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LETTER

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Jing-Yu Liu^{1,2,6} , Shinichiro Fujimori^{2,3,4} , Kiyoshi Takahashi², Tomoko Hasegawa^{2,4,5}, Wenchao Wu², Jun'ya Takakura² and Toshihiko Masui²

¹ School of Environmental Science and Engineering, Shanghai Jiaotong University, 800 Dongchuan Road, Shanghai 200240, People's Republic of China

² Center for Social and Environmental Systems Research, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba 3058506, Japan

³ Department of Environmental Engineering, Kyoto University, 361 Kyoto University Katsura Campus, Nishikyo-ku, Kyoto 6158540, Japan

⁴ International Institute for Applied Systems Analysis, Schlossplatz-1, A-2361, Laxenburg, Austria

⁵ Department of Civil and Environmental Engineering, Ritsumeikan University, 1-1-1 Nojihigashi, Kusatsu, Shiga 525-8577, Japan

⁶ The author to whom correspondence should be addressed.

E-mail: liu.jingyu@sjtu.edu.cn

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Supplementary material for this article is available [online](#)

Abstract

The Paris Agreement set long-term global climate goals to pursue stabilization of the global mean temperature increase at below 2 °C (the so-called 2 °C goal). Individual countries submitted their own short-term targets, mostly for the year 2030. Meanwhile, the UN's sustainable development goals (SDGs) were designed to help set multiple societal goals with respect to socioeconomic development, the environment, and other issues. Climate policies can lead to intended or unintended consequences in various sectors, but these types of side effects rarely have been studied in China, where climate policies will play an important role in global greenhouse gas emissions and sustainable development is a major goal. This study identified the extent to which climate policies in line with the 2 °C goal could have multi-sectoral consequences in China. Carbon constraints in China in the 2Deg scenario are set to align with the global 2 °C target based on the emissions per capita convergence principle. Carbon policies for NDC pledges as well as policies in China regarding renewables, air pollution control, and land management were also simulated. The results show that energy security and air quality have co-benefits related to climate policies, whereas food security and land resources experienced negative side effects (trade-offs). Near-term climate actions were shown to help reduce these trade-offs in the mid-term. A policy package that included food and land subsidies also helped achieve climate targets while avoiding the adverse side effects caused by the mitigation policies. The findings should help policymakers in China develop win-win policies that do not negatively affect some sectors, which could potentially enhance their ability to take climate actions to realize the global 2 °C goal within the context of sustainable development.

1. Introduction

The Paris Agreement reaffirmed the ultimate climate goal of keeping the increase in global average temperature to well below 2 °C above pre-industrial levels [1]. Individual countries submitted their near-term climate targets as part of their Nationally Determined

Contributions (NDCs). At the same time, the UN has established Sustainable Development Goals (SDGs) regarding poverty, hunger, gender, and other important issues. SDGs and climate actions are strongly related; in fact, climate action is SDG 13, and the concept of sustainable development was included in the Paris Agreement. This implies that governments

need to consider multiple objectives and be aware of the fact that climate change mitigation measures can have positive or negative consequences (i.e. co-benefits and trade-offs) in various sectors. This interactive nature of policies requires coordination between societal groups to promote sustainable development in its broadest sense.

SDGs could be used to shore up support for climate actions [2]. SDGs provide both challenges and opportunities in terms of climate change mitigation because trade-offs between the climate change mitigation and other sectors can be barriers, whereas co-benefits can be incentives. Resolving the difficulties that trade-offs present and taking advantage of the co-benefits could enhance broader social acceptance of climate policies and promote climate actions in general.

Climate policy affects various SDG-related sectors, such as energy security [3, 4], air quality [5, 6], human health [7, 8], land management [9, 10], food security [11–13], water scarcity [14, 15], and biodiversity [16]. In addition, the timing of climate change mitigation and the implementation of policy instruments can change the multi-sectoral consequences. For example, weak short-term climate policy could lead to less synergy and substantial trade-offs being locked into the system [17]. Land resources are relevant, among other reasons, for afforestation and the large-scale use of bioenergy crops, both of which are considered as major negative emission technologies required for deep decarbonization [18]. Gao and Bryan [19], however, noted that substantial contributions from sectors other than the land sector are needed, such as from clean energy, food systems, and water resource management. Nevertheless, when implementing land-based climate policies, careful design of land policies is essential. Calvin *et al* [9] assessed the trade-offs in achieving climate targets under five alternative bioenergy and land-use policies and found that deforestation would be widespread if no complementary land policy was implemented. Fujimori *et al* [20] suggested that inclusive food policies should be considered together with climate policies to avoid the food security concerns often linked to climate change mitigation.

Consideration of as many SDG dimensions as possible can provide better insights to policymakers to formulate better policies. This implies that a systematic assessment framework of the impacts of climate policies on multiple SDGs is necessary. Studies by von Stechow *et al* [17], Jakob *et al* [21] and Iyer *et al* [22] are examples of assessments of climate policies in multiple sectors closely related to global SDGs.

Generally, assessing synergies and trade-offs is the first step in studying this issue, and a next step is searching for solutions to resolve sustainability issues. Van Vuuren *et al* [23] analyzed how different combinations of technological measures and behavioral changes could achieve multiple sustainability goals. Humpenöder *et al* [24] discussed methods of resolving

sustainability trade-offs brought by large-scale bioenergy production, such as forest or water protection (but these caused increases in food prices) or agriculture intensification and fertilization efficiency improvement. Bertram *et al* [25] discussed solutions to reduce the sustainability risk for the 1.5 °C case through regulation policies (alternative climate policies), early action, and lifestyle changes. Actual countermeasures or policy implementations are mostly made at national or even local scales, even though climate change is a global issue. Similarly, specific SDG targets are set at the national level and on a national scale. Within that context, national policy proposals are essential to resolve sustainability issues associated with climate actions but studies at the national level are still limited. Gao and Bryan [19] is an exception that explored land sustainability in Australia, but they did not include the energy system in their modeling scheme, and co-benefits such as air quality or energy security improvement were not considered as part of the sustainable pathway.

