.65	8.81
United States	3.96	−3.63	3.43	3.38	3.03
World					
GLO	13.47	1.28	2.92	2.14	1.35
Regions					
LAM	10.26	−12.44	−13.90	−13.37	−11.21
OAS	45.92	31.13	28.96	25.31	20.42
SSA	34.89	7.00	−5.80	−7.08	−5.55
EUR	1.78	−5.58	1.48	1.47	1.36
NEU	14.50	7.37	10.91	10.10	8.86
MEA	57.35	30.42	23.30	19.23	16.09
REF	−1.72	−15.06	−18.68	−17.61	−14.97
CAZ	2.91	−6.08	−1.36	−1.59	−1.48
JPN	2.76	1.30	5.06	4.46	3.97

the United States and India being relatively more affected than Tanzania and China, and only China managing to keep a positive growth rate. India is in fact one of the most severely hit economies, see Table 2: in the group of countries with above-median population and GDP, India is the third most affected by the Covid shock, coming only after the Philippines and Myanmar.

It is worth to note the brevity of the Covid pandemic's impact on economic growth when considering the entire scenario timeframe. The pandemic is what can be considered a black swan event, an event that was unforeseeable, with major impacts in the short-term, but after which it can be expected that the status-quo is quickly reinstated. India's and the United States' GDP per capita recover quickly to pre-2020 values: both have higher income in 2021 than in 2019. This stems from the fast and strong recovery predicted for these countries: 8.4% and 5.7% growth in 2021, for India and the United States respectively. Tanzania has a slightly slower recovery, only surpassing its 2019 income level in 2023, by which it still hasn't reached pre-pandemic growth rates. Finally, China is predicted to recover quickly (7.7% growth in 2021) but then drop down to a lower growth rate than before the pandemic, and continue to decreases thereafter. This slow decrease of China's economic growth, from an admittedly high level, is in essence a continuation of a pre-pandemic trend.

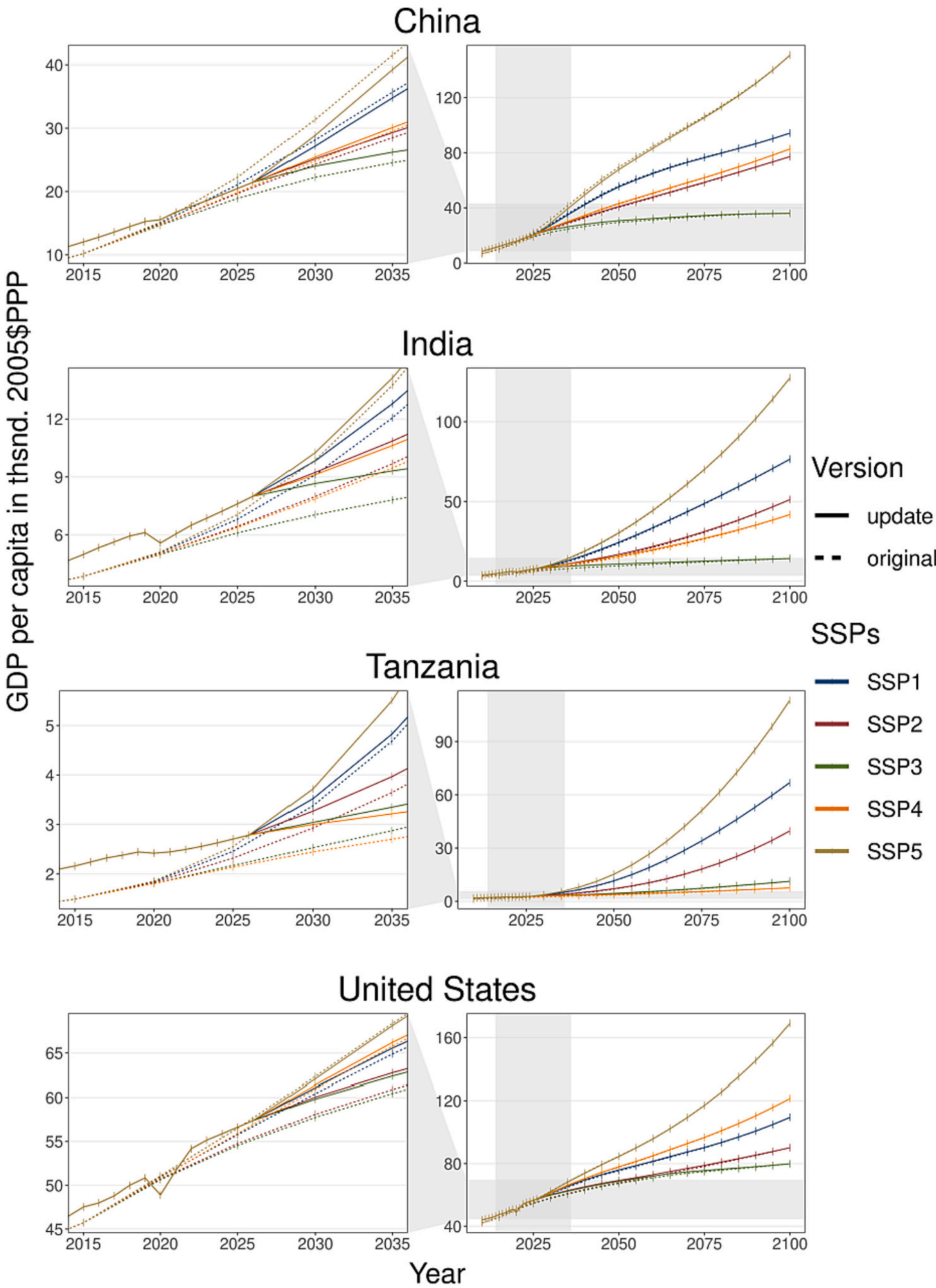

Fig. 5. GDP per capita in thsnd. 2005$PPP for select countries. The left-hand panels depict only the years between 2015 and 2035, and the right hand-panels all years until 2100. By construction, the updated GDP per capita values converge to the original by the year 2100.

