Conditions for low-carbon green growth

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The movement toward low-carbon human system over the last decade has been remarkable. Numerical scenarios describing future energy and land-use systems that attain climate change mitigation goals have been considered important sources of guidance for climate policymaking. However, no clear strategy for materialising green growth, i.e. vastly reducing greenhouse gas emissions without diminishing economic growth, has been outlined. Here, we describe the conditions needed for green growth under a wide range of carbon budgets. The results indicate that integration of multiple socioeconomic transformative measures would support green growth, including lowering energy demand, shifting to an environmentally friendly food system, technological progress on energy technologies and the stimulus of capital formation induced by green investment. No single measure is sufficient to offset mitigation costs fully, indicating that holistic societal transformation is needed, as the realisation of all measures depends on effective government policies as well as uncertain social and technological changes.

1. Introduction

Economic growth that coincides with consideration of environmental protection or conservation, known as green growth or low-carbon green growth, has long been discussed[1]. Green growth is not a simple and well-defined concept but, conventionally, encompasses cessation of environmental degradation, consideration of natural capital and general promotion of sustainability or sustainable development[2, 3, 4, 5]. Over the last decade and especially since the Paris Agreement (PA)[6], green growth has been a central objective of national and international organisations addressing climate change[7, 8, 9].

The PA 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. Along with the PA, national-level climate policies have developed rapidly. Nationally Determined Contributions (NDCs) outline short-term greenhouse gas (GHG) emissions reduction goals and, recently, NDCs have changed rapidly via two main channels. One of these channels is related to the long-term strategies submitted to the United Nations Framework Convention on Climate Change (UNFCCC) in 2020, also known as mid-century strategies, as some nations have updated their long-term targets since the initial submission, mostly to target carbon neutrality in the middle of this century[10]. The other channel is updating of the existing NDCs.

The scenarios for achieving global climate mitigation goals have been intensively assessed and compiled in the literature[11, 12, 13], including in Intergovernmental Panel on Climate Change (IPCC) reports[14, 15], 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 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, macroeconomic costs are often discussed within the scenarios. Some consider these costs inevitable to support the needed societal changes, while others think they will be offset by the reduction of costly impacts from climate change, which are associated with the social cost of carbon[16, 17].

Green growth is a major paradigm that may be attractive to the public and policy makers, but is also controversial[18]. This controversy revolves around the broad meaning of the concept, as well as definition of its tenets and underlying measurements[19]. Moreover, coverage in the existing literature is uneven (i.e. ranging from the context of specific technologies such as renewable energy to discussion of major changes to human society), which makes it difficult to reach general conclusions[20]. Very little is known about emissions reduction strategies that do not impair economic growth, and no agreement has been reached on whether this goal is possible or how it might be achieved[21, 22]. While there are some indications (or hopes) that greening of the economy may stimulate the economy and lead to structural changes that, in turn, have positive economic impacts, 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 green growth 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. The conditions are based upon climate change mitigation scenarios that assume carbon pricing, as well as additional societal changes. To capture the effects of a wide range of such changes, we considered five major social transformations, namely, lowering energy demand[23] in conjunction with enhancement of electrification[24], technological progress in the energy supply system leading to renewable and carbon capture and storage (CCS) cost reduction[24], shifting to environmentally friendly food consumption including low-meat diets and reduction of food waste[25, 26], stimulus of capital formation induced by green investment[27], and implementation of all of these measures. We designated these scenarios "Energy-Demand-Change (EDC)", "Energy-Supply-Change (ESC)", "Food-System-Transformation (FST)", "Green-Investment (GI)", and "Integrated-Social-Transformation (IST)" respectively. Each scenario includes unique methods of boosting the economy, which are discussed in the **Results** section. The default socioeconomic assumptions behind the scenarios are based on the middle-of-the-road scenario of the Shared Socioeconomic Pathways (SSP2). For the mitigation scenarios, we apply carbon budgets corresponding to long-term climate goals throughout this century [28]. On top of these default conditions, we implement the social transformative options described above. For quantification of the scenarios, we use the integrated assessment model AIM (Asia-pacific Integrated Model). The model and input data are explained in the **Methods**. In this study, we define the green growth condition as showing no adverse effect on Gross Domestic Product (GDP) from climate change mitigation, without accounting for the impacts of climate change. GDP is not the best metric for inclusively representing human welfare, which we discuss in more depth below. Naturally, emissions abatement can mitigate the impacts of climate change, leading to a variety of side effects (e.g. air pollution reduction) that may eventually affect GDP. Although we exclude climate impacts from the main analysis, we discuss this issue further below.

