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Climate change mitigation costs reduction caused by socioeconomic-technological transitions

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Numerical scenarios generated by Integrated Assessment Models describing future energy and land-use systems that attain climate change mitigation goals have been considered important sources of guidance for climate policymaking. The climate change mitigation cost is one of the concerns in the emissions reduction efforts. However, how to moderate climate change mitigation costs is not well understood. Here, we describe the conditions needed for reducing or taking away climate change mitigation costs by implementing socioeconomic-technological transitions into numerical scenario assessment. The results indicate that integration of multiple socioeconomic-technological transitions would be effective, including lowering energy demand, shifting to an environmentally friendly food system, energy technology progress and the stimulus of capital formation that is additionally imposed to the normal carbon pricing mechanism. No single measure is sufficient to fully take away mitigation costs. These results indicate that cross-sectoral transformation is needed, as the realisation of all measures depends on effective government policies as well as uncertain social and technological changes.

npj Climate Action (2023)2:9 ; https://doi.org/10.1038/s44168-023-00041-w

INTRODUCTION

The Paris Agreement (PA)[1] defines an international long-term climate change mitigation goal of limiting the increase in global average temperature to well below 2 °C above pre-industrial levels and encourages pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels. The scenarios for achieving global climate mitigation goals have been intensively assessed and compiled in the literature[2–4], including in Intergovernmental Panel on Climate Change (IPCC) reports[5,6], supporting international and national climate policy formulation. These assessments present, primarily, the energy system and land-use conditions needed to attain climate change mitigation goals, as these sectors are currently the largest sources of greenhouse gas (GHG) emissions. Numerical scenarios are essential for national policymakers who aim to shift human society toward carbon-neutral measures using political instruments.

From an economic perspective, the climate change mitigation cost is one of the concerns for the climate policy[7]. They are typically measured by GDP, consumption or welfare losses as relative changes compared with baselines or reference scenarios which excludes climate mitigation actions[6]. Most existing studies and also IPCC sixth assessment report (AR6) indicated that there would be positive mitigation cost which is also correlated with the stringency of emissions reduction[8,9]. How to moderate these costs would be essentially important for policymakers. Some researches have examined to address that question. Energy-demand changes via either energy efficiency and/or lifestyle changes could reduce the mitigation cost[10–13]. Some find that climate change mitigation could increase the GDP implying that mitigation cost is negative. The studies based on a macroeconomic modelling framework[14–16] assume that climate change mitigation would induce green investments which do not crowd-out investment in other parts of the economy- and therefore offers an economic stimulus. Another example is Stern review[17] which showed the negative mitigation cost under optimistic technological assumptions. There is also examination made by RICE model, which implemented induced technological progress[18]. Looking at national studies, Dai et al.[19] focused on China's long-term scenarios and indicated that renewable energy development could lead to a positive feedback in the macroeconomy. While earlier studies provide meaningful information on mitigation cost, there is room to investigate emissions reduction strategies that do not impair economic growth. The literature addressing this topic to date remains rather limited and unclear about the types of efforts or policies required.

Here, we show the conditions needed for reducing or taking away the climate change mitigation cost under a wide range of stringent carbon budgets spanning global mean temperature increases of 1.5 to 2.0 °C relative to the pre-industrial level[5]. To capture the effects of a wide range of societal changes in addition to carbon pricing, we considered four major socioeconomic-technological transition, namely, lowering energy demand[20] in conjunction with enhancement of electrification[21], technological progress in the energy-supply system leading to renewable and carbon capture and storage (CCS) cost reduction[21], shifting to environmentally friendly food consumption including low-meat diets and a reduction of food waste[22,23], stimulus of capital formation (this is general capital, which can be used by all sectors). Socioeconomic-technological transition in this paper is defined as the societal or technological changes that can ease the GHG emissions reduction and moderate its cost, which additionally happens to the future baseline assumptions and the ordinal responses to carbon pricing. While a similar idea was attempted in the earlier studies[24] to distinguish the effects of different policy interventions on short- and long-run mitigation costs, here we investigate mainly the macroeconomic impacts by using a computable general equilibrium model that can assess details of the economic interactions. We also examined one more scenario that implemented all of these measures. We designated these

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scenarios "Energy-Demand-Change (EDC)", "Energy-Supply-Change (ESC)", "Food-System-Transformation (FST)", "Additional-Capital-Formation (ACF)", and "Integrated-Social-technological Transition (IST)" scenarios, respectively. Each scenario includes unique measures for boosting the economy, which are discussed in the "Methods and Results" section where we discuss how they are contextualised by previous studies. The default socioeconomic assumptions behind the scenarios are based on the middle-of-the-road scenario of the Shared Socioeconomic Pathways (SSP2). On top of these default conditions, we implement the social transformative options. In this study, we define the climate change mitigation cost non-positive condition as showing no adverse effect on Gross Domestic Product (GDP) from climate change mitigation, and here we use global total cumulative GDP loss over the period from 2021 to 2100 expressed as net present value (NPV). It should be noted that energy supply and demand, and food system, would respond to carbon pricing even under the default mitigation scenarios. Thus, the above assumptions in each sector should be interpreted as additional measures to the ordinal responses to the carbon price. In other words, energy and food system changes happen in all scenarios in conjunction with additional social-technological transformative measures.

While our primary focus is to analyse the mitigation cost, we also conducted an additional assessment comparing the mitigation cost with air pollution costs[25–27] and climate change impact damage costs (see Methods), which intends to add the possibility to make another interpretation of this mitigation cost decrease. Currently, there is limited available information to quantify and monetise the value of co-benefit of climate change mitigation efforts and, therefore, we only considered the impacts of air pollution and climate change. However, it should be recognised that there were a number of important social factors, such as energy security, poverty and the health benefits of transport choices, which we did not take into account in this study.

RESULTS

Mitigation cost and the effects of socioeconomic-technological transitions

The main argument presented in the results section is the need to use GDP loss reduction, which is the GDP loss in the default scenarios minus the loss in the socioeconomic-technological transition scenarios. Total costs of global climate change mitigation are projected to range from 1 to 7% of GDP per year in the literature that summarises the latest available mitigation scenarios[28]. For a carbon budget of 1000 Gt CO_2, our estimates fall within this range (see green circle in Fig. 1a). These costs are associated with additional energy system costs related to decarbonising the energy system, non-CO_2 emissions abatement and economic structural changes. The mitigation cost is inversely correlated with the carbon budget, which is consistent with previous reports[29]. The periodic mitigation cost over this century is illustrated in Fig. 1c. Mitigation costs are relatively large in the first part of this century, while the absolute cost (not relative to GDP) increases continuously over time (see Supplementary Fig. 1). This periodic tendency is apparent regardless of carbon budgets and, as the budget becomes tighter, the magnitude of the cost increases (Supplementary Fig. 1). CO_2 emissions reach net zero at mid-century, around 2050–2070, leading to drastic energy and land-use transformations (Supplementary Figs. 2, 3, 4). Note that the magnitude and periodic characteristics of emissions and mitigation costs are highly dependent on the model used, due to differences in model structures and parameters (see Supplementary Fig. 5, based on the IPCC database).

The costs of climate change mitigation can be moderated through socioeconomic-technological transition (Fig. 1). Even if such measures are implemented alone, there would be a benefit compared to default scenarios. Full implementation of all socioeconomic-technological transition measures (IST) allows mitigation costs to reach almost zero or even become negative for most carbon budgets, indicating that the non-positive condition is met (Fig. 1a). The scenarios in which carbon budgets are larger than 700 Gt CO_2 have negative mitigation costs, meaning mitigation would be beneficial over inaction. As the carbon budget tightens, the degree of the GDP loss decreases. For the budget of 500 Gt CO_2, 3.9% recovery occurs from the default case and the reduction effects are smaller than under a budget of 1000 Gt CO_2. Thus, a larger carbon budget may provide a better opportunity to abrogate completely the GDP loss associated with climate change mitigation. This finding leads to a conclusion that stronger climate mitigation goals will make it more difficult to become non-positive cost.

In some cases, the early part of this century exhibits GDP losses, but the cost approaches the neutral line around mid-century and becomes strongly negative in the second half of century under a budget of 1000 Gt CO_2 (Fig. 1c). At the end of the century, GDP shows 4.0% gain (-4.0% GDP loss). The other budget cases show similar tendencies (Fig. 1e).