The large differences of GDP per capita values in the initial periods are barely noticeable in the long run (Fig. 6, left panel), due to the convergence mechanism: the updated GDP per capita converges back to the original values, so that by 2100 they are identical. This convergence can be seen in Fig. 6 (right panel): After the near-term variation in growth rates, mainly due to the Covid shock and recovery thereof, the updated GDP per capita levels and growth rates steadily approach the original values, across SSPs, and for all four countries.

Similar to what can be seen on the global scale, the large differences in GDP per capita between the updated and original scenarios in 2015, that can be seen for China, India, and Tanzania (see Table 1), are attenuated by 2020 because of the Covid shock. Between 2015 and 2020, the relative difference for China drops from 18.1% to 5%, from 29.6% to 10.9% for India, from 44.9% to 32.2% for Tanzania and from 4.0% to −3.6% for the USA. Looking at the regions in Table 1 emerging and developing regions are all affected similarly. It is only for the high-income regions, for which GDP accounting and PPPs did not change substantially, and for countries in Latin America, that the Covid shock leads to the 2020 value of the updated scenarios being lower than that of the original ones.

Fig. 6 illustrates furthermore that the SSP specific assumptions and quantifications for growth underlying the original projections remain the same. In SSP1 and SSP5, Tanzania and India have very high growth rates compared to that of the United States; a characteristic that stems from the scenario assumption of high-income convergence speed of lower-income countries. In SSP3 and SSP4, convergence is slower. In SSP3, catch up is slow for all countries, while in SSP4, there is an actual divergence in income: SSP4 is the only SSP in which Tanzania has a lower growth than India and China. The cumulative effect of the convergence assumptions on income levels can be clearly seen in 2100.

Table 2
GDP per capita growth rates of the updated SSP scenarios between 2015 and 2025, for a selection of countries. The growth rates are yearly growth rates in %/year, with the column "2015–2019" holding the average annual growth rates over that 5-year period. Source data is from the World Bank (2021c) and the International Monetary Fund (2021).

Country	2015–2019	2020	2021	2022	2023	2024	2025
Example countries							
China	6.11	1.98	7.73	5.36	5.08	5.09	4.99
India	5.28	−8.87	8.44	7.50	5.59	5.34	5.26
Tanzania	3.10	−0.95	1.01	2.07	2.45	2.76	2.94
United States	1.70	−3.82	5.69	4.83	1.80	1.33	1.33
Most affected countries							
These are the 10 countries with above median population and GDP, most affected by the Covid shock, measured by the decline in growth rate between 2015 and 2019 and 2020.							
Philippines	5.12	−10.78	1.67	4.70	5.35	5.13	4.85
Myanmar	4.46	−10.59	−18.48	−0.68	1.89	1.96	1.89
India	5.28	−8.87	8.44	7.50	5.59	5.34	5.26
Peru	1.50	−12.39	8.95	3.53	3.48	2.23	2.18
Iraq	1.08	−12.40	1.02	7.70	3.03	0.75	0.48
Spain	2.22	−11.25	5.64	5.93	2.20	1.57	1.21
United Kingdom	0.86	−10.30	6.44	4.43	1.50	1.23	1.16
Portugal	2.89	−7.74	4.63	5.32	2.73	2.45	2.26
Malaysia	3.43	−6.80	2.19	4.67	4.40	4.04	3.79
Italy	1.47	−8.60	5.88	4.32	1.69	1.07	1.03

In an SSP5 world, Tanzania's income in 2100 is about 2/3 of that of the United States, compared to 1/10 in SSP3 and to 1/16 in SSP4.

4. Impact on integrated assessment studies

The SSP GDP scenario update can have a significant impact on the results of integrated assessment studies, as for instance climate change and climate change mitigation assessments performed by IAMs. To illustrate this, the impact of the update on the results of the DICE model (Nordhaus, 1992a) is examined, specifically with regards to the Social Cost of Carbon (SCC).

4.1. GDP projections in DICE

The DICE model was chosen as an example due to its simplicity and prominence in the IAM community. Over the last decades, DICE established itself as *the* iconic stylized model, used as exploration tool and typical reference point for cost-benefit analyses. As part of their paper on dynamic realism in IAMs, Grubb et al. (2021) review the significance of DICE, and find that it is still widely used, with hundreds of citations of the newest version (Nordhaus, 2017b) in the 2017–2020 time period alone (Grubb et al., 2021).

Mathematically, DICE is a constrained non-linear dynamic optimization model with an infinite horizon. It is an extension of the standard neoclassical optimal growth model, that includes a climate system, economic damages from temperature increases, and climate investments in addition to capital investments. Detailed documentation can be found in Nordhaus (1992b, 1992a) and Nordhaus (2017b).