2. Results

2.1. Mitigation cost and green growth conditions

Total costs of global climate change mitigation are projected to range from 1 to 7% of GDP per year in the literature[29] for a carbon budget of 1000 Gt CO_2, which is considered a cumulative mitigation cost expressed as net present value (NPV), and our estimates fall within this range (see red circle in Figure 1**a**). 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[30]. The periodic mitigation cost over this century is illustrated in Figure 1**c**. 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 Figure 1). This periodic tendency is apparent regardless of carbon budgets and, as the budget becomes tighter, the magnitude of the cost increases (Supplementary Figure 1). CO_2 emissions reach net zero at mid-century, around 2050-2070, leading to drastic energy and land-use transformations (Supplementary Figure 2, Supplementary Figure 3, Supplementary Figure 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 Figure 5, based on the IPCC database).

The costs of climate change mitigation can be moderated through societal measures, which are presented in Figure 1. Full implementation of all social transformation measures allows mitigation costs to reach almost zero or even become negative for most carbon budgets, indicating that the green growth condition is met (Figure 1**a**). 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 recovery decreases. For the budget of 500 Gt CO_2, 3.9% recovery occurs from the default case and the offset 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 the interesting conclusion that stronger climate mitigation goals will make it more difficult to achieve green growth.

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 (Figure 1**c**). At the end of the century, GDP shows 4.0% gain (-4.0% GDP loss). The other budget cases show similar tendencies (Figure 1**e**).

The Green-Investment scenario provides the largest GDP recovery among the four measures by around 1.4% (purple circle in Figure 1**a**). The assumptions behind Green-Investment include incremental 1% increases in capital formation, which might appear small, but eventually became the largest contributor. Energy-Supply-Change follows Green-Investment, with GDP recovery 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 are small and did not vary among measures (Figure 1**c**), whereas the long-term effect of Green-Investment is remarkable. In 2100, the Green-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 in green growth. 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 (Figure 1**c**).