The Additional-Investment scenario provides the largest GDP loss reduction among the four measures by around 1.4% (purple circle in Fig. 1a). The assumptions behind Additional-Investment include incremental 1% increases in capital formation, which might appear small, but eventually became the largest contributor. Energy-Supply-Change follows Additional-Investment, with GDP loss reduction of around 1.0%. Food-System-Transformation and Energy-Demand-Change would almost equally contribute to the recovery of GDP losses, with impacts of 0.62% and 0.53%, respectively. The effectiveness of these measures in the early period, such as during the first part of this century are small and did not vary among measures (Fig. 1c), whereas the long-term effects of Additional-Investment in the latter part or end of the century are substantial. In 2100, the Additional-Investment scenario exhibits 3.7% GDP gain. Other measures such as Energy-Supply-Change and Energy-Demand-Change show relatively small gains in 2100 of 1.6% and 1.1%, respectively.

Cost decreases for renewable energy production (e.g. solar and wind) are often considered the largest factor. Our results indicate that such changes may be part of the growth drivers, but their contribution is limited. More importantly, their effects in our scenario are more prominent in the short term than the long term. Investment effects are essentially driven by cumulative capital inputs, which would be largest in the second half of the century (Fig. 1c).

Surprisingly, the total macroeconomic impact of the integration scenario is almost the same as the summation of the individual scenarios although there are some interactions among the social transformative changes (Fig. 1d).

Mechanisms of decrease in climate change mitigation costs

As indicated in the previous section, individual socioeconomic-technological transition measures have differing effects on GDP growth. We conducted decomposition analysis of GDP loss reduction to identify such factors (see "Methods" and Fig. 2). We decomposed the GDP recoveries from the default scenario case using sector-wise assessments of "Value-added", "Output/Value-added", and "Final-Demand/Output". These terms represent activity level, productivity, and consumption efficiency, respectively.

The Additional-Investment condition directly boosts GDP production by adding to the capital stock (Fig. 2a and Supplementary Fig. 6). The increase in capital stock has a cumulative effect, leading to an additional 6% increase at the end of this century compared with the default scenario. The figure indicates quite small differences, but it is apparent that the impacts to GDP loss rates is substantial. These changes result in

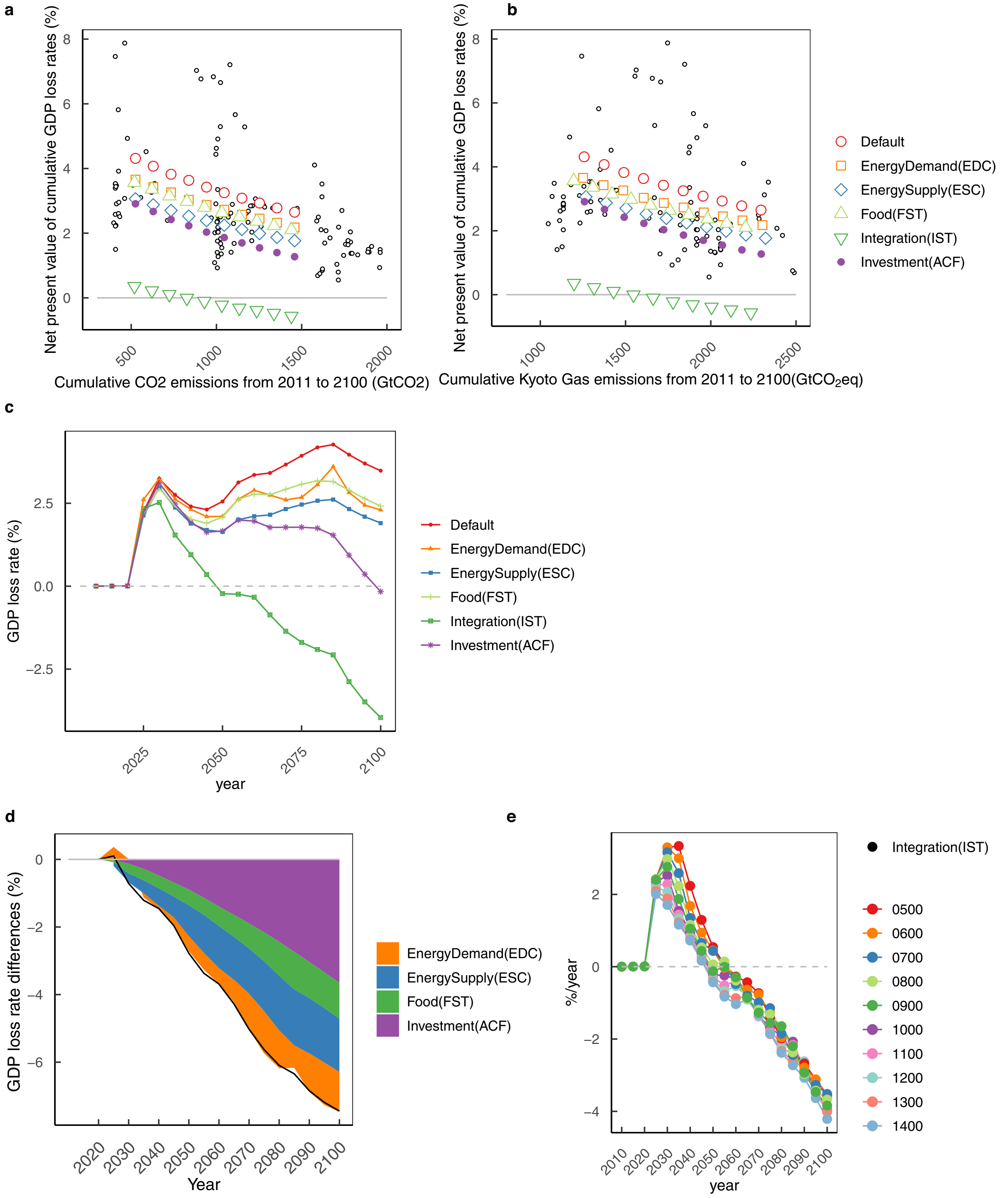

Fig. 1 Global policy costs associated with climate change mitigation (GDP loss rates). **a**, **b** Net present value of global cumulative GDP loss rates under various scenarios (coloured symbols) and IPCC SR1.5 literature values (black circles) against cumulative CO_2 (**a**) and Kyoto gas (**b**) emissions from 2011 to 2100. **c** Periodic global GDP loss rates associated with socioeconomic-technological transition measures under a 1000-Gt CO_2 budget. **d** Global GDP loss recovery rates of individual components from default socioeconomic conditions to socioeconomic-technological transition cases. **e** GDP loss rates of full-integration scenarios under various carbon budgets.