In DICE the production function is a Cobb-Douglas with exogenous labor and exogenous Hicks-neutral technical change. The labor and total factor productivity parameters are calibrated to existing data and best-guess projections. For labor, these are the population projections from the United Nations. For total factor productivity, these are the result of expert surveys on projected GDP (Nordhaus, 2017b). The calibration of the total factor productivity is an important step but comes with large uncertainties related to the variability of the estimation of GDP (past, present and future) over time, see Fig. 2 and the discussion on GDP differences between international database versions above. After reviewing the changes of DICE over time, Nordhaus himself found that the upward revisions of GDP used to calibrate TFP accounted for the most significant changes in results: between the 2013 and 2016 versions of DICE, 31% of the increase of the SCC in 2015 was accounted for by revised economic parameters (Nordhaus, 2017a).

4.2. The SSP GDP update's impact on DICE

To investigate the impact of changing from the old SSP GDP scenarios to the new, we calibrate DICE to the original scenarios, then to the updated ones, and compare the results. Calibration was done is such a way as to match DICE's net output per capita with global SSP GDP per capita in 2015 and 2050. Both the old and the new SSP DICE runs, have the "optimized" setting in DICE turned on, meaning that the carbon price equals the social cost of carbon.

Table 3 illustrates the change in major variables between DICE calibrated to the original and updated SSP2 scenarios. Shown are the major drivers and outcome variables for the years 2015 (the start year), 2020, 2030 and 2050. To be clear, the only difference between the "DICE-original" and "DICE-updated" models are the TFP parameters, calibrated to the original and updated GDP per capita, respectively. The population, carbon intensity of GDP ("CO2/output" in Table 3) and radiative forcing from non-CO2 source ("Other forcings" in Table 3) are all kept constant.[15] The difference in outcome variables is therefore only due to the change in TFP parameters resulting from the use of different calibration data.

We focus our attention on the 2015–2050 timespan, since it is over this timespan that we calibrated DICE. Looking at recalibration results further into the future would make more sense if there were substantial differences in the calibration data further in the future, which unfortunately – and this underscores a clear limitation to our approach - is not the case for our update, see Fig. 4.

The higher economic activity in the years 2015, 2020 and 2030 in "DICE-updated" compared to "DICE-original", leads to higher industrial CO2 emissions and higher SCCs in those years. The shift in emissions towards the present, causes temperature to increase faster in "DICE-updated" than in "DICE-original",[16] and the SCC to remain high even in 2050 where economic activity is very similar between the scenarios. Noticeable is the size of the differences in the SCC, specifically in the near future (up to 31%), which is similar to the size of the difference Nordhaus found when comparing the 2013 and 2016 versions of DICE.

[15] In DICE, the CO2 over output ratio is a fixed parameter, and the industrial CO2 emissions are a simulation result, i.e., the product of output and the CO2 over output ratio.

[16] In general, it may be worth to note that temperature in DICE is fixed in the start year and reacts sluggishly to emissions. New research has found a more instantaneous reaction of temperature to emissions, see Dietz and Venmans (2019).

