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Mitigating Carbon Leakage in China's Carbon Neutrality Through Coordinated Greenhouse Gas Reductions and Increased Natural Carbon Uptake

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ABSTRACT

As a major emitter of carbon dioxide (CO_2), China is committed to achieving carbon neutrality (CN). However, unilateral climate policies risk carbon leakage through the relocation of emission-intensive industries, potentially undermining their intended benefits. Herein, we couple an integrated assessment model with a simple climate model to quantify the carbon leakage associated with China's CN by 2100 and assess its impact on global warming. The results show that China achieving CN will lead to carbon leakage of 6.9% to 14.9%. While the emissions-level changes appear modest, the leakage leads to an increase in CO_2 concentrations, rising from 2.1 ppm in the target year to 7.7 ppm by 2100. The global cooling effect of China's CN is 0.15–0.19 °C, with leakage weakening this effect by 0.02 °C. Increased carbon sink capacity mitigates 8.9%–11.3% of the warming caused by leakage, and synergistic reductions in methane and nitrous oxide emissions offset over 70.5% of the leakage-induced warming. Therefore, solutions to carbon leakage should go beyond merely preventing increased emissions and focus on offsetting the broader climate impacts caused by leakage. These findings underscore the critical importance of addressing carbon leakage in climate policy design to mitigate the risks of global warming and maximize the benefits of CN efforts.

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1. Introduction

To meet the Paris Agreement climate goals, over a hundred countries have announced net-zero targets, aiming to balance greenhouse gas emissions with removal efforts [1]. However, unilateral climate policies for production-based emissions lead to the relocation of high-carbon industries to countries or regions with looser regulations, raising concerns about carbon leakage [2–6]. According to the Intergovernmental Panel on Climate Change (IPCC), carbon leakage refers to the portion of emission reductions that is offset by an increase in emissions in non-constrained countries above their baseline levels [7]. Carbon leakage brings both environmental and economic challenges: For one thing, the offshoring of carbon emissions weakens the effectiveness of climate policies by lessening actual emission reductions and may even lead to an overall increase in global emissions [8]. For another, carbon leakage undermines the competitiveness of energy-intensive industries, promotes investment relocation, and causes job losses in regulated markets, further exacerbating inequalities in international climate efforts [9,10].

Initially, research on carbon leakage focused on the carbon dioxide (CO_2) emissions of climate policies. For instance, an *ex-post* analysis of the Kyoto Protocol indicated that binding emission commitments led to an approximate 8% increase in embodied carbon imports from non-committed countries, along with a 3% rise in the carbon intensity of these imports, particularly in the metals, cement, and chemical sectors [2]. With the advancement of research, a broader range of greenhouse gases, including methane (CH_4) and nitrous oxide (N_2O), have been incorporated into carbon leakage studies, depending on the scope of targeted climate policies. A study has shown that, under the Paris Agreement, greenhouse gas leakage rates among countries range from 1% to 9%. Moreover, the deterioration of international trade relations, such as the United States' withdrawal from the Agreement, could

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approximately double leakage rates to 3%–16% [11]. Current research on carbon leakage mainly employs four methodological approaches: computable general equilibrium (CGE) models, econometric models, input–output models, and integrated assessment models (IAMs). Early studies used global CGE models to simulate the effects of unilateral climate policies. Employing a CGE model, Kuik and Hofkes [12] found that the carbon leakage rate in the steel sector under the European Union Emissions Trading System (EU ETS) was 35%. Since then, econometric and input–output models have been employed to conduct empirical studies on carbon leakage. An empirical study based on econometric models indicated that the EU ETS did not lead to the relocation of multinational corporations' carbon emissions abroad [13]. Meng et al. [10] employed multi-regional input–output models and found that carbon leakage between the Global North (developed countries) and Global South (developing countries) had decreased. In recent years, IAMs have become an important tool for analyzing carbon leakage, especially under long-term climate scenarios. Compared with other methods, IAMs integrate multi-sectoral details (e.g., energy and land use) and link economic modules with the climate system, allowing the tracking of terrestrial carbon leakage resulting from energy structure transitions or trade flow shifts. For example, a Global Change Analysis Model (GCAM)-based study showed that imposing import restrictions on forest-clearing production areas could shift global soybean import demand to other countries, with an emission leakage rate ranging from 8% to 65% [14]. Furthermore, coupling IAMs with climate models enables a direct linkage to be made between changes in greenhouse gas emissions and global temperature responses.