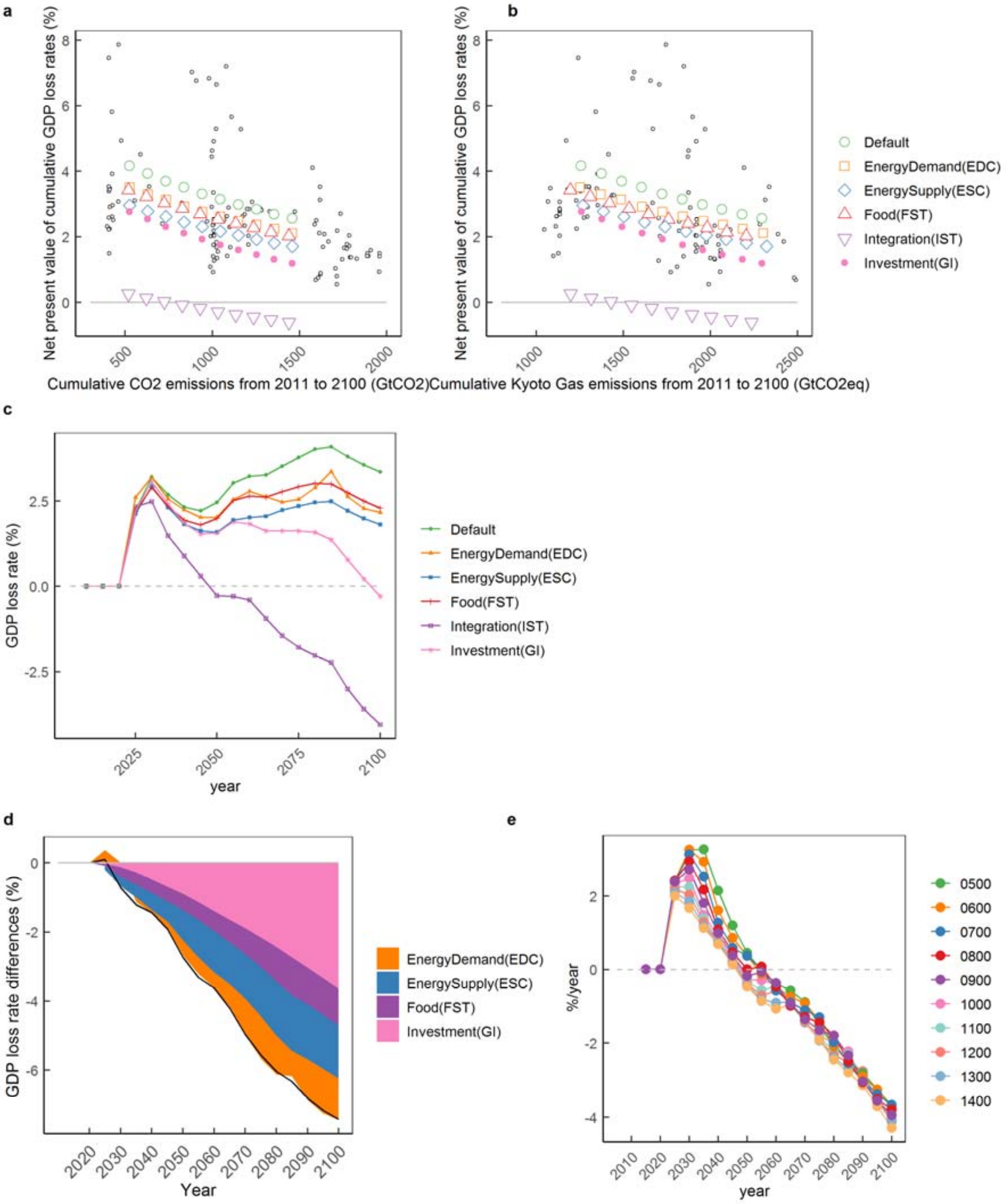

Figure 1 Global policy costs associated with climate change mitigation (GDP loss rates for green growth). **a, b**) Net present value of global cumulative GDP loss rates under various scenarios (coloured symbols) and IPCC SR1.5 literature values (black circles) against cumulative CO_2 (**a**) and Kyoto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

2.2. Mechanisms

As indicated in the previous section, individual social transformation measures have differing effects on GDP growth. We conducted decomposition analysis of GDP recovery to identify such factors (see **Methods** and Figure 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 Green-Investment condition directly boosts GDP production by adding to the capital stock (Figure 2**a** and Supplementary Figure 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. These changes result in increased activity levels, mainly in the industrial and service sectors, while productivity decreases slightly (Figure 2**h**). This productivity decrease occurs because labour is fixed and only capital is added, which causes an imbalance in production compared with the default case.

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 (Figure 2**bc**). 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 recovery (Figure 2**i**). 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 recovery 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.

The Energy-Demand-Change scenario decreases the demand for fossil fuels (Figure 2**d**) and enhances electrification, which reduces the volume of "other energy supply" (Figure 2**j**). Two factors facing the power sector may offset recovery, namely, electrification and energy savings (Figure 2**e**), 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 recovery. The contributions to GDP recovery varied among energy demand sectors (industry, transport, and service), but the original sectoral scale appears to determine the magnitude of GDP recovery, 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 (Figure 2**fg**) directly reduce the demand for food production, leading to low mitigation costs for non-CO_2 (CH_4 and N_2O) emissions from the agricultural sector (Supplementary Figure 7). 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 offset by service sector increases (Figure 2**k**). 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_2O emissions contribute to reduced total GHG emissions, causing small decreases in the global mean temperature increase at the end of this century (Supplementary Figure 8).

In the integrated scenario, these effects are generally additive, and the interaction effects are small (Figure 2**l**). A similar trend was apparent in 2050 and 2100, as well as under other carbon budgets (Supplementary Figure 9).