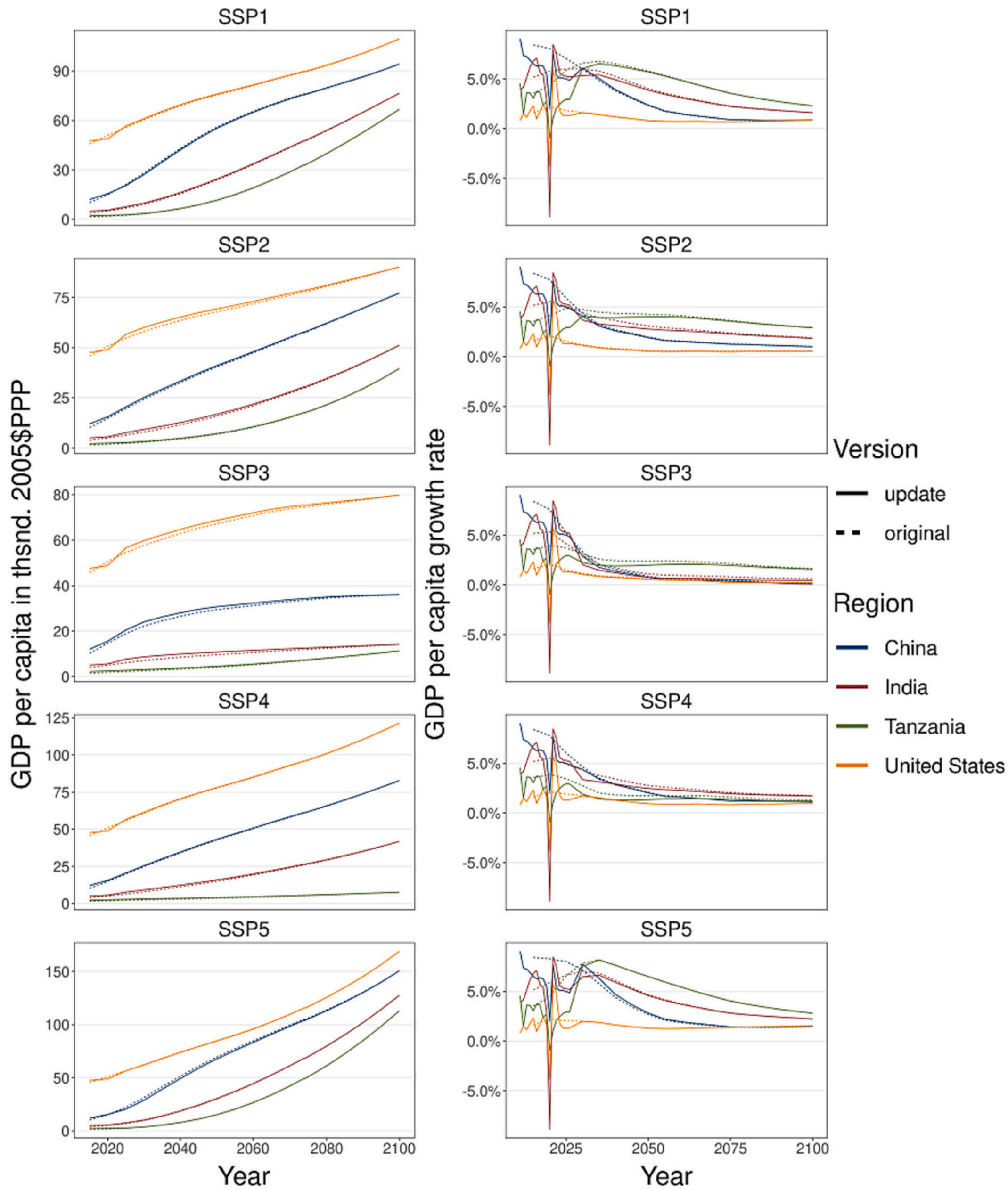

Fig. 6. Comparison across SSPs of the GDP per capita levels and growth rates. The lefthand panels show the GDP per capita levels in 2005$PPP and the right-hand panels the associated annual growth rates.

The shift in emission towards the present is also manifested in the growth rates of industrial emissions over time. After an initial drop in emission between 2015 and 2020,[17] emissions increase in both scenarios, but while the growth of emissions in "DICE-updated" decreases from 9% between 2020 and 2030 to 2% between 2030 and 2050, the growth of emissions in "DICE-original" stays at around 13% for both time-periods. This also means that the year by which emissions peak is closer to the present in "DICE-updated" than in "DICE-original".

5. Conclusion

This paper presents an update of the SSP GDP scenarios. By harmonizing the original end-of-the century GDP per capita levels with the recent data and short-term projections from the World Bank and International Monetary Fund, the updated scenarios keep the original SSP storylines of income-convergence intact, while simultaneously capturing recent changes of PPPs and GDP accounting methods, and impacts of the Covid 19 pandemic. The methodology and tools developed make it possible to express the scenarios in 2005$PPP (the unit of the original scenarios) or 2017$PPP (the unit with the most recent ICP year as base year), and allow for regular updates as new data becomes available.

A comparison of DICE models calibrated to the original and updated SSP2 GDP per capita projections illustrates how significant of an impact an update of income data can have in IAMs. Calibrating to the original instead of the updated SSP GDP per capita scenario leads to a large underestimation of the SCC, specifically in the near future (around 30%). The fact that the recalibration of DICE in light of new economic data and projections leads to such a large variation in key results, underlines the importance of paying careful attention to the validity of this data.

[17] This is due to non-optimal fixings in the start year and can be observed in all "optimal" DICE runs.

Table 3
Relative difference in major drivers and outcome variables between DICE calibrated to the "original" global SSP2 GDP per capita projections and DICE calibrated to the "updated" global SSP2 GDP per capita projections, between the years 2015 and 2050.

	2015			2020			2030			2050		
	Original	Update	Change	Original	Update	Change	Original	Update	Change	Original	Update	Change
Major drivers												
Population (millions)	7403.00	7403.00	0%	7853.09	7853.09	0%	8638.97	8638.97	0%	9790.92	9790.92	0%
GDP per capita (2010$PPP)	12,796.65	14,529.67	14%	14,229.98	16,247.38	14%	17,934.01	19,895.65	11%	28,394.52	28,424.91	0%
Other forcings (W/m2)	0.50	0.50	0%	0.53	0.53	0%	0.59	0.59	0%	0.71	0.71	0%
CO2/output (tCO2 per 2010$PPP)	0.35	0.35	0%	0.32	0.32	0%	0.28	0.28	0%	0.21	0.21	0%
Outcome variables												
Industrial CO2 emissions (Gt CO2 per year)	32.25	36.61	14%	30.30	33.34	10%	34.25	36.27	6%	38.76	37.01	−5%
Net output[1] (2010$PPP)	94.73	107.56	14%	111.75	127.59	14%	154.93	171.88	11%	278.01	278.31	0%
Consumption per capita (2010$PPP)	9.60	10.66	11%	10.67	12.00	12%	13.48	14.82	10%	21.47	21.37	0%
Atmospheric temperature increase since 1990 (°C)	0.85	0.85	0%	1.01	1.02	0%	1.34	1.36	1%	2.00	2.03	2%
Social cost of carbon (2010$PPP per tCO2)	26.29	33.54	28%	30.70	40.17	31%	42.75	55.00	29%	80.28	92.57	15%

[1] Gross world product net of abatement and damages.

The updated SSP scenarios are not the result of an overhaul of the overall SSP framework or narratives, nor do they stem from new model-based projections. They do not question any of the SSP storylines nor do they expand upon them or cover any newly in-demand narratives (e.g., sustainable development pathways (Soergel et al., 2021). They furthermore do not consider any recent insights in economic modelling or forecasting, nor any changes in long-term economic outlooks for any country.