China is among the largest greenhouse gas (GHG) emitters in the world. It can make great contributions to and set a good example for the achievement of climate goals through successful decarbonization. Some sustainability issues, however, have accompanied its rapid economic development. For example, air pollution and associated health issues are severe [6], and urbanization has encroached on croplands. In addition, China has the world's largest population, and this requires a focus on food security concerns and calls for better land management [26]. This also means that the number of people at risk of being exposed to sustainability issues would be extremely high if China fails to follow a sustainable development pathway. All of these factors make China a good country to use as a case study.

In this paper, we outline the multi-sectoral consequences of SDG-related climate policies in China and explore the pathways and solutions to counteract the trade-offs. For this purpose, we used an integrated assessment model and simulated future scenarios through 2050. We focused on two research questions: (1) What are the trade-offs and co-benefits associated with climate policies with respect to SDGs? and (2) Are there ways to implement sustainable climate policy instruments in line with the 2 °C goal that will eliminate trade-offs? The study is novel in that it includes a multi-sectoral analysis with respect to climate change mitigation in China, and moreover, provides a concrete and numerical climate policy pathway for diminished SDG-related trade-offs. The findings should help policymakers in China to consider win–win solutions that do not negatively affect other sectors and thereby promote climate actions to realize the global 2 °C goal within the context of sustainable development.

Table 1. SDG-related indicators.

SDG	Indicator	Calculation	Standardization
Energy security	TPES diversity	$Q_i \times \ln(Q_i)$, where Q_i is share of each type of primary energy in Total Primary Energy Supply (TPES). Refer to SI figure 4.	SWDI for energy security was standardized using $(\text{Value in Baseline}/\text{Value in scenario} - 1) \times 100\%$.
Energy security	TPES imports	Total primary energy imports	Other indexes were calculated using $(\text{Value in scenario}/\text{Value in Baseline} - 1) \times 100\%$
Air quality	SO ₂ emission	SO ₂ emissions per year	
Air quality	NO _x emission	NO _x emissions per year	Each standardized index represents a co-benefit if it is negative and a trade-off if it is positive. The larger the index is, the more risk occurs
Air quality	BC emission	BC emissions per year	
Food security	Food price	Consumer price of non-energy crops and livestock	
Food security	People at risk of hunger	People at risk of hunger	
Food security	Food trade dependence	Total food imports/total consumption	
Land management	Deforestation	Forest area	

2. Methodology

2.1. Model

We used the China model of AIM/CGE (Asia-Pacific Integrated Modeling/Computable General Equilibrium), which has been widely used in climate mitigation and impact assessment [8, 27–29]. AIM/CGE is a recursive dynamic general equilibrium model that includes 42 industrial classifications. The model can simulate whole economic system including energy and land use system wherein the equilibrium is determined every year and capital stock is turned over to the next year. Future socioeconomic assumptions and parameter settings were based on Shared Socioeconomic Pathway 2, and was described in detail by Fujimori *et al* [30]. Please refer to SI.A for a more detailed model description.

2.2. Selections of multi-sectoral indicators

We selected nine indicators (table 1) that are relevant to four SDG aspects other than climate action (SDG 13): combat hunger (SDG 2), reduce deaths from air pollution (SDG 3.9), affordable and clean energy (SDG 7), and sustainable forest management (SDG 15.2). For hunger, the number of people at risk of hunger is the most relevant indicator; in addition, we used indices for food price and food trade dependency. An increasing food price index can be interpreted as worsening conditions in low-income households. For reducing deaths from air pollution, we considered the annual emissions of three main air pollutants, SO₂, NO_x, and black carbon (BC), which were the indicators used in [23]. Energy security was considered as an energy aspect for SDG 7. Indices for trade dependency and energy diversity were quantified, representing two aspects of energy security: sovereignty and resilience [31, 32]. The total primary energy imports index reflects trade dependency, and the Shannon–Weiner

diversity index (SWDI) reflects diversity. Forest area was selected as an indicator of sustainable forest management because it is related to ecosystem conservation [9, 33, 34]. The Shannon–Weiner diversity index is calculated using outputs from the model. All other indicators are derived directly from the model. We could not calculate all of the indicators that were relevant to the SDGs, and therefore nine representative indicators were selected considering the model's capability. The indicators we selected had some limitations. For example, air-pollution concentrations are a direct indicator of the pollution levels in China. However, we could not calculate them in AIM/CGE due to the limitations of the model. We also did not have a species diversity index for biodiversity, but rather used forest area as a proxy indicator.

To analyze these indicators, we compared mitigation scenarios with a baseline scenario for each year. Note that the impacts of climate change, such as increased flooding risk and a rising sea level, are not specifically considered in our modeling framework because the primary goal of this study was to explore the direct consequence of climate change mitigation actions. Also, there are some areas where both consequences of climate change mitigation and climate change impacts occur simultaneously. For example, climate conditions may change crop yield, which is associated with food security, but climate mitigation may also change agricultural production costs. In this case, we only considered the mitigation effects in the model.