Due to China's deep integration into global supply chains and the nation's energy-intensive industrial structure, carbon leakage is particularly critical in its low-carbon transition [10,15,16]. Some of China's existing carbon-reduction policies have been shown to result in carbon leakage [17,18]. Through a firm-level empirical analysis, He and Chen [19] found that China's emissions trading scheme (ETS) shifted carbon leakage to regions with less stringent environmental regulations, leading to an overestimation of the ETS's mitigation effects. Similarly, Yu et al. [20] observed that China's energy-saving target policies increased CO_2 emissions in regions with less ambitious goals due to industrial relocation. Meanwhile, China's carbon neutrality (CN) goals could induce cross-border carbon leakage through changes in international trade patterns, energy price fluctuations, and technological spillovers [4,21,22]. Studies based on computable general equilibrium models indicate that China's Nationally Determined Contributions (NDCs) would lower global energy prices, thereby driving carbon leakage to other countries [23]. Existing research on China's carbon leakage has mainly focused on CO_2, because the neutrality target initially emphasized this gas. However, these studies overlook critical synergistic effects arising from other greenhouse gases [24–26]. Reductions in CO_2 emissions lead to simultaneous decreases in CH_4 and N_2O, generating additional cooling effects that can partially offset the warming caused by CO_2 leakage. Therefore, studies on carbon leakage should expand their scope to encompass multiple greenhouse gases for a more comprehensive assessment. Moreover, previous studies have primarily focused on reporting the emission impacts of carbon leakage [5,27,28], with less attention given to its indirect warming effects and ecosystem impacts. Carbon leakage directly raises atmospheric CO_2 concentrations, leading to temperature increases [29]. The rise in atmospheric CO_2 concentrations also increases the carbon fertilization effect, indirectly increasing carbon sink uptake capacity [30]. This, in turn, partially offsets the warming effects of carbon leakage, creating a complex feedback loop [31,32]. While the temperature changes caused by carbon leakage may appear modest in the short term, delayed amplification effects could arise through intricate climate feedback mechanisms, such as changes in ice albedo and forest biomass [33–35]. Quantifying the delayed climate responses to carbon leakage is therefore critical for policymakers, as doing so can guide the development of more effective medium- and long-term strategies for mitigating and adapting to climate change.

To bridge this gap in the literature, this study combines an integrated assessment model with a simplified climate model to analyze the carbon leakage caused by China's CN by 2100 and evaluate its effects on global warming. Scenarios based on four shared socioeconomic pathways (SSPs) and representative concentration pathways (RCPs) are considered: SSP126, SSP245, SSP370, and SSP585. First, GCAM is used to estimate the pattern of carbon leakage caused by China's CN. Subsequently, the finite-amplitude impulse response (FaIR) model is applied to quantify the temperature response and determine how ecosystem carbon uptake mitigates leakage impacts. Finally, simulation experiments are used to identify key contributors to the global cooling effects resulting from China's CN. This study aims to address three questions: ① What is the magnitude of greenhouse gas leakage associated with China's CN, and which countries or sectors are most vulnerable to its impacts? ② How much does carbon leakage reduce the global cooling effect of CN, considering carbon cycle feedback? ③ Can synergistic greenhouse gas reductions and natural carbon uptake feedback offset the warming impacts of such leakage?

The structure of this paper is as follows: Section 2 details the methods, Section 3 highlights the main results, Section 4 discusses implications and limitations, and Section 5 provides conclusions.

2. Methods

This study develops a framework that combines GCAM and the FaIR climate response model to assess carbon leakage under China's CN policy. GCAM is used to simulate emission and trade dynamics by solving market balances across 32 regions under China's emission constraints, generating global greenhouse gas emission pathways. These emission pathways are then fed into the FaIR model, which simulates the corresponding global temperature responses.