Updates stemming from new model-based projections that address these limitations are being discussed and prepared by the community, but require time before becoming available. Hence, as near-term climate action becomes more and more important, the proposed scenarios and methods can be used by the community to make sure that their work is in harmony with recent data and short-term projections.

Code availability

Two open-source R-Packages were created to facilitate the scenario construction and are available on Github. "GDPuc", a GDP unit converter available at https://github.com/pik-piam/GDPuc#readme, and "mrdrivers", a scenario constructer available at https://github.com/pik-piam/mrdrivers - readme. The DICE source code can be downloaded at https://williamnordhaus.com/dicerice-models.

Declaration of Competing Interest

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

Data availability

The DICE output files, and all SSP scenarios used in the paper are available at https://doi.org/10.5281/zenodo.7523033. This includes the original SSP population, GDP and GDP per capita scenarios (GDP in 2005$PPP), and the updated SSP population, GDP and GDP per capita scenarios (GDP in both 2005$PPP and 2017$PPP).

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Appendix A. Database selection

The choice of databases to be used as historical reference source was the result of a comprehensive comparison exercise of available and applicable databases. These are databases that contain GDP or GDP per capita data at purchasing power parity (PPP) for a wide number of countries. In total, 7 databases were considered:

- the World Development Indicator (WDI) database from the World Bank (available at https://databank.worldbank.org/source/world-development-indicators, accessed on the 23 of October 2021),
- the October 2021 World Economic Outlook (WEO) from the IMF (available at https://www.imf.org/en/Publications/WEO/Issues/2021/10/12/world-economic-outlook-october-2021),
- the Penn World Tables (PWT) 10.0 (available at https://www.rug.nl/ggdc/productivity/pwt/)
- the 2020 release of the Maddison database from the Groningen Growth and Development Center (GGDC) (available at https://www.rug.nl/ggdc/historicaldevelopment/maddison/releases/maddison-project-database-2020),
- the Economic Outlook from the Organization for Economic Co-operation and Development (OECD) No 108 (Edition 2020/2) (available at https://www.oecd-ilibrary.org/economics/data/oecd-economic-outlook-statistics-and-projections/oecd-economic-outlook-no-108-edition-2020-2_c59fcffd-en),
- a data set created by James et al. (2012) and hosted by the Institute for Health Metrics and Evaluation (IHME) (available at https://ghdx.healthdata.org/record/ihme-data/gross-domestic-product-gdp-estimates-country-1950-2015),
- and finally a data set created by Gütschow et al. (2019) and hosted at the Potsdam Institute for Climate Impact Research (PIK) (available at https://dataservices.gfz-potsdam.de/pik/showshort.php?id=escidoc:4742890).

The last 2 data sets are constructed out of combinations and extensions of the others and could thus be considered as "tertiary" sources, with the WDI, WEO, PWT, Maddison, and OECD databases being secondary sources, and the national accounts of the individual countries being primary ones.

The main criteria by which databases were evaluated were completeness (in terms of the number of countries and the number of years for which data is available[18]), credibility, update-frequency and use in the community. Fig. A1 shows the number of countries covered in the databases every year, between 1800 and 2100. The coverage of the original SSPs from the IIASA database was added for comparison. The database with the highest coverage in recent years is the WDI, followed by the 2 tertiary sources and the WEO. The data sets by James et al. (2012) and Gütschow et al. (2019) were created specifically in order to cover a large number of countries consistently over time (in this case approx. 50 and 130 years, respectively) and thus compare favorably with regards to the others. However, they have not been adopted and used as much as the WDI and are thus also not as well-tested. Furthermore, there is no guarantee of regular updates. The databases hosted by the GGDC cover a lower number of countries but extend further back in time, and the OECD covers only a few countries.

[18] At the time of writing, specific focus was on finding sources with up-to-date data for the year(s) of the COVID pandemic. Sources and databases that fulfilled this requirement were the WB's WDI, the IMF's WEO and the OECD's EO.

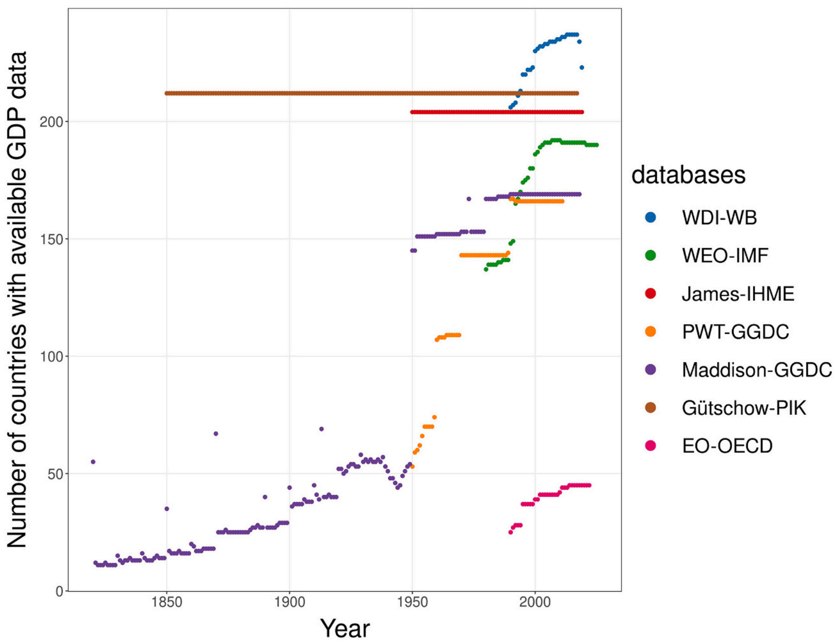

Fig. A1. Number of countries per year in available databases with GDP or GDP per capita data. Original SSP coverage added for comparison.