2.3. Scenario design

Three kinds of scenario were used in our analysis. In the first set of scenarios, a carbon price (or carbon emission cap) is implemented without considering other sector conditions. With this group, our aim was to identify the trade-offs and co-benefits of climate

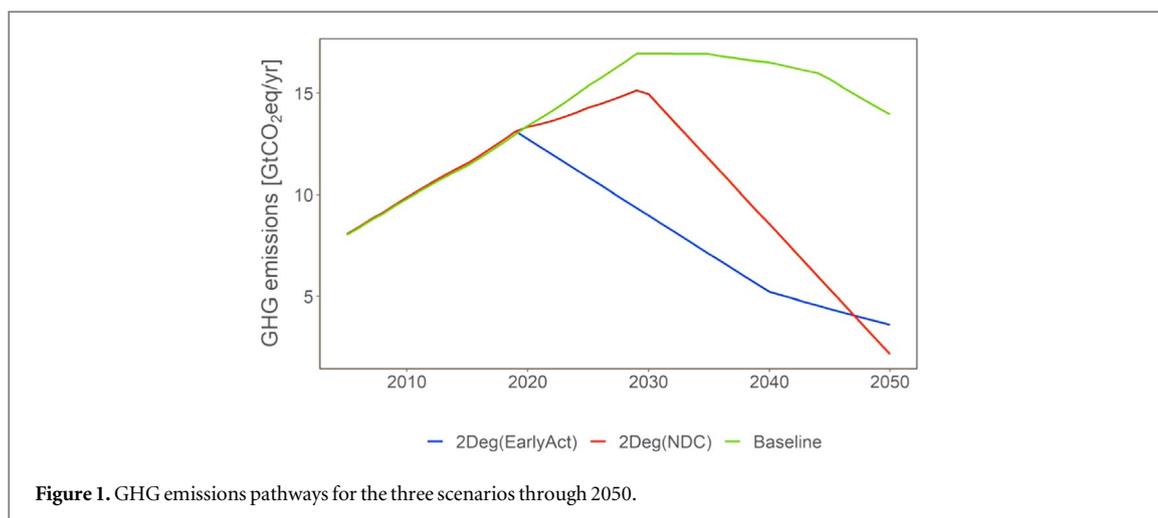


Table 2. Policy representations in the scenarios.

Scenarios	Targets in government plans	2015	2020	2030	Data source
All scenarios	Bioelectricity	10300 MW	15 000 MW		Renewables 13th 5 year plan [35]
	Gas	66030 MW			Energy 13th 5 year plan [36]
	Nuclear	27170 MW	58 000 MW		Electricity 13th 5 year plan [37]
	Hydro	319540 MW	340 000 MW		Renewables 13th 5 year plan
	Wind	129000 MW	210 000 MW		Renewables 13th 5 year plan
	PV	43180 MW	105 000 MW		Renewables 13th 5 year plan
	Air pollutants	SO _x : 19.74 Mt NO _x : 20.78 Mt		15% off (Cumulative)	
NDC scenarios	Forest cover	21.63%	>23%	>24%	China land planning [39]
	Carbon intensity		40%–45%	60%–65%	NDC [40]
	CO ₂ peak			Yes	NDC
	Non-fossil share		15%	20%	NDC

policies. In the second set of scenarios, we added policy instruments that resolve the negative side effects identified in the first set of scenarios. In these scenarios, we used the same climate change mitigation targets (i.e. the same carbon price and GHG emissions pathways). In the third set, we conducted a sensitivity analysis to explore the robustness of our primary findings.

With respect to the simple climate mitigation measures, we implemented two types of climate policy assumptions that are consistent with the 2 °C goal, but the timing of the start of implementation of stringent actions differed. One assumed the current Chinese NDC target is achieved by 2030 and then goes on to the deep decarbonization target (2Deg(NDC)). The other assumed that drastic emission reduction starts immediately. This latter 2Deg(EarlyAct) scenario is normally interpreted as a so-called cost-effective mitigation scenario for the global 2 °C goal. The emissions trajectories for these assumptions and a Baseline scenario (no carbon price assumed) are shown in figure 1. The determination of carbon budget in China can be found in SI.B. In addition to climate policies in the form of carbon constraints in the model, we simulated

policies regarding energy, air, forest and NDC targets based on government plans (table 2). The 2Deg(NDC) scenario implemented NDC policies, such as CO₂ peaking in 2030, increased non-fossil fuel share, and the carbon intensity goal (60%–65% reduction from the 2005 level). The energy policy in 2020 was assumed to follow China's thirteenth 5 year plan for hydro, wind, PV, and nuclear energy. The afforestation policy was assumed to achieve the forest area goal in 2020 and 2030 in all scenarios, based on China's land-use plans. The air-quality policy assumed SO_x and NO_x emission constraints in 2015 and 2020 in all scenarios based on China's thirteenth 5 year plan.

The second set of scenarios implemented subsidies for forest land rent and food goods. We chose these policy instruments because food security and land management risk were identified as negative side effects of the implementation of the simple climate policy (see the Results). Note that we merely demonstrate one example from the wide array of possible policy packages, and this is not intended to reflect exhaustive measures. To configure the subsidy rate, we used a trial-and-error procedure to determine the subsidy level that canceled out the negative side effects

Table 3. Scenario designs.

Scenario category	Research purposes	Scenario description
Baseline	Reference to derive multi-sectoral implications	No carbon prices
Simple policy scenarios	Identify trade-offs and co-benefits of climate policies on SDGs and test near-term action impacts	2Deg(NDC): reflects the tendency of current policy in China before 2030 but meets 2 °C goal by the end of this century 2Deg(EarlyAct): follows the least-cost mitigation scenario
Comprehensive policy scenarios	Add complementary policies to combat trade-offs: forest land rent subsidy and food price subsidy	2Deg(EarlyAct)+Combine: 180% forest land rent subsidy and 67% food price subsidy were assumed on the basis of 2Deg(EarlyAct) scenario.
Sensitivity scenarios	Test the robustness of our findings	See table 4

Table 4. Sensitivity scenarios.

Scenario name	Description
GDP_High	SSP1 assumption, higher GDP
GDP_Low	SSP3 assumption, lower GDP
POP_High	SSP3 assumption, higher population
POP_Low	SSP1 assumption, lower population
Trs_High	SSP3 assumption, higher transportation demand
Trs_Low	SSP1 assumption, lower transportation demand
Yield_High	SSP1 assumption, higher yield
Yield_Low	SSP3 assumption, lower yield
NoCCS	CCS not available
NoBECCS	BECCS not available

caused by the simple climate mitigation policy. We aimed to design a scenario in which there was no increase in the number of people at risk of hunger and no deforestation compared with the BaU scenario. Based on such a consideration, we selected a subsidy rate that was just enough to eliminate the trade-off effects. The actual subsidy rates chosen were 67% for food price and 180% for forest land rent. The food subsidy means that 67% of the consumer price of food is paid by the government, reducing the price to 33% of the unsubsidized price. The forest subsidy represents a government subsidy that is transferred to households holding forests based on the area of the forest. A 180% subsidy rate means that twice the rental value of the land can be given as a subsidy for holding a forest area. Table 3 summarizes the first and second sets of scenarios.