2.1. Estimation of carbon leakage at the emission side

GCAM v6.0 was employed to assess the carbon leakage associated with China's CN policy. GCAM is a widely used integrated assessment model that represents five interconnected systems—namely, economy, energy, agriculture and land use, water, and climate—across 32 global geopolitical regions [36]. The model operates in five-year intervals from 2015 to 2100, solving for equilibrium prices and quantities in energy, agricultural, water, land-use, and CO_2 markets for each period and region. At each time step, market equilibrium is achieved by identifying prices at which supply equals demand, with production, consumption, and trade flows dynamically adjusted in response to policy and market signals. Simulation outcomes are primarily driven by exogenous assumptions, including population growth, labor productivity, resource availability, technological development, and policy interventions [37].

As a mainstream IAM, GCAM offers unique advantages for carbon leakage analysis. Its multi-sectoral structure enables detailed modeling of changes in global production, consumption, and trade patterns induced by emission reduction policies. In addition, GCAM incorporates multi-gas emission modules that track not only CO_2 but also CH_4 and N_2O emissions, allowing for a more comprehensive assessment of carbon leakage and related mitigation co-benefits.

Considering that land-use emissions also involve carbon leakage [38], both fossil fuel emissions and land-use emissions are considered in this study. CO_2 emissions related to fossil fuels in GCAM are based on fuel consumption and global emission factors by fuel type (oil, unconventional oil, natural gas, and coal). Emission factors refer to the Carbon Dioxide Information and Analysis Center (CDIAC) global inventory [39]. Land-use emissions (vegetation/soil) are calculated as follows:

$$E_t^{\text{veg/soil}} = A_t \times D_t^{\text{veg/soil}} - A_{t-1} \times D_{t-1}^{\text{veg/soil}} \quad (1)$$

where $E_t^{\text{veg/soil}}$ represents the carbon emissions resulting from land-use changes in period t, A_t denotes the land area, and $D_t^{\text{veg/soil}}$ is the average carbon density in that area (which can be subdivided into vegetation and soil carbon density).

For CO_2 emissions, the carbon price affects emissions by raising the cost of high-emission technologies, reducing their market share. A logistic function distributes market share among different technologies and fuels, based on their relative costs and predefined share weights:

$$s_i = \frac{\alpha_i c_i^{\gamma}}{\sum_{j=1}^{N} \alpha_j c_j^{\gamma}} \quad \text{or} \quad s_i = \frac{\alpha_i \exp(\beta c_i)}{\sum_{j=1}^{N} \alpha_j \exp(\beta c_j)} \quad (2)$$

where s_i represents the market share of technology or sub-sector i, α_i is the share weight that captures preferences and facilitates the gradual adoption of new technologies, and c_i is the cost of technology or sub-sector i. j is the index representing all alternative technologies or sub-sectors within the same market as i (including i), and N indicates the total number of such alternatives in that market. α_j and c_j are the share weight and cost of technologies or sub-sectors j, respectively. β and γ represent the logit exponents, indicating the extent to which cost influences market share. When a carbon cap is implemented, a carbon tax is added to the costs of technologies or sub-sectors (e.g., liquid-fueled vehicles), affecting their market activity.

$$E_{\text{non-CO}_2,t} = A_t \times \text{EF}_{t_0} \times (1 - \text{MAC}(E_{\text{price},t})) \quad (3)$$

where $E_{\text{non-CO}_2,t}$ represents the emissions of non-CO_2 greenhouse gases (CH_4 and N_2O) during period t, and EF_{t_0} refers to the base-year emissions per unit of activity, with 2015 as the reference year in this study. The marginal abatement cost (MAC) curve represents the cost of reducing emissions and is assigned to various technologies, as mapped directly from the US Environmental Protection Agency (EPA) [40]. $E_{\text{price},t}$ denotes the emissions price (carbon price) applied in the model.

China's CN target is represented in GCAM as a national emissions cap. The model adjusts CO_2 prices iteratively to find the price that meets the emissions cap while ensuring market equilibrium. Changes in domestic economic activity, energy trade, or production processes can result in increased emissions in other countries due to global dynamic feedback mechanisms.