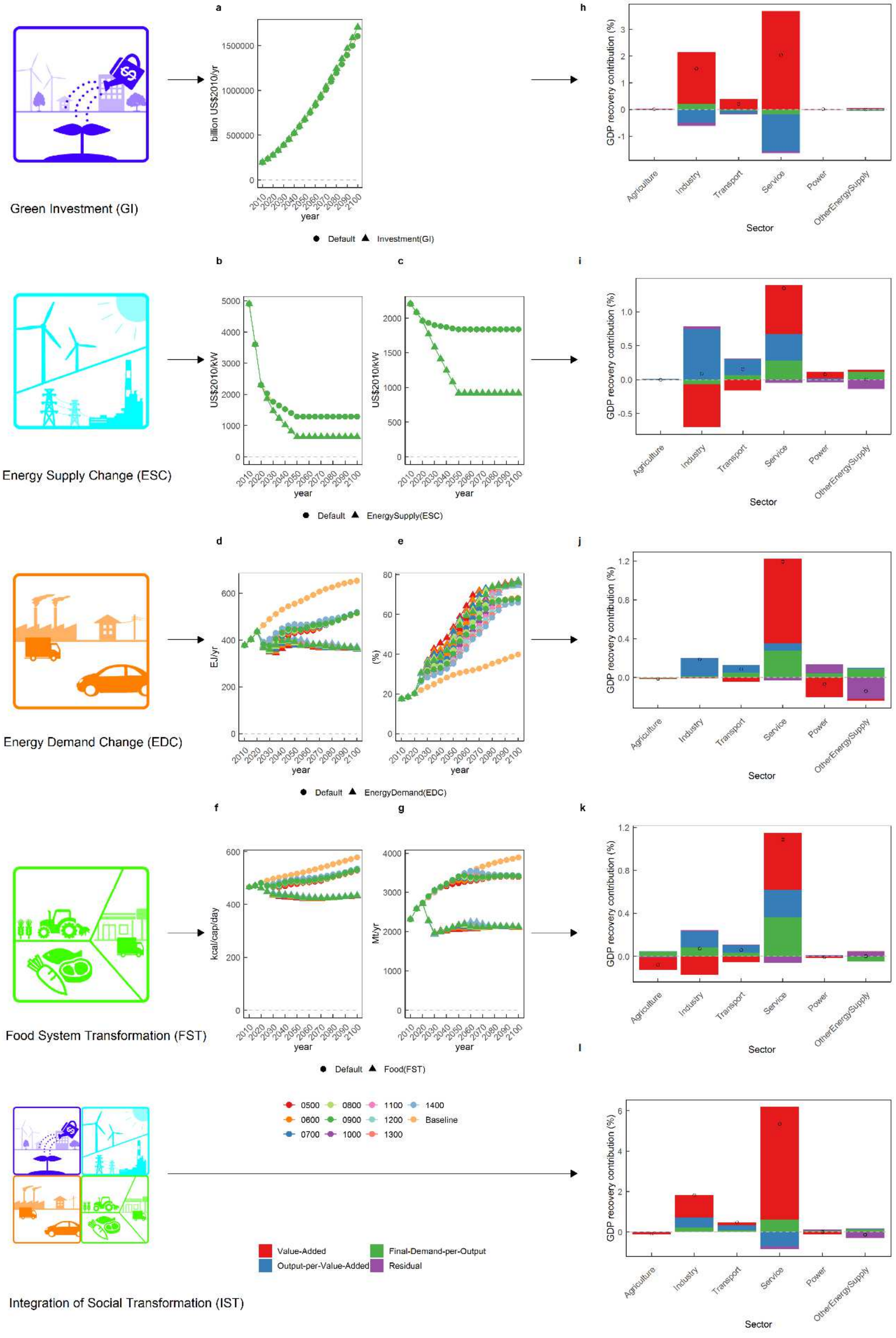

Figure 2 Mechanism of GDP recovery associated with social transformation and decomposition

analysis of GDP recovery from the default to social transformation 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 social transformation scenarios with a 1000-Gt CO_2 budget (panels **a, b, c, d, e, f** and **g,** respectively). Panels **h, i, j, k,** and **l** show decomposition analyses of GDP recovery by sector. The black circles indicate the total net impacts on GDP recovery by sector.