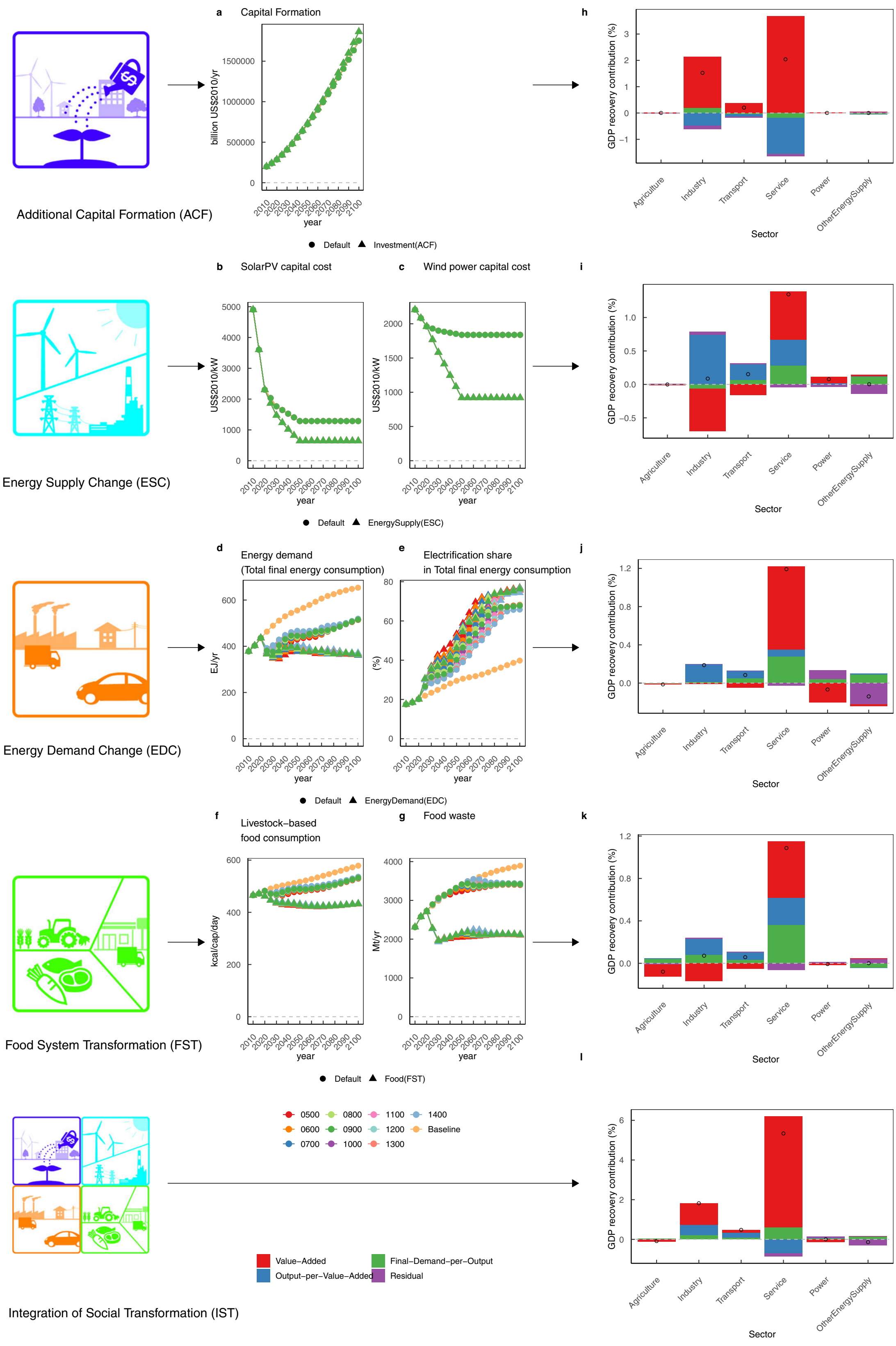

Fig. 2 Mechanism of GDP loss reduction associated with socioeconomic-technological transition and decomposition analysis of GDP loss reduction from the default to socioeconomic-technological transition scenarios under a 1000-Gt CO_2 budget for 2100. Global capital stock, capital cost of solar photovoltaic (PV) and wind turbine technologies, final energy consumption and electrification rates, livestock-based food consumption and food waste generation under various socioeconomic-technological transition scenarios with a 1000-Gt CO_2 budget (**a**, **b**, **c**, **d**, **e**, **f**, **g**, respectively). **h**, **i**, **j**, **k**, **l** Shows decomposition analyses of GDP loss reduction by sector. The black circles indicate the total net impacts on GDP loss reduction by sector. All values are expressed in terms of % of overall GDP with different y-axis ranges.

increased activity levels, mainly in the industrial and service sectors, while productivity decreases slightly (Fig. 2h). This productivity decrease occurs because labour is fixed and only capital is added, which causes an imbalance in production compared with the default case. It should be noted that in the household sector, the additional saving to realise additional investment would remove some of the opportunity for consumption and the energy demand is lower than the default value in the first part of the century, which could also involve further energy-supply side change, leading to a decrease in carbon prices, leading to a decrease in carbon prices. As the capital accumulation effect increased, the carbon price becomes higher than the default scenario (Supplementary Fig. 7).

The Energy-Supply-Change condition primarily induces cost reductions in electricity generation, resulting in a relatively large share of energy being renewable. Then, the average electricity price decreases, which increases electricity demand, leading to an increase in activity levels (Fig. 2b, c). This energy price decrease is beneficial to all sectors and, therefore, productivity rises. In particular, indirect effects on the service sector are the main driver of GDP loss reduction (Fig. 2i). Energy-Supply-Change includes two main pathways for moderating mitigation costs, namely, cost decreases for renewable energy and CCS. We examined which factor, renewable energy or CCS, is the major player in GDP loss reduction by modelling sensitivity scenarios to isolate these factors. The results show that the renewable energy and CCS cost decreases account for recovery of 0.7% and 0.3% of GDP respectively, indicating that cost decreases related to renewable energy would have a stronger influence than CCS. Consumption efficiency improvement was also observed in the service sector and was caused by a decrease in the energy-supply sector's intermediate inputs. As a consequent, the share of household consumption in the total output (output-intermediate inputs) increased. Regarding the CCS amount, the CCS carbon sequestration amount reaches around 15GtCO$_2$/year in 2050 in the default 1000-GtCO scenario. While this value is around the middle of the range in the AR6 database, it positions relatively higher in the entire database. CCS implementation as Giga-ton per annual scale globally should have many challenges. The earlier literature[30] argues that there would be such as (1) a potential decline in the injection rate under long-term uses, (2) the higher the injection rate, the decline could happen, and (3) there must be the local context that would limit the CCS potential which should be investigated regionally. Considering these points, it might be better to interpret our scenarios as it implicitly includes the condition that overcomes many obstacles related to the large-scale CCS implementation.

The Energy-Demand-Change scenario decreases the demand for fossil fuels (Fig. 2d) and enhances electrification, which reduces the volume of "other energy supply" (Fig. 2j). Two factors facing the power sector may reduce the GDP loss, namely, electrification and energy savings (Fig. 2e), but the results indicate decreases related to these processes. The magnitude of the predicted changes is small relative to other energy-supply factors. This supply-side energy decrease causes capital and labour to shift to other industries, supporting GDP loss reduction. The contributions to GDP loss reduction varied among energy-demand sectors (industry, transport, and service), but the original sectoral scale appears to determine the magnitude of GDP loss reduction, making the service sector effect prominent.

The Food-System-Transformation condition includes three pathways for lowering mitigation costs. First, reductions in livestock-based food demand and food waste (Fig. 2f, g) directly reduce the demand for food production, leading to low mitigation costs for non-CO$_2$ (CH$_4$ and N$_2$O) emissions from the agricultural sector (Supplementary Fig. 8). Second, decreases in meat demand lessen demand for pasture area, which expands the potential for afforestation. Third, a portion of the production factors, labour and capital used for production activities in the agricultural sector under the default scenario, could be transferred to more productive sectors, such as the manufacturing and service sectors, thereby increasing total economic productivity. Small agricultural activity decreases are apparent under this scenario, which are eventually compensated by service sector increases (Fig. 2k). The total effect of Food-System-Transformation over this century is not as large as that of energy system transformation in terms of GDP loss recovery; however, the decreases in CH$_4$ and N$_2$O emissions contribute to reduced total GHG emissions, causing small decreases in the global mean temperature increase at the end of this century (Supplementary Fig. 9).

In the integrated scenario, these effects are generally additive, and the interaction effects are small (Fig. 2l). A similar trend was apparent in 2050 and 2100, as well as under other carbon budgets (Supplementary Fig. 10).

Regional implications of social transformative measures

The implications of social transformative measures differ among regions (Fig. 3a). The degree of total mitigation cost recovery differs among regions, with generally progressive results. This trend occurs because the mitigation costs without socioeconomic-technological transition measures are regressive, as reported previously[31]. Comparing measures for Organisation for Economic Co-operation and Development (OECD) countries, Additional-Capital-Formation is relatively important, accounting for around 60% of the total impact. In contrast, Additional-Capital-Formation in reforming regions accounts for only around 20%, which is the lowest value among the five aggregated regions (Fig. 3b). Because reforming regions have greater mitigation cost rates than other regions even under the default scenarios (Fig. 3a), which may be due in part to dependence on fossil fuels and low energy efficiency (Fig. 3c, d), measures to improve the energy system could be more effective in such regions (Fig. 3b). The Middle East and Africa (MAF) show a big impact from Food-System-Transformation, driven by the large share of agricultural value added in total GDP although the livestock originated food consumption share in the total calorific intake is not so large (Fig. 3e).

Sensitivity analysis of discount rates

The discount rate has long been a controversial topic related to the economics of climate change, and our results are also sensitive to assumptions related to this factor. The model simulates the GDP losses for each year recursively. We varied the discount rates, which changed the way that the total periodic GDP losses were combined. At the end of this century, a discount rate of 3% leads to zero or negative mitigation costs under the Integrated-Socioeconomic-technological transition scenario, as discussed above (Fig. 4c). A discount rate of 1% yields greater gains, whereas 5% shows a small positive mitigation cost (0.1 to 1.1%). In contrast, the results for 2030 and 2050 show consistently positive values from 1.9 to 2.9% and 1.0 to 2.4%, respectively, regardless of mitigation level (Fig. 4a, b). NPV results based on discount rates depend on the difference between periodic mitigation cost trajectories and the exponential curves of discount rates over the period, which has two main implications for this analysis. First, in the long term, socioeconomic-technological transition can carry almost zero or negative mitigation cost, even with high discount rates because social transformative measures become more effective year by year. Thus, within the context of intergenerational considerations, the mitigation cost can be either moderated or increased by those measures. Second, in the short term (e.g. 2030), the mitigation cost would not be much affected by socioeconomic-technological transition because the measures are not implemented suddenly and remain, regardless of the discount rates. Thus, a clear trade-off exists between intergenerational and short-term considerations.