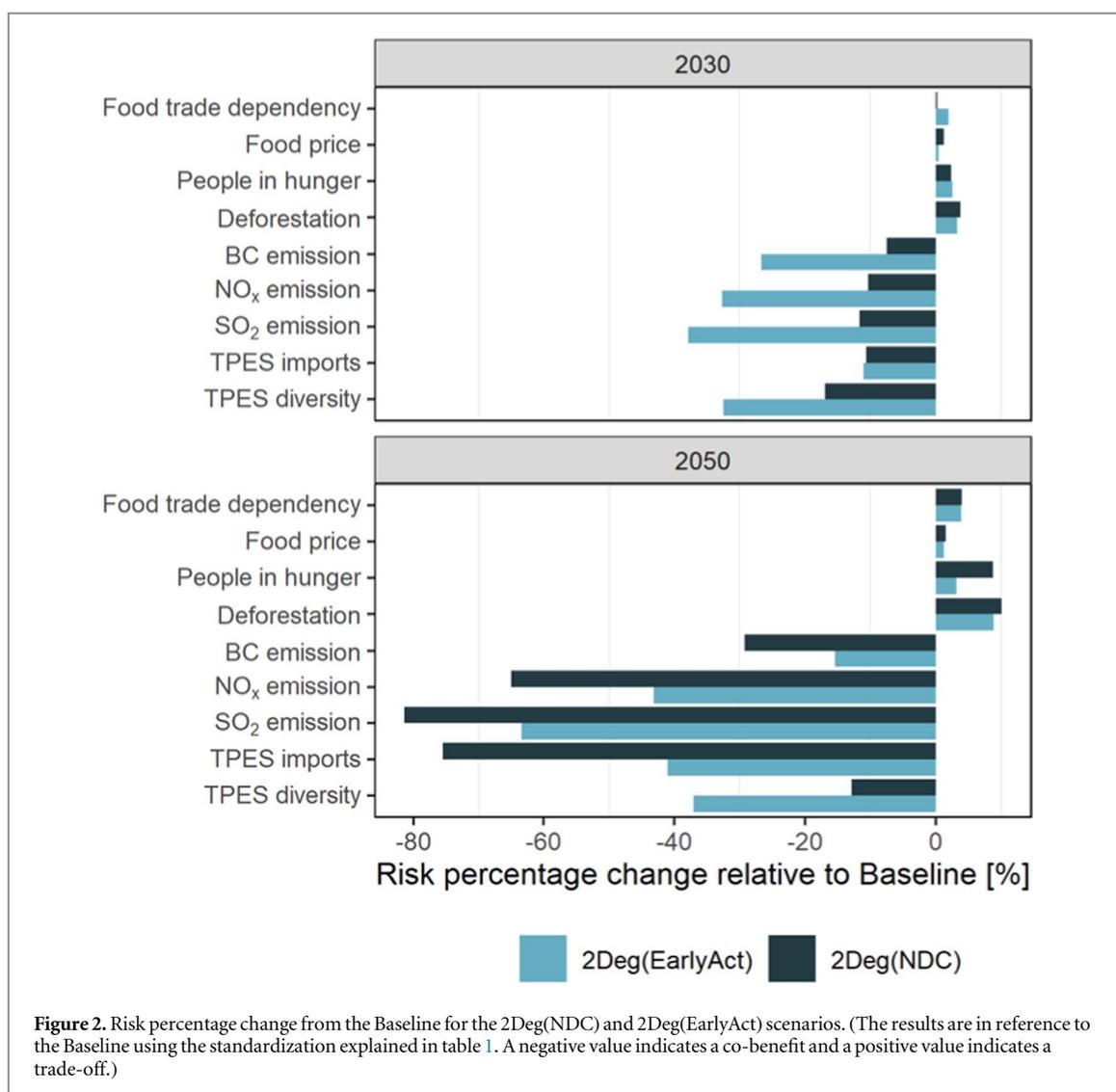
We selected several major uncertain socio-economic factors as presented in table 4, which are often taken into account in integrated assessment model studies. GDP_High, GDP_Low, POP_High, and POP_Low represent socioeconomic development conditions, which are drivers of GHG emissions as well as drivers of air pollutant emissions, land use, and other sustainable development factors. Trs_Low and Trs_High represent people's behavioral changes in transportation toward a sustainable direction or a non-sustainable direction. China's economy is growing quickly and has rapidly urbanized, which has resulted in an increase in the demand for transportation. The development of the transportation sector

could have large effects on future challenges related to emission mitigation, air pollution, energy security, and other factors. Yield_High and Yield_Low represent uncertainty in agricultural technology development because agricultural land requirements may be closely related to the future yields [41, 42]. The NoCCS and NoBECCS sensitivity scenarios represent uncertainties in the availability for carbon capture and storage (CCS) technology. Uncertainty related to CCS is a current focus in the research community and will be an important determinant for shaping both the energy and land-resource systems [43]. All sensitivity scenarios are based on 2 Deg(EarlyAct) + Combine scenario

3. Results

3.1. Positive and negative side effects of climate policy

Figure 2 illustrates the indicators in the climate mitigation only scenarios. All of the air quality and energy security indices exhibit co-benefits. SO₂, NO_x, and BC emissions in 2030 are 8.02, 10.2, and 0.72 Mt in the 2Deg(EarlyAct) scenario, much better than those of the Baseline (12.9, 15.2, and 0.98 Mt, respectively) (supplementary figure SI.1 is available online at stacks.iop.org/ERL/14/124070/mmedia). Those in 2Deg(INDC) scenario were between the two (11.4, 13.6, and 0.91 Mt, respectively). Time series data indicated that carbon prices and pollutant emissions are well interlinked (figures SI.1 and SI.2). In the Baseline scenario, air pollutants peak in 2030 and then sharply decrease, whereas the early action scenario cuts off the near-term peaks. Thus, early climate action is preferable from the perspective of reducing air pollution. In terms of energy security, both the primary energy diversity index and imports in the mitigation scenarios are better than those in the Baseline. For example, in 2050 they are 2.1 and 36.4 EJ in 2Deg(EarlyAct), respectively, 1.32 and 61.6 EJ in BaU scenario and 1.51 and 15.1 EJ in 2Deg(NDC) (figure SI.3). For China, a large use of renewable energy such as wind and solar can improve energy security significantly.