2.3. Regional implications

The implications of social transformative measures differ among regions (Figure 3**a**). The degree of total mitigation cost recovery differs among regions, with generally progressive results. This trend occurs because the mitigation costs without social transformation measures are regressive, as reported previously[31]. Comparing measures for Organisation for Economic Co-operation and Development (OECD) countries, Green-Investment is relatively important, accounting for around 60% of the total impact. In contrast, Green-Investment in reforming regions accounts for only around 20%, which is the lowest value among the five aggregated regions (Figure 3**b**). Because reforming regions have greater mitigation cost rates than other regions even under the default scenarios (Figure 3**a**), which may be due in part to dependence on fossil fuels and low energy usage (Figure 3**cd**), measures to improve the energy system could be more effective in such regions (Figure 3**b**). 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 (Figure 3**d**).

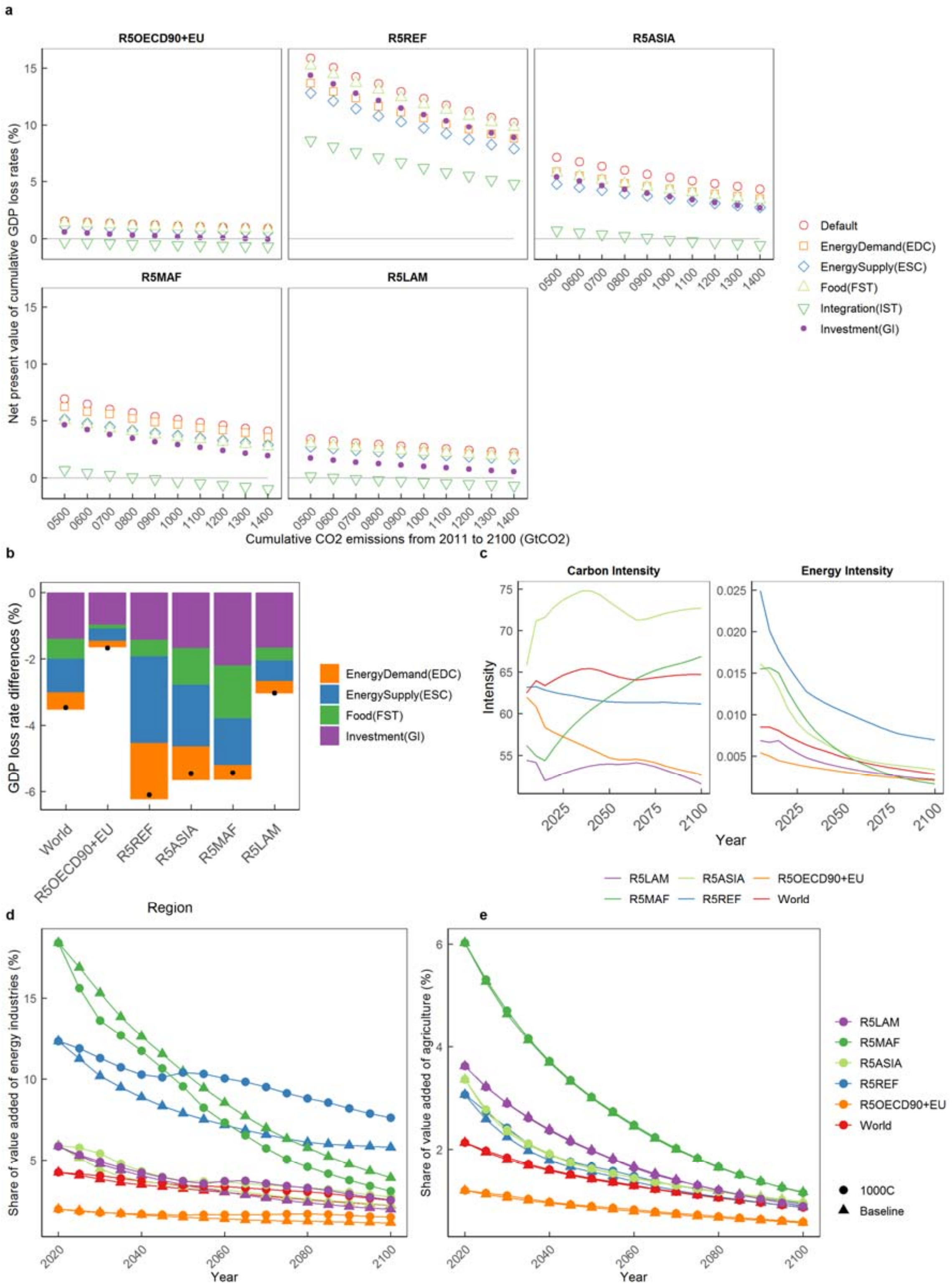

Figure 3 Regional implications of social transformation. **a**) Regional cumulative GDP loss rates expressed as NPV. **b**) Regional GDP loss recovery relative to the default scenario by region under a 1000-Gt budget. **c**) Regional carbon and energy intensity (units, kgCO$_2$/\$ and MJ/\$). **d, f**) Shares of

value added by the energy, industrial, and agricultural sectors. Regional definitions are provided in Supplementary Note 1.

2.4. Sensitivity analysis

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. At the end of this century, a discount rate of 3% leads to zero or negative mitigation costs under the Integrated-Social-Transformation scenario, as discussed above (Figure 4**c**). 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 (Figure 4**ab**). NPV results based on discount rates depend on the difference between periodic mitigation cost trajectories and exponential curves, which has two main implications for this analysis. First, in the long term, social transformation can carry almost zero or negative mitigation cost, thereby meeting the condition of green growth, even with high discount rates. Thus, within the context of inter-generational considerations, the mitigation cost can be either moderated or increased by those measures. Second, in the short term, attaining net zero or negative conditions will be difficult. Thus, a clear trade-off exists between inter-generational and short-term considerations.

In our main analysis, we assumed that stringent mitigation efforts would begin immediately in 2021 but, until 2030, current NDCs might pin the emissions reductions to certain levels[32, 33, 34]. We tested scenarios incorporating the current NDCs and confirmed that the overall results are similar to the main results, but small differences were observed (Figure 4**de**). NDCs postpone the emissions reduction to later periods and may decrease short-term mitigation costs, but do not affect the GDP recovery level or the qualitative conclusions discussed above.