All technological and socioeconomic assumptions align with the core version of GCAM v6.0. The socioeconomic pathways, such as regional population growth, labor force participation rates, and labor productivity, follow the trajectories defined by the SSPs. The emission factors for each country are specified, with fossil fuel emission factors sourced from the Carbon Dioxide Information Analysis Center (CDIAC) global inventory [39], and non-CO_2 mitigation cost curves are directly mapped from the MAC curves [41]. Additionally, one endogenous assumption in GCAM is that the price mechanism adjusts in time to ensure supply and demand balance in markets such as energy and land at each time step. More detailed assumptions and parameter settings are available in Note S1 in Appendix A.

2.2. Estimation of climate response

The FaIR model version 2.1 was used to simulate the global climate system and carbon cycle dynamics. A detailed introduction to the FaIR model is provided in Note S2 in Appendix A. This simple emissions-based climate model incorporates a carbon cycle influenced by background warming levels and cumulative carbon uptake by land and ocean sinks [42]. The FaIR model is calibrated to align with historical data, accounting for uncertainties in factors such as ocean heat content, atmospheric CO_2 concentrations, and aerosol radiative forcing. This calibration ensures the model is consistent with the ranges presented in the IPCC's Sixth Assessment Report (AR6) [43]. The FaIR model was selected for its ability to simulate global temperature responses to emission pathways while maintaining consistency with IPCC AR6 uncertainty ranges. Unlike full Earth system models, it enables the large ensemble runs necessary for evaluating multiple carbon leakage scenarios, capturing uncertainties in carbon cycle feedbacks and short-lived climate forcers.

The calibration process consists of two main steps. First, historical simulations are aligned with observed climate trends to replicate past global temperature changes accurately, as detailed in Fig. S1 in Appendix A. Second, model parameters are constrained to fall within established ranges for key climate metrics, including equilibrium climate sensitivity (1.8–5.1 °C, with a best estimate of 3.1 °C), transient climate response (1.2–2.4 °C, with a best estimate of 1.8 °C), and aerosol effective radiative forcing (−2.0 to −0.6 $W \cdot m^{-2}$, with a best estimate of −1.3 $W \cdot m^{-2}$) [44]. These constraints ensure that the model captures a broad spectrum of possible climate outcomes while remaining consistent with widely accepted scientific assessments [45].

Using 841 calibrated parameter sets, we examine uncertainties in the global climate impact of China's CN targets and the associated risks of carbon leakage. Each ensemble member achieves a root-mean-square error of less than 0.17 °C when comparing modeled and observed global mean surface temperatures, consistent with historical emissions data from sources such as the Reduced Complexity Model Intercomparison Project (RCMIP) [44]. The future analysis includes running the SSP-RCP scenarios in FaIR using precalculated climate response calibrations from CMIP6 models [44]. We operate in stochastic mode to capture internal variability. Additionally, we enable the methane lifetime routine, which is influenced by short-lived climate forcers and reactive gases [46].

To evaluate carbon leakage risks under varying trade and climate policy conditions, we couple GCAM v6.0 with FaIR v2.1. This integration offers several advantages over other IAM–Earth system model (ESM) frameworks:

(1) High sectoral resolution, which allows detailed assessment of both fossil fuel and land-use-related emissions shifts across regions, providing a stronger capacity to capture sectoral leakage effects compared with many other IAMs.

(2) Probabilistic ensemble simulation, which enables transparent representation of emissions-to-warming uncertainty—a feature absent in Hector (GCAM's default climate module).

(3) Computational efficiency, which supports large-scale ensemble simulations across multiple trade and policy scenarios.

Overall, the GCAM–FaIR coupling provides a balanced combination of sectoral detail, climate response interpretability, and computational efficiency, making it suited for policy-relevant carbon leakage analysis.

2.3. Scenario designs

We analyze eight scenarios across two key dimensions (Table 1) to assess the carbon leakage associated with China's CN goal. The

first dimension involves combinations of the SSPs–RCPs: SSP126, SSP245, SSP370, and SSP585. These scenarios are selected to examine variations in policy-induced carbon leakage across different climate pathways. SSP126 represents a low-emission pathway aimed at limiting global warming to below 2 °C relative to pre-industrial levels (1850–1900). SSP245 reflects an intermediate-emission pathway, with temperatures projected to rise by approximately 2.7 (2.1–3.5) °C by 2100. SSP370 and SSP585 represent high-emission pathways characterized by heavy fossil fuel dependence, with temperatures rising by 3.6 (2.8–4.6) °C and up to 4.4 (3.3–5.7) °C by 2100, respectively [47,48]. The reference year for future projections in the GCAM and FaIR models is 2015.