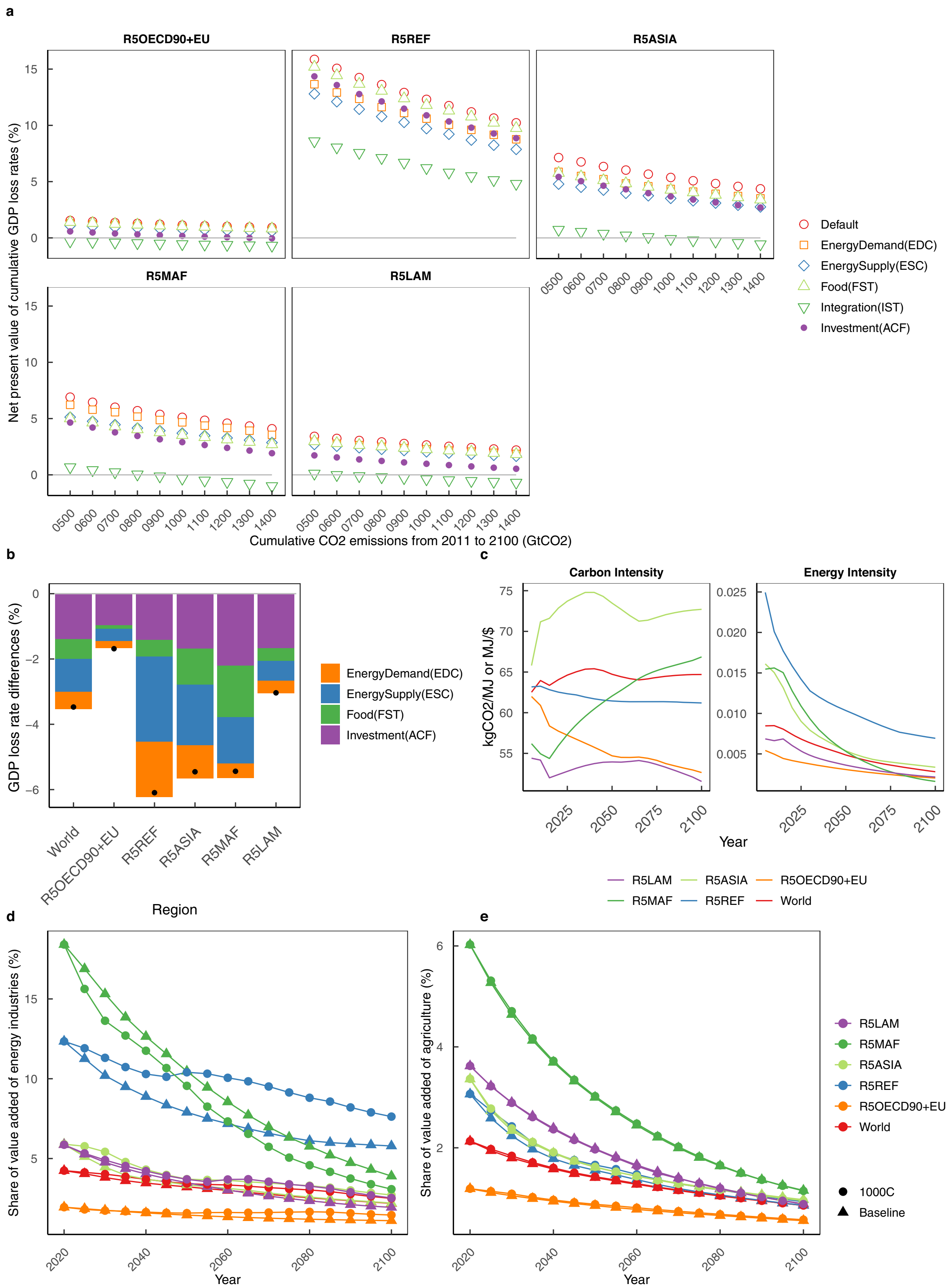

Fig. 3 Regional implications of socioeconomic-technological transition. **a** Regional cumulative GDP loss rates expressed as NPV. **b** Regional GDP loss recovery relative to the default scenario by region under a 1000-Gt budget. **c** Regional carbon and energy intensity (units, kgCO$_2$/MJ and MJ/$) in the baseline scenario. **d**, **e** Shares of value added by the energy, industrial, and agricultural sectors. Regional definitions are provided in Supplementary Note 1.

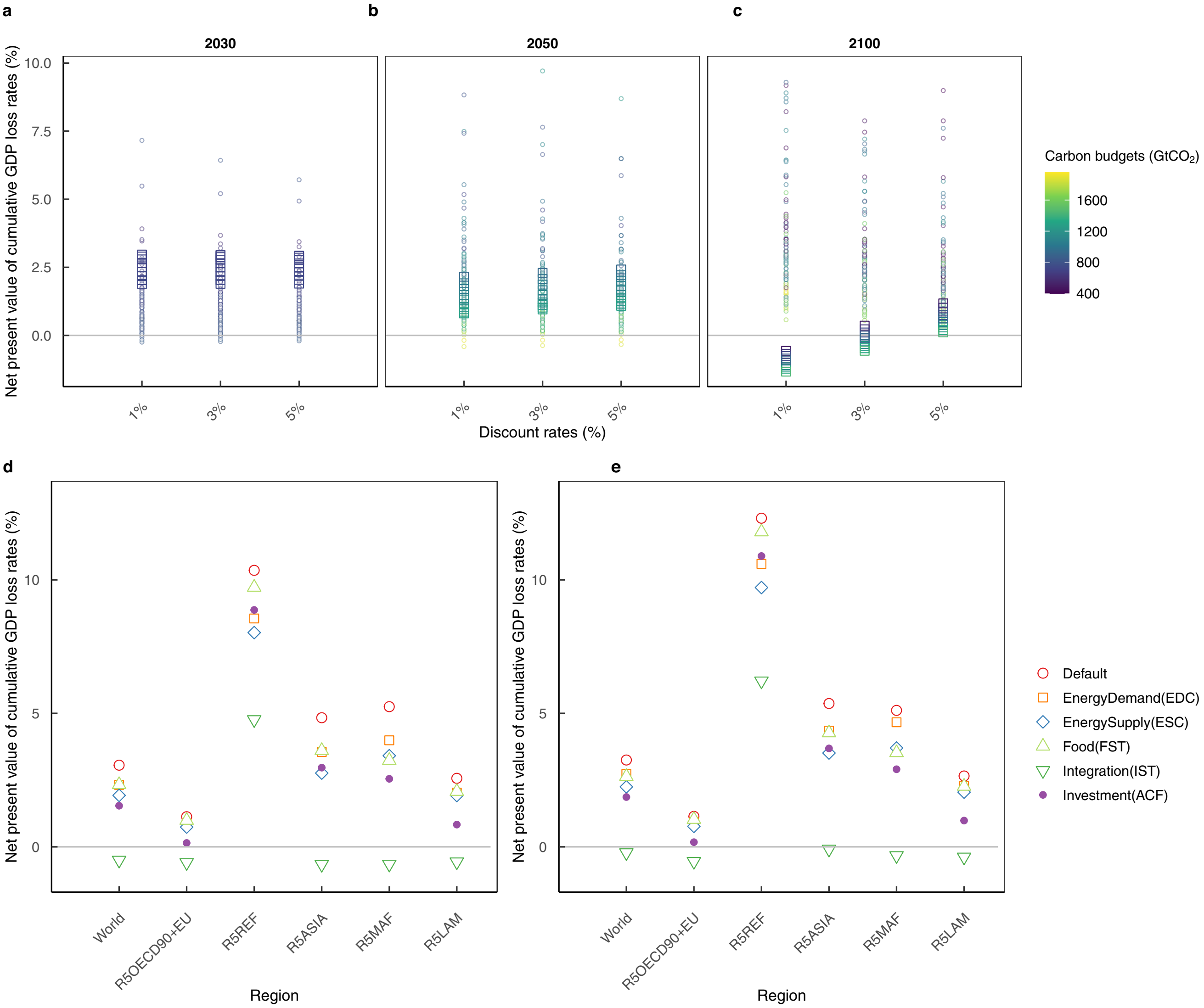

Fig. 4 Total accumulated policy costs expressed by net present value (NPV) of GDP losses. NPV variations by discount rate (**a**, **b**, **c**) and differences between immediate and delayed climate change actions (**d**, **e**) are presented. In panels **a**, **b**, **c**, squares and circles present IST scenarios and the rest of scenarios respectively. **d** Cost optimal without consideration of NDC implementation which means 2030's emissions levels are basically lower than with NDCs (**e**).