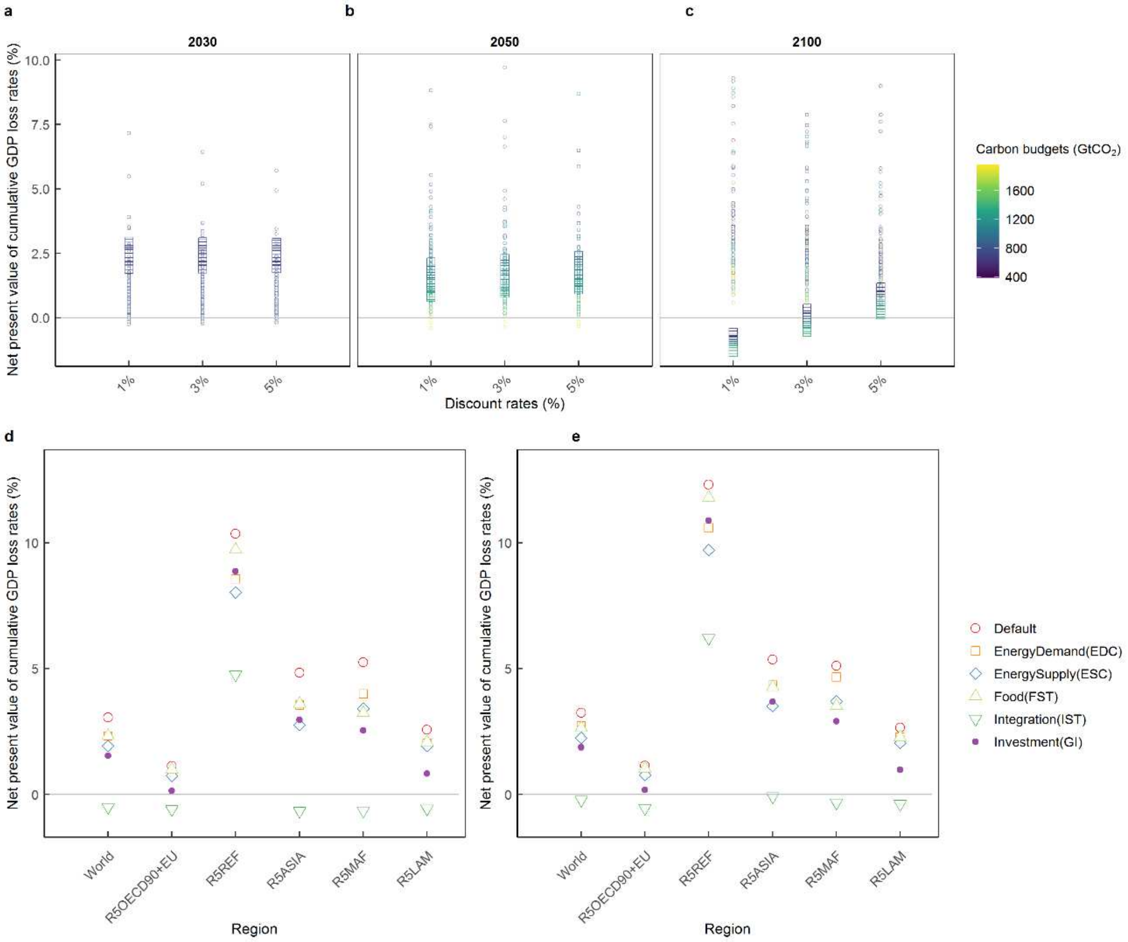

Figure 4 NPV variations by discount rate (panels **a, b, c**) and differences between delayed and immediate climate change actions (panel **d** and **e**)

3. Discussion and conclusion

We examined green growth conditions under climate mitigation targets spanning the stringency range associated with 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 offset the mitigation costs under several scenarios, including Energy-Demand-Change, Energy-Supply-Change, Food-System-Transformation, and Green-Investment. Our scenarios showed that only integration of all of these measures could offset the total cumulative mitigation cost. These changes can effectively boost the economy; however, no single measure is sufficient to meet the green growth condition, indicating that societal transformation from multiple angles is required.

We defined the green growth condition from the perspective of GDP growth. It is also useful to focus on household consumption rather than GDP, which includes capital formation and net trade volume, as household consumption might be more relevant to human welfare. Naturally, Green-Investment directly boosts production through capital formation, while consuming some income that otherwise would have been used for household consumption. Therefore, the green growth condition, as defined based on household consumption, was not met under the scenarios in this study (Supplementary Figure 10). This finding suggests that stronger measures than were included in our scenarios are needed to realise green growth defined by household consumption rather than economic growth.

The impacts of climate change are the elephant in the room in the context of green growth and, therefore, they have been intensively reported and addressed in several recent articles[17, 35, 36, 37] that consider some aspects of the green growth concept. The damage function of the economic loss or growth associated with the temperature changes reported in some studies may be equivalent to or even greater than the climate change mitigation costs, indicating that economic growth would not be harmed by emissions reductions if climate change impacts in the baseline scenarios are considered. However, due to the nature of the delayed response of the earth system, short-term temperature changes would not differ greatly, even with steep emissions reductions. Therefore, the qualitative conclusions of this study would not differ for the short term. Moreover, incorporation of the impacts of temperature change on GDP would strengthen our argument, increasing the advantage of climate change mitigation actions.

Similarly, a co-benefit of air pollution reduction associated with the GHG emissions reduction has often been noted as an additional source of green growth[38, 39, 40]. Incorporation of this factor into the green growth accounting would have different implications from the impacts of climate change, as the reduction in air pollution associated with climate change mitigation primarily carries short-term benefits. Although the benefit of avoiding premature death is often associated with the Value of Statistical Life (VSL) and accounted as an economic benefit, the actual economic market impacts would be limited[41].