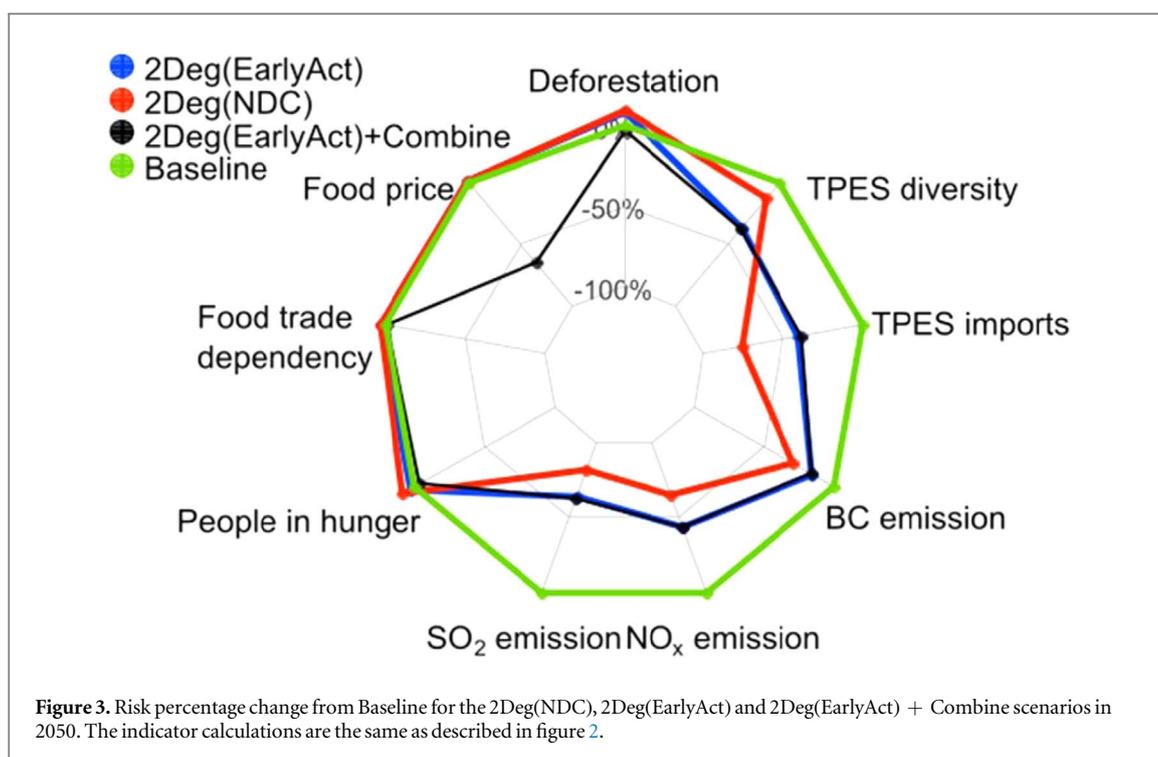


We also identified adverse side effects in land management and food security (figure 2). 2030 and 2050 show similar tendencies, but the effect is smaller in 2030. The 2Deg(EarlyAct) scenario has less deforestation than that of 2Deg(NDC) in 2050, mainly due to drastic emission reductions after 2030 in the 2Deg(NDC) scenario that compensate for emissions before 2030 with delayed mitigation. The immediate near-term emission reduction relieves the burden of carbon constraints in the long term and lessens the need for negative emission techniques that could harm land sustainability.

The indicators overall suggest the operation of trade-offs trade-off and food security in both the 2Deg(EarlyAct) and 2Deg(NDC) scenarios, in which food consumption decreases and the number of people with hunger increases due to the carbon policies. Toward 2050, income growth contributes to reducing the number of people at risk of hunger (figure SI.5) in all scenarios. In the mitigation scenarios, land resources are demanded for energy crop production, which is stimulated from the demand for biomass associated with negative emissions. In addition, non-CO₂

emissions in the agricultural sector can cause additional production costs. Both of these dynamics cause increased food prices.

A large-scale biomass expansion can compete with food production and afforestation via competition for land resources. This is the central point where trade-offs between climate change mitigation and other sectors are observed. There is little incentive to grow biomass in the Baseline scenario (figure SI.6), but in the 2Deg(EarlyAct) and 2Deg(NDC) scenarios, land competition between energy crops, forest, and food begin in 2020. By 2030, land use for energy crops is 49.7 million ha in the 2Deg(EarlyAct) scenario and 24.0 million ha in the 2Deg(NDC) scenario. To compensate for the additional emissions in the near term, the carbon price is much higher by 2050 in 2Deg(NDC) than in 2Deg(EarlyAct) (figure SI.2), which drives the increase in the amount of land used for energy crops. The forest area in the 2Deg(NDC) scenario in 2050 is 215.6 million ha, which represents a 10.1% decrease from the Baseline. The forest areas in the 2Deg(EarlyAct) and Baseline scenarios are 218.5 and 239.7 million ha, respectively.