In our main analysis, we assumed that stringent mitigation efforts would begin immediately in 2021 but, until 2030, current Nationally Determined Contributions (NDCs) might pin the emissions reductions to certain levels[32,33]. We tested scenarios incorporating the current NDCs and confirmed that the overall results are similar to the main results, but small differences were observed (Fig. 4d, e). NDCs postpone the emissions reduction to later periods and may decrease short-term mitigation costs, but do not affect the GDP loss reduction level or the qualitative conclusions discussed above.

Inclusion of climate change impacts and health impacts associated with air pollution

We further assessed the impacts of climate change and air pollution implications to assess any other benefits to mitigation in conjunction with mitigation costs (Fig. 5). As indicated, while this assessment is not the study's main objective, we would like to add this information to allow another interpretation of this study. We found that climate change impacts and air pollution changes will provide additional gains but their orders of magnitude are smaller than the benefit of social transformative measures regardless of carbon budget and region. For example, the global total cumulative economic value of avoided climate change impacts until 2100 for the 500, 1000, and 1400 GtCO$_2$ carbon budgets are 0.88%, 0.78%, and 0.71% of GDP, respectively, while the air pollution reductions relative to the baseline scenario are 0.26%, 0.21%, and 0.16% of GDP, respectively. There is both temporal and spatial variation in these results (see more details in Supplementary Fig. 13). For example, the climate change impacts are relatively large in non-OECD regions such as Asia, Africa, and the Middle East, consistent with a previous study[34]. The air pollution co-benefits are relatively large in the mid-term (2050) compared to the long-term (2100) because the air pollution levels improved, allowing maximum air quality to be reach in the mid-century, when most scenarios have near-zero CO$_2$ emissions. We further discuss the uncertainties related to this assessment in the Methods.

DISCUSSION

We examined one of the illustrative examples of conditions to non-positive climate change mitigation costs under climate mitigation targets spanning the stringency range associated with

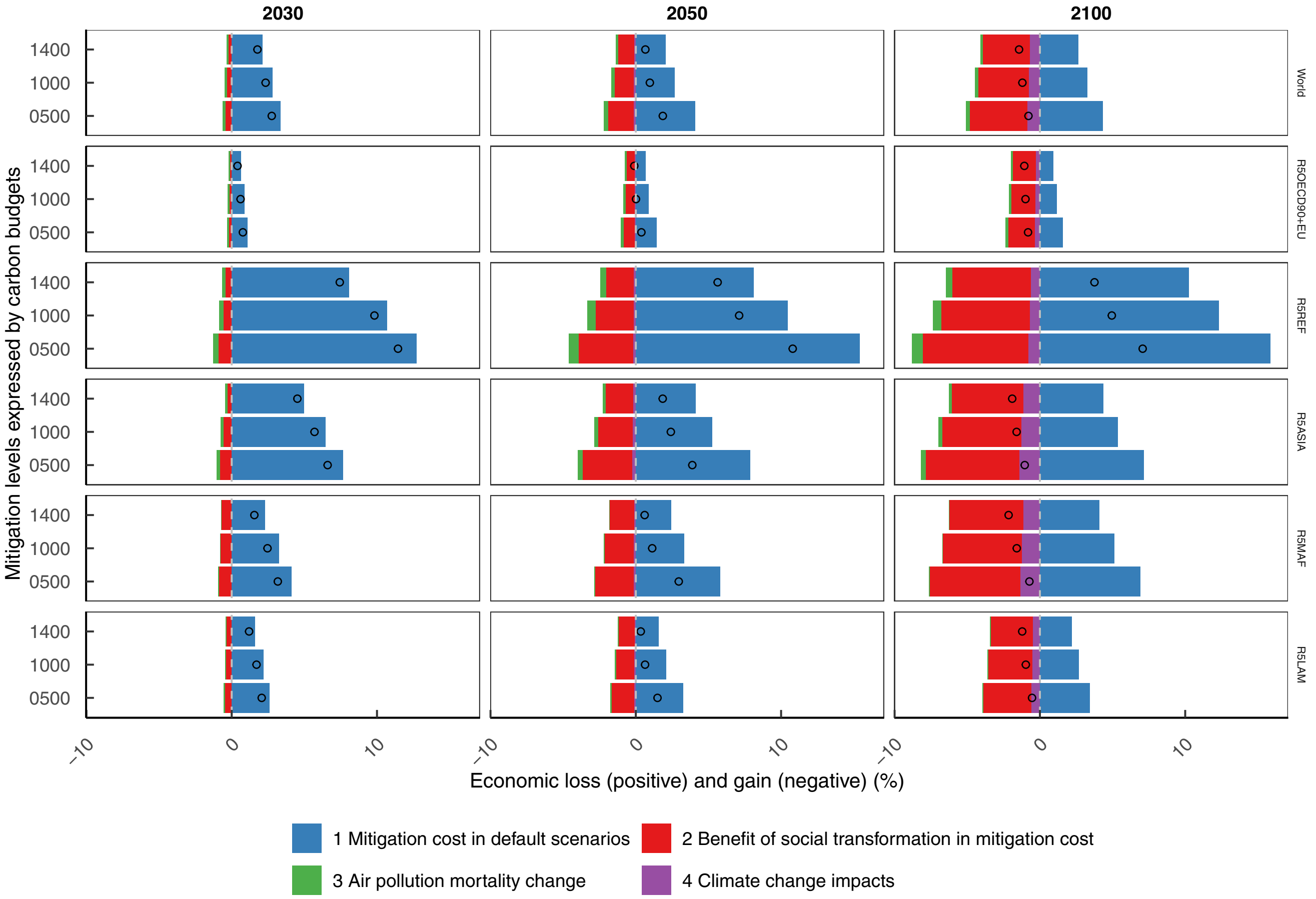

Fig. 5 Comparison of overall NPV economic costs for 3 years in terms of the world total and aggregated regions, and the carbon budget. All economic values are expressed in NPV from 2020 to each year of analysis. The “Mitigation cost in default scenarios” corresponds to the mitigation cost under default scenarios. “Benefit of socioeconomic-technological transition in mitigation cost” is derived from the GDP loss differences between the IST and default scenarios. “Climate change impacts” are the direct output of the emulator using the global mean temperature, which includes market and non-market sectors. “Air pollution mortality changes” are derived from the PM2.5 concentration generated by a chemical transport model, which was fed into the health impact function and monetised by the VSL (Value of Statistical Life) and the relative changes to baseline scenarios are presented.

global mean temperature increases from 1.5 to 2.0 °C relative to the pre-industrial level. We assessed how societal transformations can moderate or taken away the mitigation costs under several scenarios, including Energy-Demand-Change, Energy-Supply-Change, Food-System-Transformation, and Additional-Capital-Formation. Our scenarios showed that only integration of all of these measures could make the total cumulative mitigation cost non-positive. These changes can effectively boost the economy; however, no single measure is sufficient to meet the mitigation cost non-positive condition, indicating that societal transformation from multiple angles is required. It would be better to note that while there would be uncertainties in the estimation, our scenarios showed the decreases in climate change mitigation cost under some conditions. Also, the conditions used in this paper is not necessary condition and thus, there could be more possibilities to realise the above-mentioned conditions.

We defined the mitigation cost non-positive condition from the perspective of GDP growth and there should be at least two points that we should argue. First, it would also be useful to focus on household consumption rather than GDP, which consists of consumption, capital formation and net trade volume, because household consumption might be more relevant to human welfare. Naturally, Additional-Capital-Formation directly boosts production through capital formation, while consuming some income that otherwise would have been used for household consumption. Therefore, the mitigation cost non-positive condition, as defined based on household consumption, was not met under the scenarios in this study (Supplementary Fig. 11). This result implies that the additional investment linked with saving would consume a part of the income and would not be compensated for by the growth effects. This finding suggests that stronger measures than were included in our scenarios are needed by household consumption rather than economic growth. We also conducted a sensitivity analysis of capital formation by doubling the incremental capital formation from the original Additional-Capital-Formation scenario (0.1 to 0.2%). The results showed that GDP could be increased, but that was not necessarily the case for household consumption, particularly in the first part of this century (Supplementary Fig. 14). This implied that increasing investment would not eventually help to increase household welfare, and there is a need to consider the balance of capital formation and household consumption. It was also true that the disadvantage of this Additional-Capital-Formation scenario i.e. reduction of the household consumption in the first part of the century could be also complemented by the other social measures such as energy-demand reduction and dietary changes examined in this study. Second, the assessment of global total cumulative NPV GDP loss ignores temporal and spatial GDP conditions. As we have discussed in the results section, a reforming region still experienced large GDP losses even under the IST scenario. Furthermore, in all regions, there were positive GDP losses during the first part of the century. This implies that the current generation will not obtain GDP gains. We were unable to identify ways to overcome this problem and further investigations may be required, which should also consider inequality issues.