Appendix B. Harmonization methods

The GDP per capita harmonization method can be described by:

$$x_u(c,t,s) = \begin{cases} x_{wdi}(c,t), if\ t \leq 2020 \\[2ex] x_u(c,t,-1,s)\dfrac{x_{weo}(c,t)}{x_{weo}(c,t-1)}, if\ 2020 < t \leq 2026 \\[2ex] x_o(c,t,s) + d(c,s), if\ 2026 < t \leq t_h(s,d) \\[2ex] x_o(c,t,s) + d(c,s)\dfrac{2100 - t}{2100 - t_h(s,d)}\ if\ t_h(s,d) < t \leq 2100 \end{cases} \tag{A-1}$$

with

$$d(c,s) = x_u(c,t = 2026,s) - x_o(c,t = 2026,s) \tag{A-2}$$

and

$$t_h(s,d) = \begin{cases} 2026, if\ s \in [SSP1, SSP5] \wedge d(c,s) \leq 0 \\ \quad or\ s \in [SSP3, SSP4] \wedge d(c,s) > 0 \\[2ex] 2031, if\ s = SSP2 \\[2ex] \quad if\ s \in [SSP1, SSP5] \wedge d(c,s) > 0 \\ 2036\ or\ s \in [SSP3, SSP4] \wedge d(c,s) \leq 0 \end{cases} \tag{A-3}$$

where $x_u(c,t,s)$ is the updated GDP per capita of country c, in year t and for SSP s ($s \in$ [SSP1, SSP2, SSP3, SSP4, SSP5]), $x_{wdi}(c,t)$ and $x_{weo}(c,t)$ are the GDP per capita from the WDI and WEO databases, respectively, $x_o(c,t,s)$ is the original GDP per capita available from the IIASA database, $d(c,s)$ the difference between the updated and original GDP per capita in the year 2026, and $t_h(s,d)$ the starting year of the period of convergence back to the original GDP per capita. $t_h(s,d)$ follows the underlying SSP storylines shown in Table B1 and illustrated in Fig. B1.

The population harmonization method can be described as:

$$P_h(c,t,s) = \begin{cases} P_{wdi}(c,t,), \textit{if } t \leq 2020 \\ P_h(c,t-1,s)\dfrac{P_{peap}(c,t)}{P_{peap}(c,t-1)}, \textit{if } 2020 < t \leq 2026 \\ P_h(c,t-1,s) = \dfrac{P_u(c,t-1,s)}{P_u(c,t-1,s)} \textit{ if} 2026 < t \leq 2100 \end{cases} \tag{A-4}$$

where $P_{wdi}(c,t)$, $P_{peap}(c,t)$ and $P_u(c,t,s)$ are the population of country c in year t and for SSP s, of WDI, PEAP and Lutz et al. (2018) and K. C., S (2020), respectively.

Table B1

SSP scenario-specific assumptions and quantifications for TFP-related growth drivers, extracted from Tables 1 and 2 in Dellink et al. (2017). "Convergence speed" refers to the income convergence speed of lower-income countries to the income of countries at the frontier, and "Openness" to trade-openness.

	SSP1	SSP2	SSP3	SSP4	SSP5
Scenario assumptions					
TFP frontier growth	Medium	Medium	Low	Medium	High
Convergence speed	High	Medium	Low	LI[1]: Low MI: medium HI: medium	High
Openness	Medium	Medium	Low	LI: Low MI: medium HI: medium	High
Scenario quantifications					
TFP frontier growth (annual growth rate)	1.0%	1.1%	0.6%	1.2%	1.6%
Convergence speed (deviation from SSP2)	+0.05	0	−0.015	LI: −0.025 MI: +0.01 HI: +0.05	+0.09
Openness (deviation from SSP2)	0	0	−0.1	LI: −0.1 MI: 0 HI: 0	+0.1

[1] LI = Low Income, MI = Middle Income, HI = High Income.