3.2. Necessity of a complementary policy package

To avoid the above-mentioned adverse side effects, we implemented a complementary policy package as an illustrative example. The land and food security indicators, which became worse under simple climate mitigation, remained near the baseline level with this policy package (figure 3). Under forest and food subsidy policies, all of the investigated indicators achieved a zero trade-off in 2050 as compared with the Baseline scenario. The cost for these policies can be measured by macroeconomic indicators such as GDP losses. In 2050 this policy package is actually cost negative (i.e. it contributes to a greater GDP; figure SI.7).

We also examined the cases where only the forest protection policy or only the food policy is implemented (see table SI.1 for additional scenario descriptions). However, the forest-only policy addition worsened food security in terms of people in risk of hunger (figure SI.8), mainly because the forest protection policy tightened the land market and forced decreases in the food production area. Similarly, the food subsidy alone increased deforestation risk (figure SI.9). Therefore, these two packages need to be implemented simultaneously.

3.3. Sensitivity analysis

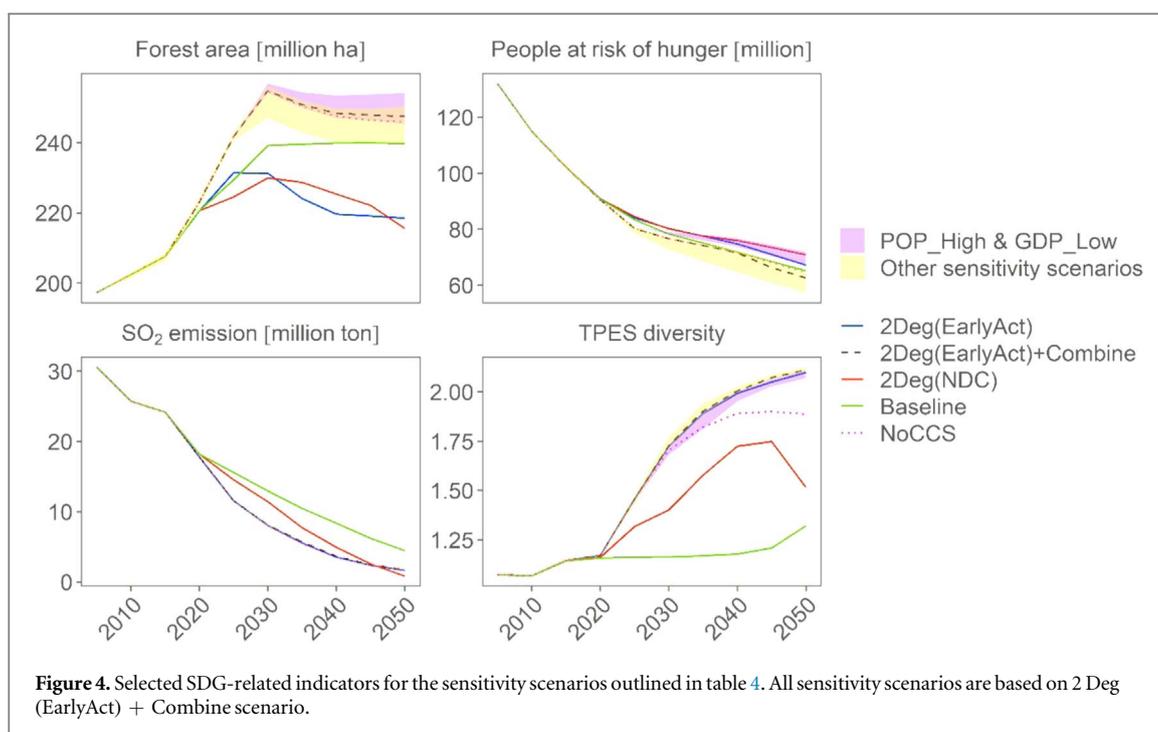
The results of the sensitivity analysis (figure 4) showed the robustness of the sustainability of our chosen climate mitigation pathway. In figure 4, the sensitivity scenarios are shown into 3 groups. The NoCCS scenario is shown alone because its impacts are larger for some of the SDG-related indicators. And the POP_High and GDP_Low scenarios are grouped

because they both have negative impacts on food security. Excluding these 3 scenarios that need paid special attention to, the remaining 7 were grouped together.

The 10 sensitivity scenarios had a forest area in 2050 that ranged from 239.9 million to 254.1 million ha, whereas that of the baseline was 239.9 million ha. The uncertainty in deforestation, energy security (CCS availability is an exception), and air pollution caused by social development uncertainties is not as large as the uncertainty caused by climate policy uncertainties. Conversely, food security indicators are largely affected by socioeconomic conditions rather than the climate policies. In particular, the POP_High and GDP_Low sensitivity scenarios showed much greater negative impacts on hunger as compared to the Baseline.

4. Discussion

We first identified sectors where simple climate mitigation policies can have positive and negative side effects. The land-related sectors, food security and forest area, were negatively affected (trade-offs), whereas the energy and air-quality related indicators were positively affected (co-benefits). Early climate action is preferable because it would increase the co-benefits in the near term and decrease the trade-offs in the mid-term. We then showed how an illustrative complementary policy package would mitigate the negative side effects. The policy package was formulated by implementing subsidies targeted specifically at food consumption and forest land area. The cost of these measures was shown to be relatively small or



even negative. We also confirmed that these findings are robust to some socioeconomic factors.

To implement a 67% food-subsidy policy, the government needs to allocate approximately 2%–3% of GDP each year. This could be financed partly by carbon revenue. The remainder could be financed by reducing government expenses and cutting investment projects that do not meet environmental standards. There are many difficulties in financing food subsidies. This indicates the necessity of additional complementary policies that will help to resolve the food security problem, such as improvements in agricultural technology that will lead to yield increases. It is important to stress that the complementary policy is only an illustrative example and somewhat naively represents the CGE model. There was assumed to be no difference in the subsidy rates between crops or forest types. The subsidy for food was simply assumed to return to the producers to keep the price down. Also, there was no differentiated treatment for different income levels among buyers. Spatial differences and local information were not considered. Therefore, this policy package was not meant to be exhaustive, and actual policy implementation can be much more complicated and encounter difficulties associated with specific local circumstances. In addition, subsidies are not the only way to accomplish the same result—regulatory measures or even taxes could be used as well.