There are various factors that drive socioeconomic-technological transition. Some may be related to policy decisions (e.g. urban planning, investment in R&D), whereas others may be related to people's general behaviour (e.g. consumer choices and preferences on how to spend time and money). They could induce additional costs although we dealt with them as if costless. For example, technological progress may need investment in R&D which would eventually be a social cost. Another example is that in order to promote electrification more than the levels beyond simple carbon pricing effects, additional energy consumption-related device costs such as subsidies would be needed. Here we admit that we cannot quantify such cost required to realise socioeconomic-technological transition, and it would be better to interpret our results as reference information for use in consideration of relevant policies. For instance, R&D for solar and wind panel technological development might be worth reducing the GDP loss, but it would not be more than 1% of GDP. However, at the same time, it would be better to note that some new technologies can be invented unexpectedly, which can completely change the landscape of the market. There are also implicit or explicit costs associated with behavioural changes, which could also happen without costs through shifting in the awareness of environmental issues. Meanwhile, there could also be some challenges in behavioural changes. The demand-side transition is partly related to technological things but more closely linked with the behavioural changes which would not be easily realised without external forces. The supply side transition would be more concerned with technological things. Once the technology is advanced, such as assumed in this study, the transition might be realised. Also, the supply side and investment transition could be induced or enhanced by the economic measures.

Although we attempted to cover broad economic value changes associated with climate change mitigation, we admit that there are the inequality and employment issues that have been discussed associated with green growth but not addressed in this study[35]. Unfortunately, directly addressing these factors in our modelling framework would be difficult. Notably, unemployment is more relevant to short-term than long-term conditions. The inequality implications of climate change mitigation would be much greater concerns that could be associated with carbon pricing and industrial structural changes[36–38]. Moreover, accounting natural capital[39], such as ecosystem benefits may add more value although they were beyond the scope of our study. At the same time, it is also true that the attention of society is still largely focused on GDP growth. Furthermore, to the best of our knowledge, only limited previous studies have developed scenarios that can avoid climate change mitigation costs with societal changes. Therefore, this study contributes to the literature by highlighting the conditions required to compensate the climate change mitigation costs. We believe that our study will eventually stimulate a discussion of how to minimise the economic impacts as much as possible.

Assuming that mitigation cost can be non-positive, as shown in this study, the next question is how to transform society. Our scenario exercises implementing socioeconomic & technological transformative measures are based on SSP2 assumptions and selectively change four aspects, or combinations of them, from the conventional SSP2. Considering the original SSP concept and architecture, which should have been qualitatively and quantitatively internally consistent within each SSP, these additional social changes from SSP2 would be challenging and require more than a simple historical extension. These assumptions might give the impression that it violates the original SSP logic which is true because we do not follow the original SSP concept. However, meanwhile, we can explore the possibility that energy demand and supply technology conditions would change to somewhat SSP1 assumptions by climate change awareness while GDP and population are kept as SSP2. It would be better to note that such assumptions have been made in the past in some studies[20,21,40]. Obviously, technological progress and innovation must play critical roles. The government could promote these improvements by changing the existing tax system or other regulations, which would lead to changes such as increased research and development expenditures for greening the economy. Another possible mechanism involves leadership guiding the direction of society to promote technological innovation. This process would require not only specific environmental policies but also broader industrial policies that consider carbon neutrality. Food system transformation, again, may rely on technological improvements, such as the development of artificial meat. However, more importantly, the environmental and health consciousness of individuals would be critical to reducing meat consumption[41,42]. For Additional-Capital-Formation, the assumptions in our scenarios might be interpreted as unrealistic. However, serious concern for future generations could lead to prioritisation of future consumption and savings of current money, providing many opportunities to change investment behaviour via Environment, Social and Governance (ESG) policies. In that sense, behavioural changes in investment occur naturally with changes in environmental and inter-generational consciousness.

Our findings open many new avenues for further research. The central question of such research is how the societal transformation assumed in this study can be realised. This could be addressed through modelling that extends the current framework by incorporating more granularity in the sectoral and regional data, or by improving the realism of the energy and food demand models used to assess feasibility. These changes may require additional data collection, including microdata such as household or industrial surveys. Whether behavioural changes in saving and investment associated with environmental consciousness will occur, and the degree of such changes, remain open topics for discussion. These factors are related to the on-going discourse over short-term and long-term growth.

METHODS

Overview

We used the AIM (Asia-Pacific Integrated Model) modelling framework as a tool for scenario quantification, which allowed us to assess macroeconomic factors globally, including the energy system, land use, agriculture, GHG emissions and climate, and has been utilised in various global and national studies[43,44]. The core of the modelling framework is the computable general equilibrium (CGE) model AIM/Hub (formerly named AIM/CGE). Model details have been reported by Fujimori et al.[45].

For the climate change economic impact assessment, we applied an emulator that mimicked complex sector-wise regional impacts according to global mean temperature[46]. The air pollution implications were derived from GEOS-Chem[47], which is a state-of-the-art global chemical transport model, in conjunction with a health impact function[48]. Its assessment framework was also used in the Global Burden of Disease[49,50]. Finally, we calculated the VSL associated with death induced by air pollution.

We analysed multiple climate change mitigation scenarios classified in two-dimensional space consisting of socioeconomic-technological transition and the stringency of climate mitigation. All scenarios used SSP2 as the background socioeconomic assumption, which has been widely applied in the literature[51,52], and we ran the model for baseline conditions by assuming no carbon pricing, with the energy and land-use systems projected from their historical trends. We varied some specific socio-economic conditions, characterised as socioeconomic-technological transition, which are described below. These assumptions are additionally imposed normal carbon pricing to the mitigation scenarios. We conducted scenario analysis from 2021 to 2100. Further AIM model implementation of SSPs has been documented by Fujimori et al.[43].

Model

AIM/Hub is a one-year-step recursive-type dynamic general equilibrium model that covers all regions of the world. The AIM/Hub model includes 17 regions and 42 industrial classifications (Regional classification can be found in Supplementary Note and Supplementary Table 1). For appropriate assessment of the energy system, energy-supply technologies are disaggregated. Moreover, for bioenergy and land use, agricultural sectors are represented explicitly[53]. The details of the model structure and mathematical formulae have been described previously. Production sectors are assumed to maximise their profits through multi-nested constant elasticity substitution (CES) functions and input prices. Input energy and value added for the energy transformation sector are fixed coefficients of the output. They are treated in this manner to handle energy conversion efficiency appropriately for the energy transformation sector. Power generation values from several energy sources are combined using a logit function. This function was used to ensure energy balance, which is not guaranteed by the CES function. Moreover, curtailment and battery storage are represented within this framework as reported[54]. Household expenditures on each commodity type are described with a linear expenditure system function. The parameters adopted for the linear expenditure system function are recursively updated based on income elasticity assumptions[55]. Land use is determined through logit selection[53]. In addition to energy-related CO_2, CO_2 from other sources, CH_4, N_2O, and fluorinated gases (F-gases) are treated as GHGs in the model. Energy-related emissions are associated with fossil-fuel feedstock use. Non-energy-related CO_2 emissions include land-use changes and industrial processes. Land-use change emissions are derived from the change in forest area relative to the previous year, multiplied by the carbon stock density, which differs among global AEZs (agro-ecological zones). Non-energy-related emissions from sources other than land-use changes are assumed to be proportional to the level of each activity (such as output). CH_4 has a range of sources, led by rice production, livestock, fossil-fuel mining, and waste management. N_2O is emitted as a result of fertiliser application and livestock manure management as well as by the chemical industry. F-gases are emitted mainly from refrigerants used in air conditioners and industrial cooling devices. Air-pollutant gases (black carbon, CO, NH_3, non-methane volatile organic compounds, NO_X, organic compounds, and SO_2) are associated with both fuel combustion and activity levels. Emissions factors change over time with the implementation of air-pollutant removal technologies and related legislation.

The base year of AIM/Hub is 2005 and we utilised the recent energy information available in order to make the model results regarding energy supply and consumption mostly following the IEA Energy Balance Table until 2015[56]. While the latest statistics covers until 2020, considering the risk of taking the extreme cases in the latest statistics, and practical resources to maintain the model, we use the data until 2015. This could also lead underestimates of renewable energy penetration largely happening in the recent several years, which would be addressed in the forthcoming studies.