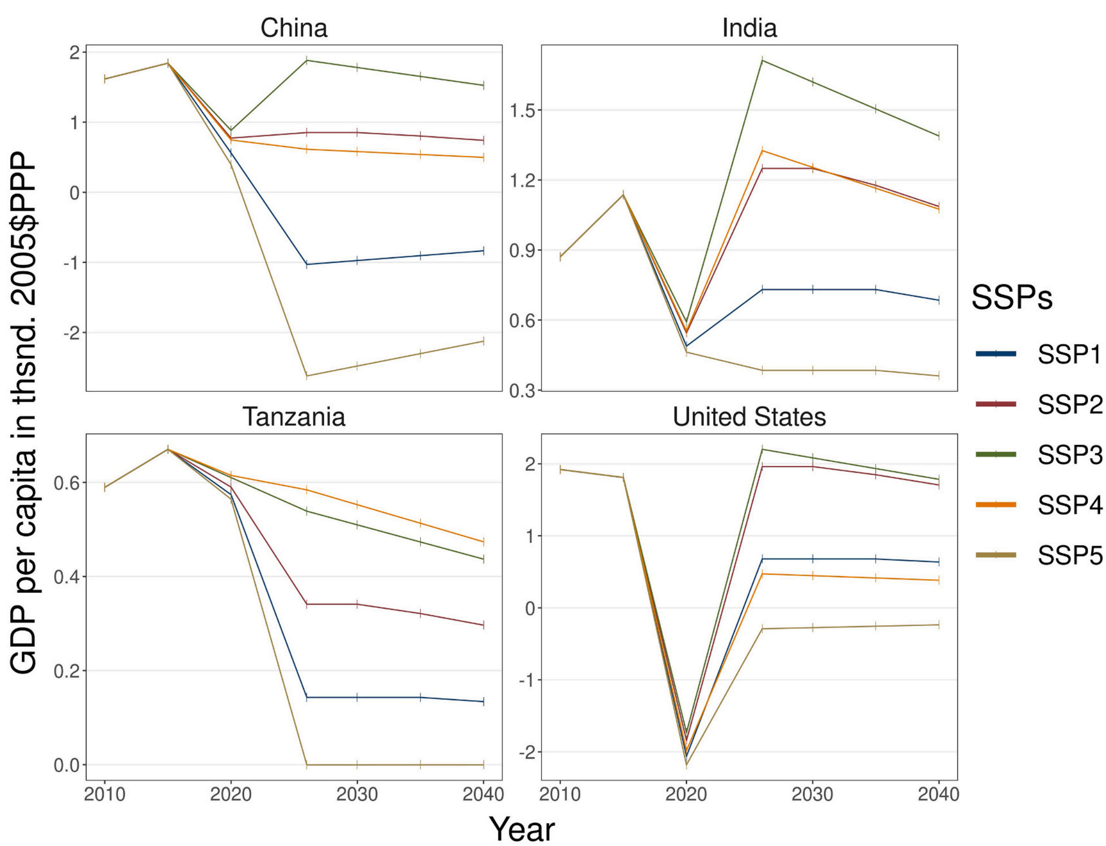

Fig. B1. Difference between updated and original GDP per capita. Depending on the SSP and the sign of the difference in 2026, the absolute difference is either kept constant for 5 or 10 years, or reduced immediately. See Section 2.3.2.

Appendix C. Country to region mapping

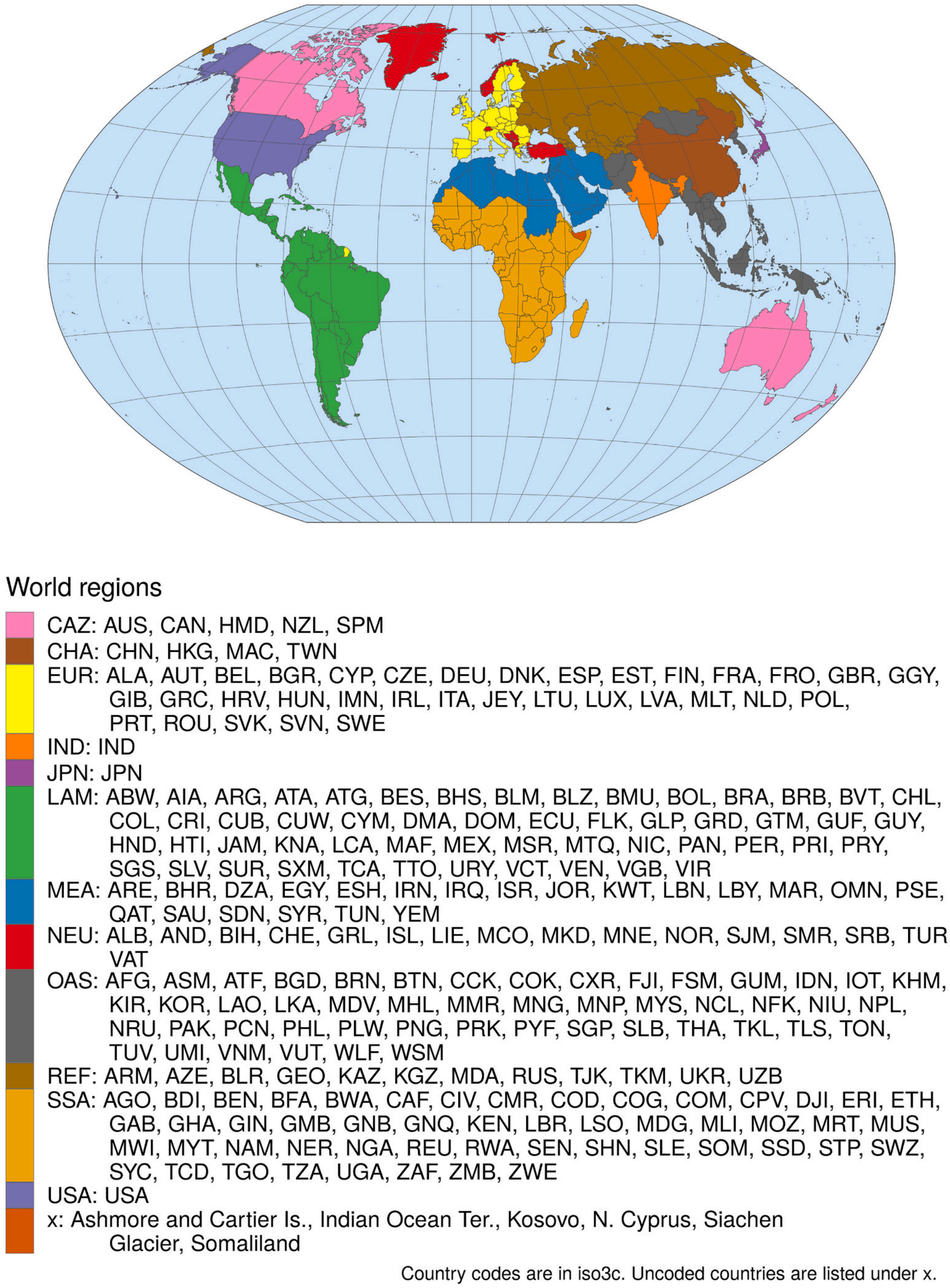

Fig. C1. Country to region mapping.