The question of how to promote near-term climate actions, for example, moving from the 2Deg (NDC) pathway to 2Deg(EarlyAct) arises from the results. The co-benefits in the near term can act as incentives to promote climate policies for several reasons. First, these co-benefits offset the costs of climate

policies by, for example, reducing the required legislation policy cost [44] or providing additional welfare gain [6]. Second, as shown in our results, air quality improvement and energy security gains can be realized in the near term, but climate change gain is expected in the future. Finally, co-benefits also have privatizing effects [45]. The presence of co-benefits may sometimes actually be the main reason certain climate change mitigation actions are taken [46]. Therefore, we should utilize our understanding of co-benefits across multiple sectors to promote more stringent climate policies in the near term.

Land resource limitations are a determinant in the trade-offs among development-related indicators. Our results confirmed that forest protection policies can protect natural areas but could harm food security. To address this concern, (1) additional measures should be taken to tackle the energy-food-land nexus, such as technology improvements in the agriculture sector, better agriculture and land management, and improved food trade policy; and (2) coordination is needed between environmental policy, climate policy, and food security policy [26]. Each of these requires better governing and collaboration among multiple government departments. Political and governmental leaders need to be better prepared and trained for such requirements.

This study has several limitations and several future research directions are indicated. First, we only show country-level indicators, but local-level conditions should also be presented. For many SDGs, local conditions are for the primary consideration of policy-makers. In addition, climate policy strategies may vary across local regions and have varying impacts on SDG-related indicators. In future research, we plan to

include spatial models with more local details. Second, the SDGs incorporated in this study do not cover all indicators. To have a more comprehensive understanding of side effects and provide more information for policymakers, we should include as many aspects as possible. For example, we plan on including indicators such as water scarcity in future analyses. Finally, we cannot compare the level of urgency between different indicators; that is, the relative importance of SDG-related indicators is not represented. For example, air pollution may be of high priority to the Chinese government, but another factor may be more important to others.

5. Conclusions

This study assessed the side effects of climate policies on multiple SDG-related sectors and found a climate policy pathway that is reconciled with SDGs. Energy security and air pollution can have great co-benefits from climate mitigation measures, whereas food security and land resources experience trade-offs. To resolve the trade-offs, early climate action is preferable, and near-term climate action to reduce GHG emissions is a critical factor because it also helps to reduce trade-offs in the mid-term. We proposed a subsidy mechanism for food goods and land rent as an illustrative example of a complementary policy package that successfully diminished the negative side effects while maintaining the co-benefits. In the mid-term, policy coordination among the target spaces is essential to prevent the negative impacts associated with climate change actions.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available for legal and/or ethical reasons.

ORCID iDs

Jing-Yu Liu  <https://orcid.org/0000-0002-8643-0217>

Shinichiro Fujimori  <https://orcid.org/0000-0001-7897-1796>

References

- [1] UNFCCC 2015 Adoption of the Paris Agreement FCCC/CP//L.9/Rev.1. 2015
- [2] Fusco Nerini F 2018 Shore up support for climate action using SDGs *Nature* **557** 31
- [3] Jewell J, Cherp A and Riahi K 2014 Energy security under decarbonization scenarios: an assessment framework and evaluation under different technology and policy choices *Energy Policy* **65** 743–60
- [4] Guivarch C, Monjon S, Rozenberg J and Vogt-Schilb A 2015 Would climate policy improve the European energy security? *Clim. Change Econ.* **06** 1550008
- [5] van Vuuren D P, Cofala J, Eerens H E, Oostenrijk R, Heyes C, Klimont Z, den Elzen M G J and Amann M 2006 Exploring the ancillary benefits of the Kyoto protocol for air pollution in Europe *Energy Policy* **34** 444–60
- [6] Xie Y, Dai H, Dong H, Hanaoka T and Masui T 2016 Economic impacts from PM_{2.5} pollution-related health effects in China: a provincial-level analysis *Environ. Sci. Technol.* **50** 4836–43
- [7] Markandya A, Armstrong B G, Hales S, Chiabai A, Criqui P, Mima S, Tonne C and Wilkinson P 2009 Public health benefits of strategies to reduce greenhouse-gas emissions: low-carbon electricity generation *Lancet* **374** 2006–15.
- [8] Hasegawa T, Fujimori S, Takahashi K, Yokohata T and Masui T 2016 Economic implications of climate change impacts on human health through undernourishment *Clim. Change* **136** 189–202
- [9] Calvin K, Wise M, Kyle P, Patel P, Clarke L and Edmonds J 2014 Trade-offs of different land and bioenergy policies on the path to achieving climate targets *Clim. Change* **123** 691–704
- [10] Popp A *et al* 2014 Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options *Clim. Change* **123** 495–509
- [11] Smith P *et al* 2013 How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Glob. Change Biol.* **19** 2285–302
- [12] Hasegawa T *et al* 2018 Risk of increased food insecurity under stringent global climate change mitigation policy *Nat. Clim. Change* **8** 699
- [13] Hasegawa T, Fujimori S, Shin Y, Tanaka A, Takahashi K and Masui T 2015 Consequence of climate mitigation on the risk of hunger *Environ. Sci. Technol.* **49** 7245–53
- [14] Hanasaki N *et al* 2013 A global water scarcity assessment under shared socio-economic pathways: II. Water availability and scarcity *Hydrol. Earth Syst. Sci.* **17** 2393–413
- [15] Fujimori S, Hanasaki N and Masui T 2017 Projections of industrial water withdrawal under shared socioeconomic pathways and climate mitigation scenarios *Sustain. Sci.* **12** 275–92
- [16] Smith P, Price J, Molotoks A, Warren R and Malhi Y 2018 Impacts on terrestrial biodiversity of moving from a 2 degrees C to a 1.5 degrees C target *Phil. Trans. R. Soc. A* **376**
- [17] von Stechow C, Minx J C, Riahi K, Jewell J, McCollum D L, Callaghan M W, Bertram C, Luderer G and Baiocchi G 2016 2 °C and SDGs: united they stand, divided they fall? *Environ. Res. Lett.* **11** 034022
- [18] Bustamante M, Robledo-Abad C, Harper R, Mbow C, Ravindranat N H, Sperling F, Haberl H, Pinto Ade S and Smith P 2014 Co-benefits, trade-offs, barriers and policies for greenhouse gas mitigation in the agriculture, forestry and other land use (AFOLU) sector *Glob. Change Biol.* **20** 3270–90
- [19] Gao L and Bryan B A 2017 Finding pathways to national-scale land-sector sustainability *Nature* **544** 217–22
- [20] Fujimori S, Hasegawa T, Rogelj J, Su X, Havlik P, Krey V, Takahashi K and Riahi K 2018 Inclusive climate change mitigation and food security policy under 1.5 °C climate goal *Environ. Res. Lett.* **13** 074033
- [21] Jakob M and Steckel J C 2016 Implications of climate change mitigation for sustainable development *Environ. Res. Lett.* **11** 104010