One point that has been discussed in the literature but not addressed in this study is the inequality and employment conditions associated with growth[22]. 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 depend on the carbon tax recycling scheme[42]. Moreover, green growth itself could be defined more broadly to account for natural capital[19], but we could not do so in this assessment. For example, ecosystem benefits such as biodiversity conservation should be considered but were beyond the scope of our study.

Assuming that green growth is achievable, as shown in this study, the next question is how to transform society. 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[43, 44]. For green investment, 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 green growth. It might be a straightforward assumption that richer people place more priority on future generations, while such prioritisation would be very challenging for the poorest people. In that context, promoting solutions to poverty and development issues may indirectly contribute to the realisation of green growth, and is thus a possible application of carbon tax revenue[42].

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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[45, 46, 47, 48, 49]. 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.[50, 51, 52].

We analysed multiple climate change mitigation scenarios classified in two-dimensional space consisting of social transformation and the stringency of climate mitigation. All scenarios used SSP2 as the background socioeconomic assumption, which has been widely applied in the literature[53, 54], 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 socioeconomic conditions, characterised as social transformations, which are described below. We conducted scenario analysis from 2021 to 2100. Further AIM model implementation of SSPs has been documented by Fujimori et al.[55].

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. For appropriate assessment of the energy system, energy supply technologies are disaggregated. Moreover, for bioenergy and land use, agricultural sectors are represented explicitly[56]. The details of the model structure and mathematical formulae have been described previously[57]. 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. 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[58]. Land use is determined through logit selection[56]. 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.

Scenarios

We employed a two-dimensional climate change mitigation scenario framework, as described above (Supplementary Table 1). The stringency of climate change mitigation is 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 mitigation level in relation to the Paris Agreement, which suggests limiting global mean temperature in 2100 to well below 2°C or 1.5°C. Climate actions are assumed to occur immediately, beginning in 2021, with uniform global carbon prices (Supplementary Figure 11). 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 Figure 11). NDC pledges limit carbon budgets based on feasibility[59, 60], 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 social transformation to explore the effects of social transformations on climate change mitigation cost. We tested four social transformations, namely Energy-Demand-Change, Energy-Supply-Change, Food-System-Transformation, and Green-Investment. 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[61] baseline energy demand measures[55]. The autonomous energy efficiency improvement parameter and shared parameters for the logit selection of fuel type in energy demand sectors are affected. Compared with previous findings (around 250 EJ/yr in 2100)[23], the reduction in energy demand is not as large in this study, but may nonetheless have meaningful impacts on the macroeconomy.

The Energy-Supply-Change scenario explores the possibility that energy supply-side technological progress is accelerated, specifically in relation to low-carbon energy. 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 (Figure 2**bc**). 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[55]. We illustrate the primary energy supply in each scenario under a budget of 1000 Gt CO_2 in Supplementary Figure 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 (Figure 2**fg**). 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 each Sustainable Development Goal is met. Recently, some reports have indicated that a healthy diet could also provide benefits to the environment[44], and the dietary shift in this scenario meets both of those goals.

Green-Investment is a scenario wherein more priority is placed on future generations, and consequently, some current consumption is shifted to investment. Numerically, incremental 1% capital formation is added to the default case, which is assumed to last throughout this century. 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.

Decomposition analysis of GDP loss recovery

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

$$GDP_{r,s,t} = \sum_i FD_{r,s,t,i} = \sum_i VA_{r,s,t,i} \cdot {}^{OP_{r,s,t,i}}\!\big/_{VA_{r,s,t,i}} \cdot {}^{FD_{r,s,t,i}}\!\big/_{OP_{r,s,t,i}} \quad r,s,t \in RST \qquad (1)$$

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 social transformation scenarios under the same climate goal (carbon budget).

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

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,

References for method)

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Data Availability

Scenario data are accessible via (https://drive.google.com/file/d/1IJsH8d43EIS6ugdXySCSl8vwpB6jPcuK/view?usp=sharing) (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
DOI: XXX/zenodo.XXX

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