World regions:

- USA = United States of America
- EUR = EU27 and United Kingdom
- JPN = Japan
- CHA = China and Hongkong
- IND = India
- REF = Reforming economies including Russia
- SSA = Sub-Saharan Africa (including Republic of South Africa)
- MEA = Middle East and North Africa
- LAM = Latin America
- OAS = Other Asia (Central and South-East Asia)
- CAZ = Canada, Australia, New Zealand

- NEU = Non-EU European countries.

Appendix D. Changes in GDP per capita

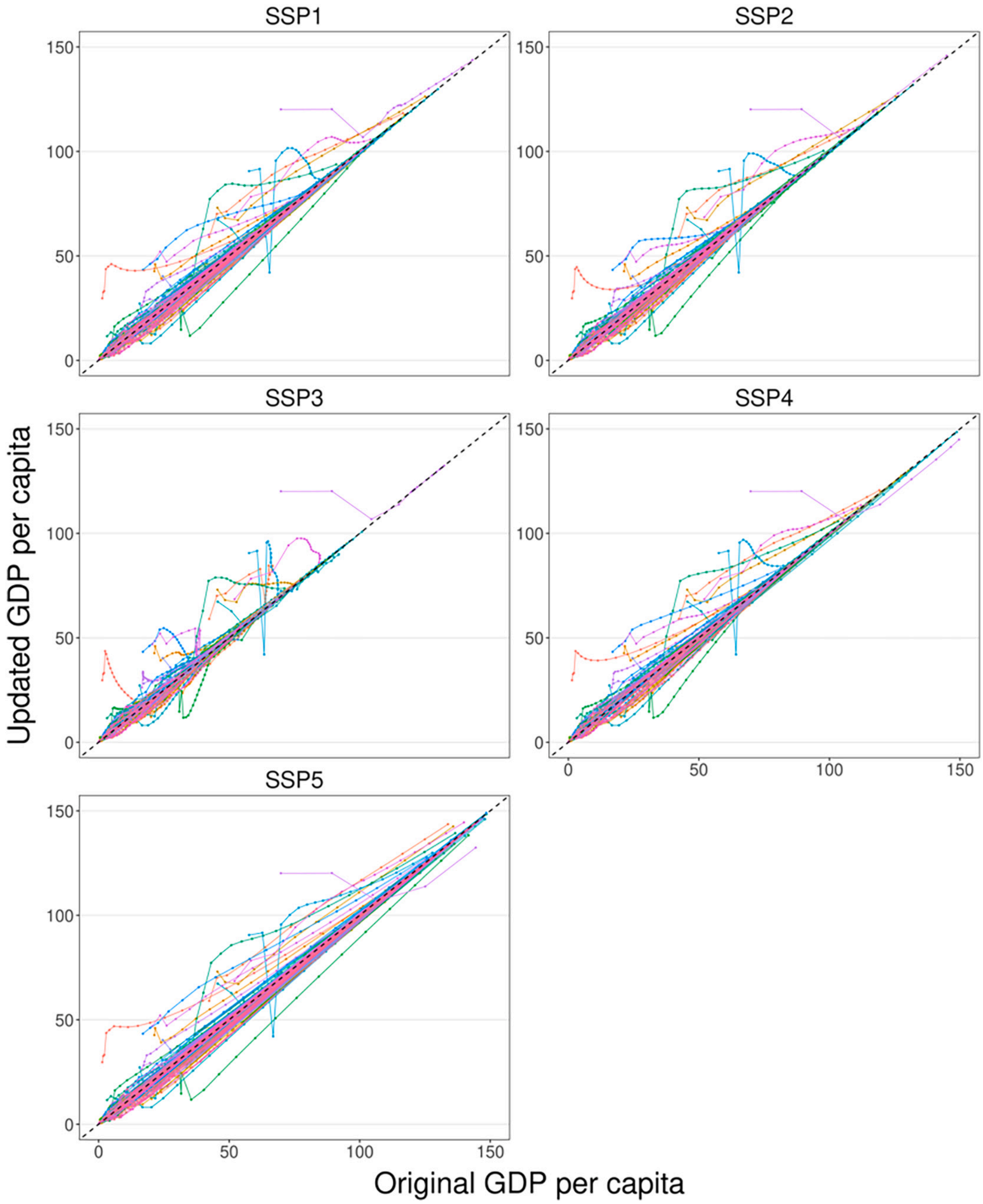

Fig. D1. Updated vs original GDP per capita in 2005$PPP, for 183 countries between 2010 and 2100. Every point is a country-year value, and every color is a country. Most countries are close to the 45° diagonal with only a couple displaying very large differences between updated and original scenarios. All countries have one point (the point corresponding to their 2100 value) directly on the diagonal.

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