- [22] Iyer G, Calvin K, Clarke L, Edmonds J, Hultman N, Hartin C, McJeon H, Aldy J and Pizer W 2018 Implications of sustainable development considerations for comparability across nationally determined contributions *Nat. Clim. Change* **8** 124–9
- [23] van Vuuren D P *et al* 2015 Pathways to achieve a set of ambitious global sustainability objectives by 2050: explorations using the IMAGE integrated assessment model *Technol. Forecast. Soc. Change* **98** 303–23
- [24] Humpenöder F *et al* 2018 Large-scale bioenergy production: how to resolve sustainability trade-offs? *Environ. Res. Lett.* **13** 024011
- [25] Bertram C, Luderer G, Popp A, Minx J C, Lamb W F, Stevanović M, Humpenöder F, Giannousakis A and Kriegler E 2018 Targeted policies can compensate most of the increased sustainability risks in 1.5 °C mitigation scenarios *Environ. Res. Lett.* **13** 064038
- [26] Lu Y *et al* 2015 Addressing China's grand challenge of achieving food security while ensuring environmental sustainability *Sci. Adv.* **1** e1400039
- [27] Mittal S, Dai H, Fujimori S and Masui T 2016 Bridging greenhouse gas emissions and renewable energy deployment target: comparative assessment of China and India *Appl. Energy* **166** 301–13
- [28] Dai H C, Herran D S, Fujimori S and Masui T 2016 Key factors affecting long-term penetration of global onshore wind energy integrating top-down and bottom-up approaches *Renew. Energy* **85** 19–30
- [29] Fujimori S, Kainuma M, Masui T, Hasegawa T and Dai H 2014 The effectiveness of energy service demand reduction: a scenario analysis of global climate change mitigation *Energy Policy* **75** 379–91
- [30] Fujimori S, Hasegawa T, Masui T, Takahashi K, Herran D S, Dai H C, Hijioka Y and Kainuma M 2017 SSP3: AIM implementation of shared socioeconomic pathways *Glob. Environ. Change* **42** 268–83
- [31] McCollum D L, Bauer N, Calvin K, Kitous A and Riahi K 2014 Fossil resource and energy security dynamics in conventional and carbon-constrained worlds *Clim. Change* **123** 413–26
- [32] Cherp A, Jewell J, Vinichenko V, Bauer N and De Cian E 2016 Global energy security under different climate policies, GDP growth rates and fossil resource availabilities *Clim. Change* **136** 83–94
- [33] Wise M, Calvin K, Thomson A, Clarke L, Bond-Lamberty B, Sands R, Smith S J, Janetos A and Edmonds J 2009 Implications of limiting CO₂ concentrations for land use and energy *Science* **324** 1183–6
- [34] Sala O E *et al* 2000 Global biodiversity scenarios for the year 2100 *Science* **287** 1770–4
- [35] NDRC 2016 13th Five-Year Plan development plan for renewable energy
- [36] NDRC 2016 13th Five-Year Plan development plan for energy sector
- [37] NDRC 2016 13th Five-Year Plan development plan for electricity sector
- [38] SCPRC 2017 13th Five-Year Plan for Protection of Ecological Environment
- [39] MNR 2017 The National Land Plan (2016–2030)
- [40] UNFCCC 2015 Enhanced actions on Climate Change: China's intended nationally determined contributions (<https://4.unfccc.int/sites/ndcstaging/PublishedDocuments/China%20First/China%27s%20First%20NDC%20Submission.pdf>)
- [41] Lotze-Campen H, Popp A, Beringer T, Muller C, Bondeau A, Rost S and Lucht W 2010 Scenarios of global bioenergy production: the trade-offs between agricultural expansion, intensification and trade *Ecol. Modell.* **221** 2188–96
- [42] Smith P 2013 Delivering food security without increasing pressure on land Pete Smith *Glob. Food Security* **2** 18–23
- [43] Krey V, Luderer G, Clarke L and Kriegler E 2014 Getting from here to there—energy technology transformation pathways in the EMF27 scenarios *Clim. Change* **123** 369–82
- [44] McCollum D L, Krey V, Riahi K, Kolp P, Grubler A, Makowski M and Nakicenovic N 2013 Climate policies can help resolve energy security and air pollution challenges *Clim. Change* **119** 479–94
- [45] Pittel K and Rubbelke D T G 2008 Climate policy and ancillary benefits: a survey and integration into the modelling of international negotiations on climate change *Ecol. Econ.* **68** 210–20
- [46] Somanathan E *et al* 2014 National and sub-national policies and institutions. *Climate Change 2014: Mitigation of Climate Change* (Cambridge and New York, NY: Cambridge University Press)