Regarding the data for AIM/Hub, the Global Trade Analysis Project (GTAP)[57] and energy balance tables[58] were used as the basis for the SAM, and data were reconciled with other available data, such as national accounting statistics[59]. The concept behind the reconciliation method id described in an earlier study[60]. Greenhouse gases and air-pollutant emissions were calibrated to the EDGAR4.2 database[61]. For the land-use and agricultural sectors, agricultural statistics[62], land-use representative concentration pathways (RCP) data[63], and GTAP data[64] were used as physical data. The quantity of agricultural consumption] was converted into caloric intake using a conversion factor derived from agricultural statistics[62]. Solar and wind resource energy potentials were obtained from a previous study[65], which calculated potentials using high-spatial-resolution data (0.5 arc-minute or ~1 km at the equator). Fossil-fuel resources were obtained from a previous study[66]. Technoeconomic information related to energy-supply facilities such as capital cost, operation cost and so on are basically set based on the information from the available information at around the year 2020 including IEA World Energy Outlook (IEA, 2019)[67] and so on.

Climate change impact assessment

We used an economic impact emulator, which is an open-source model that can produce multi-level regional aggregations (https://doi.org/10.5281/zenodo.4692496), to assess the impacts of climate change[46]. This emulator considers nine individual sector-specific, climate change impacts: agricultural productivity, undernourishment, heat-related excess mortality, cooling/heating demand, occupational-health costs, hydroelectric generation capacity, thermal power generation capacity, fluvial flooding, and coastal inundation due to climate change. The original estimates were based on process-based multiple GCMs and impact assessment models, and market values were quantified by AIM/Hub[34]. The performance of this emulator has been validated by comparing original process-based model results, which has fed into the emulator and outcomes of the emulator[34]. While this assessment initially took into account regional climate conditions and the uncertainty associated with GCMs, we used global mean temperature, which were calculated using a simplified climate model (MAGICC)[68]. Greenhouse gases and air-pollutant emissions computed by AIM/Hub were fed into MAGICC. The rates of economic loss relative to GDP are shown in Supplementary Fig. 15.

The impacts of climate change are uncertain. In this study, we relied on a single model representation[34,46]; however, several recent articles[69,70] have reported substantially larger impacts. The impacts of climate change are summarised in chapter 16 of working group 2 in the IPCC Sixth assessment report[71], and selected studies based on the Burke et al. method have predicted high levels of climate damage, while other studies have predicted that damage would be restricted to a smaller area. Moreover, previous studies have largely ignored adaptation potential. Thus, the benefits of avoiding climate change impacts could therefore be larger or smaller; however, our qualitative conclusion was unaffected because the GDP loss reduction associated with socioeconomic-technological transition measures had a much larger influence. If the economic impacts of climate change were more sensitive to changes in temperature than current estimates, our conclusions would be strengthened.

Calculation of the health impacts associated with air pollution

For the calculation of PM2.5 concentrations, we used GEOS-Chem, which was originally described by Bey et al.[47]. This is a global three-dimensional chemical transport model that includes detailed state-of-the-art gas–aerosol chemistry. GEOS-Chem is used by a large international community in a broad range of research on atmospheric chemistry, and is continually updated and openly accessible[72]. The model has been continually evaluated against atmospheric observations[73]. Emissions are aggregated, parameterised, and computed using the Harmonised

Emissions Component (HEMCO) described by Keller et al.[74]. The model is driven by the assimilated meteorology from the Goddard Earth Observing System-Forward Processing (GEOS-FP) product of the NASA Global Modelling and Assimilation Office (GMAO), using the GEOS-5.13.1 GCM at a global horizontal resolution of 4° × 5°. The climate condition was fixed for 2016 and the period from 1 October to 31 December was used as the model spin-up. One of caveat of this approach is that inter-annual climate variability and future climate change effects on transport and chemical processes are not considered. Transport and convection in the model rely on a 10 min time step, while chemistry and emissions use a 15 min time step. We used version 12.9.3.

For the emissions data, we spatially downscaled the AIM/Hub regionally aggregated future emissions (BC, CH_4, CO, NH3, N_2O, NO_x, OC, SO_x, VOC) scenarios to the 0.5° grid using the method described by Fujimori et al.[75]. The primary PM2.5 was derived from BC and OC and we took into account the relationships between BC and OC and PM2.5 emissions[76]. We used the ratios for these materials obtained from current emissions data[77]. For temporal downscaling, the monthly, daily, and hourly global anthropogenic emissions were obtained from the Community Emissions Data System (CEDS)[78]. Biogenic volatile organic compound emissions were obtained from the Model of Emissions of Gases and Aerosols from Nature (MEGAN)[79] and biomass burning emissions were obtained from the Global Fire Emissions Database version 4 (GFED4)[80].

The health impacts were derived from an integrated exposure–response (IER) function, which represents the relationship between annual average PM2.5 concentration and relative risk of cause-specific mortality compared to theoretical minimum-risk concentration[48]. The gridded population data were taken from Jones and O'Neill[81], and country-specific and age-specific 2010 mortality rates for both men and women were used to estimate the excess mortality due to PM2.5[82]. We assumed the same mortality rate as in the base year. Finally, we monetised the mortality by accounting for it as VSL[83].

There are multiple uncertainties in emissions downscaling, chemical transport, and health assessment models. More examinations using different modelling approaches could provide more robust insight. For example, a new approach based on a health assessment model has recently been proposed[84], which has yielded a much higher mortality than that from IER function. Considering the order of the magnitude of air pollution health impacts relative to the socioeconomic-technological transition impacts, this alternative approach would not change the qualitative conclusions. The methods used to monetise the value of life and their interpretation are controversial. We adopted a simple method used in previous studies[27,85,86], which considered income levels. Moreover, the relatively coarse spatial resolution of our atmospheric simulation could be a limitation of this study. We confirmed that the number of deaths was slightly higher than the Global Burden of Disease[87], which might be due to differences in pollution concentration data. However, within the context of our study, while these uncertainties could alter the numerical results, our qualitative conclusions may not be affected.

Scenarios

The basic socioeconomic assumptions behind of all scenarios are SSP2. The SSP2 scenario describes a future with median assumptions for input parameters, making it a relevant starting point for the analysis. For the mitigation scenarios, we apply carbon budgets corresponding to long-term climate goals throughout this century. In the model, we put global emissions constraint and then the carbon price occurs to meet that constraint. We employed a two-dimensional climate change mitigation scenario framework, as described above (Supplementary Table 2). The stringency of climate change mitigation was represented by carbon budgets ranging from 500 Gt CO_2 to 1400 Gt CO_2 at increments of 100 Gt CO_2 to determine the effects of the mitigation level in relation to the Paris Agreement. The Agreement recommends limiting global mean temperature in 2100 to well below 2 °C or 1.5 °C, considering the transient climate response to cumulative emissions of carbon (Rogelj et al.[28]). We modelled the lower limits, and for the upper limit we took the 67th percentile of 2 °C, which was 1170 $GtCO_2$ (from 2018) and was equivalent to 1400 $GtCO_2$ from 2011. Here, global annual emissions constraints for corresponding carbon budgets were determined using an intertemporal optimisation model, with a framework that had been applied in past studies[88] (Supplementary Fig. 7). In the sensitivity analysis, we analysed scenarios meeting the NDC emissions targets by 2030 and then switched to global climate action with a uniform carbon price (Supplementary Fig. 7). NDC pledges limit carbon budgets based on feasibility[89,90], and here we implement a 1000-Gt CO_2 scenario for comparison with the default immediate action scenarios.

Scenarios were analysed that represent types of socioeconomic-technological transition to explore the effects of socioeconomic-technological transitions on climate change mitigation cost. We tested four socioeconomic-technological transitions, namely Energy-Demand-Change, Energy-Supply-Change, Food-System-Transformation, and Additional-Capital-Formation. Conventionally, these changes are not represented as responses to carbon pricing in integrated assessment models and are, instead, treated as independent socioeconomic assumptions; however, we associated them with emissions reduction measures, which, in turn, had significant impacts on GHG emissions and the macroeconomy.

The Energy-Demand-Change is a scenario with accelerated progress of energy technologies, strengthened demand-side energy efficiency improvements, reduced energy service demand, and electrification. This social movement may be triggered by various climate mitigation policies. For example, a straightforward measure to promote these changes would be enhanced implementation of energy standards. Formulation of stringent long-term emissions targets can have the indirect but important effect of causing all actors in those countries to promote energy-demand reduction measures. Numerically, we implemented the SSP1[91] baseline energy-demand measures[43]. The autonomous energy efficiency improvement parameter and shared parameters for the logit selection of fuel type in energy-demand sectors are affected. The concept behind these assumptions was similar to that used in a previous study[20], but in those estimates (around 250 EJ/yr in 2100)[20] the reduction in energy-demand was not as large as in this study (360 EJ/yr in 2100 under the 1000 $GtCO_2$ case). It may nonetheless have a meaningful impact on the macroeconomy. The primary energy supply in this study, i.e. around 570 EJ/yr in 2100 under the 1000 $GtCO_2$ case, was larger than in van Vuuren et al.[21] and Grubler et al.[20] because the changes in the energy-supply side in these studies shifted to renewable energy, with smaller losses than in thermal power plants.

The Energy-Supply-Change scenario explores the possibility that energy supply-side technological progress is accelerated, specifically in relation to low-carbon energy. The conceptual aim of this scenario is similar to the scenario "Renewable electricity" scenario in van Vuuren et al.[21] but its actual implementation was slightly different. Costs associated with renewable energy generation (e.g. PV and wind) and storage of variable renewable energy (e.g. batteries) decrease more sharply than for the default case (Fig. 2b, c). In the meantime, CCS-related technology improves similarly, and the cost assumption is half of that in the default case. Such rapid technological progress is uncertain and cannot be easily attained by design. However, general environmental awareness and governmental leadership toward a carbon-neutral society would motivate companies involved in the development of these technologies to improve performance, which would eventually lead to cost reduction. Numerically, here we adopted the SSP1 assumptions for supply-side energy parameters[43]. We illustrate the primary energy supply in each scenario under a budget of 1000 Gt CO_2 in Supplementary Fig. 12.

Food-System-Transformation focuses on environmental (and health) awareness by the public in conjunction with actual implementation, rather than technological improvement. In our scenarios, we assumed that livestock-based food consumption is restrained and food waste is reduced (Fig. 2f, g). For livestock-based food consumption, calorie consumption is cut in developed countries and increases moderately in developing countries. For food waste, consumption-side food waste generation is halved as Sustainable Development Goal 11 is met. A similar concept and parameter assumptions to this scenario were adopted by Leclere et al.[22], in which the scenario was called demand-side efforts. While their focus was biodiversity, the idea could be applied in this study to derive the economic implications. Recently, some reports have indicated that a healthy diet could also provide benefits to the environment[42], and the dietary shift in this scenario meets both of those goals.

Additional-Capital-Formation is a scenario wherein more priority is placed on future generations, and consequently, some current consumption is shifted to investment. Numerically, an incremental 0.1% capital formation is added to the default case for each year (a 0.1% increase happens in all years), and this is assumed to last throughout this century. This additional investment can be realised by taking a part of income which compensates the household consumption. These behavioural changes in saving and investment would involve stimulating the on-going shift to environmentally responsible investment, with more focus on ESG factors and general awareness in the population. Changes in investment with the intention of greening the economy can be classified into short-term stimuli and long-term structural changes[92]. In this study, we can interpret this Additional-Capital-Formation scenario as a long-term change.

In the AR6[6], the concept of Illustrative Mitigation Pathway (IMP) was introduced, which differentiates the characteristics of the mitigation pathways. From that perspective, the combination of EDC and FST would be a part of IMP-LD. ESC could be similar to IMP-Ren, but ESC also includes other aspects. The earlier literature has never assessed ACF and is impossible to map with IMP.

For air quality assessment, we implemented a limited number of representative scenarios and selected the years for assessment based on the computational load. Specifically, the 500, 1000, and 1400 $GtCO_2$ carbon budgets, and years of 2020, 2030, 2050, and 2100 were chosen. We demonstrated the spatial PM2.5 concentration for the baseline and 1000 $GtCO_2$ cases (Supplementary Fig. 16). The intermediate years were interpolated linearly. The global total and aggregated regional population weighted PM2.5 concentration, number of premature deaths due to air pollution, and its associated value (expressed as VSL per GDP) under these scenarios are illustrated in Supplementary Fig. 17. We also examined whether the socioeconomic-technological transition and default scenario assumptions changed the air pollution implications by comparing the IST and default cases under 1000 $GtCO_2$. It was found that they had ignorable differences that were independent of the timescale (Supplementary Fig. 18).

Metric of mitigation cost

The main metric that we assessed is GDP loss reduction which is GDP loss in default scenarios minus those in socioeconomic-technological transition scenarios. The central discussion is made by we use global total cumulative GDP loss over the period from 2021 to 2100 expressed as NPV. This would imply that there can be some regions that the NPV GDP loss happens. Temporally, there would be also some period which has positive GDP losses. Moreover, GDP is not the best metric for inclusively representing human welfare, which we discuss in more depth in the discussion.

GDP loss can be caused by additional energy system costs, other non-energy-related GHG emissions abatement costs, and the consumption changes associated with changes in the costs of goods and services caused by carbon pricing. Additional energy system costs are needed to improve energy efficiency, electrification, and shifting energy production to renewable sources. The GDP loss reduction in this study means that the GDP losses are moderated by social transformative measures. For example, the decrease in renewable energy costs directly reduces the additional system cost of decarbonisation. Another example is the dietary shift from meat to alternative food items, which will decrease the number of cattle that emit CH_4, consequently mitigating the cost of CH_4 reduction. The same situation is applied to the cumulative mitigation costs expressed as NPV and annual basis GDP losses.

Decomposition analysis of GDP loss recovery

We conducted decomposition analysis of GDP loss recovery using the formula below.

$$GDP_{r,s,t} = \sum\nolimits_i FD_{r,s,t,i} = \sum\nolimits_i VA_{r,s,t,i} \cdot {}^{OP_{r,s,t,i}}/_{VA_{r,s,t,i}} \cdot {}^{FD_{r,s,t,i}}/_{OP_{r,s,t,i}} \quad r,s,t \in RST \tag{1}$$

where

$r, s, t \in RST$: a set of region r, scenario s and year t,

$FD_{r,s,t,i}$: Final demand (household consumption, government consumption, capital formation, and net export) for region r, scenario s, year t and sector i,

$OP_{r,s,t,i}$: Output for region r, scenario s, year t and sector i,

$VA_{r,s,t,i}$: Valued-added (capital, labour, land and resource rent inputs) for region r, scenario s, year t and sector i.

Then, we derive the following decomposition equation by taking the logarithm of each sector i's consumption with its residual value. In the application of this equation, we found the difference between the default scenario and socioeconomic-technological transition scenarios under the same climate goal (carbon budget).

$$\frac{\Delta FD_{r,s,t,i}}{FD_{r,s,t,i}} = \frac{\Delta VA_{r,s,t,i}}{VA_{r,s,t,i}} + \frac{\Delta^{OP_{r,s,t,i}} /_{VA_{r,s,t,i}}}{{}^{OP_{r,s,t,i}} /_{VA_{r,s,t,i}}} + \frac{\Delta^{FD_{r,s,t,i}} /_{OP_{r,s,t,i}}}{{}^{FD_{r,s,t,i}} /_{OP_{r,s,t,i}}} + \varepsilon_{r,s,t,i} \qquad i,r,s,t \in IRST \tag{2}$$

where

$i, r, s, t \in RST$: a set of sector i, region r, scenario s and year t,

$\varepsilon_{r,s,t,i}$: residual value of region r, scenario s, year t and sector i.

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

DATA AVAILABILITY

Scenario data are accessible via Zenodo (https://doi.org/10.5281/zenodo.4763651). Data derived from the original scenario database, which are shown in figures but are not in the above database, are available upon reasonable request from the corresponding author.

CODE AVAILABILITY

All code used for data analysis and creating the figures is available at https://github.com/shinichirofujimoriKU/GGAssess (https://doi.org/10.5281/zenodo.7015792).

Received: 16 December 2022; Accepted: 23 March 2023;

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ACKNOWLEDGEMENTS

S.F., K.O., and T.H., are supported by the Environment Research and Technology Development Fund JPMEERF20211001 and JPMEERF20202002 of the Environmental Restoration and Conservation Agency of Japan and Sumitomo Foundation and The Sumitomo Electric Industries Group CSR Foundation. J.T. is supported by the Environment Research and Technology Development Fund JPMEERF20202002 of the Environmental Restoration and Conservation Agency of Japan. The GEOS-FP data used in this study/project have been provided by the Global Modelling and Assimilation Office (GMAO) at NASA Goddard Space Flight Centre.

AUTHOR CONTRIBUTIONS

S.F., K.O. and T.H. designed the research; S.F., J.T. and K.U. set up and ran the model, carried out analysis of the modelling results, created figures, and drafted the paper; and all authors contributed to writing of the entire paper.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s44168-023-00041-w.

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