In addition, we adopt an assumption based on prior studies that China's business-as-usual (BAU) scenario follows SSP1. This pathway reflects a world focused on green and sustainable development, which aligns with China's vision of ecological civilization and recent population trends [49]. For regions outside China, emissions and climate assumptions remain consistent across different SSP scenarios, as summarized in Table 1. Population and gross domestic product (GDP) data for various countries under SSP1, SSP2, SSP3, and SSP5 are integrated into GCAM to project future demands for energy, services, and goods [50].

We obtained China's CN emission scenarios (Fig. S2 in Appendix A) from the Dynamic Projection Model for Emissions in China (DPEC) developed by a previous study [49], as shown in Fig. S1. In the CN scenario, China aims to achieve CN and to sustain this target through 2100, as detailed in Fig. S2. Following assumptions from previous studies, we incorporate an exogenous carbon sink of 0.9 Gt of CO_2 per year from terrestrial ecosystems throughout the study period [49,51].

By comparing emission differences between the CN and BAU scenarios for other countries across different SSPs–RCPs, the potential impact of China's CN policy on the carbon leakage can be assessed.

$$CL_i = E_{\text{Other, CN},i} - E_{\text{Other, BAU},i}, i = CO_2, CH_4, \text{and } N_2O \quad (4)$$

where CL_i represents the carbon leakage of species i, $E_{\text{Other,BAU},i}$ represents the total global emissions excluding China under the BAU scenario, and $E_{\text{Other,CN},i}$ represents the total global emissions excluding China under the CN scenario.

2.4. Attribution analysis

2.4.1. The role of natural carbon uptake in mitigating carbon leakage

In the carbon cycle module of the FaIR model, the response of atmospheric emissions' residence time and distribution characteristics to carbon uptake is described by the following equation [42]:

$$\begin{aligned} \text{IIRF} = {} & \text{IIRF}_0 + \text{IIRF}_{\text{uptake}} \times (E_{\text{cumulative}} - E_{\text{airborne}}) + \text{IIRF}_{\text{temperature}} \times T \\ & + \text{IIRF}_{\text{airborne}} \times E_{\text{airborne}} \end{aligned} \quad (5)$$

where IIRF represents the integrated impulse response function, IIRF_0 is the baseline time-integrated airborne fraction, and $\text{IIRF}_{\text{uptake}}$ quantifies the sensitivity of the IIRF to the natural carbon uptake. $E_{\text{cumulative}}$ represents the total cumulative emissions, E_{airborne} represents the total airborne emissions remaining in the atmosphere, $\text{IIRF}_{\text{temperature}}$ is the sensitivity of the time-integrated airborne fraction to the temperature anomaly, and T is the temperature anomaly in Kelvin. By designing comparative experiments with the $\text{IIRF}_{\text{uptake}}$ parameter enabled and disabled, the role of carbon sequestration in mitigating carbon leakage can be assessed.

2.4.2. Decomposition of the cooling effect of China's CN

Three additional independent experiments are incorporated into the FaIR model beyond the BAU and CN for each SSP–RCP scenario: ① CO_2 reduction in China (China_CO_2); ② CO_2, CH_4, and N_2O reductions in China (China_CCN); and ③ global CO_2 emissions change (World_CO_2). The contributions of four factors to global warming (up to 2100) are analyzed, as detailed in the Eq. (6): ① the contribution of China's CO_2 reduction ($\Delta T_{\text{China_CO}_2}$); ② the synergistic effect of CH_4 and N_2O reductions in China ($\Delta T_{\text{China_CH}_4\&\text{N}_2\text{O}}$); ③ CO_2 leakage due to China's CN ($\Delta T_{\text{Other_CO}_2\text{_Leakage}}$); and ④ CH_4 and N_2O leakage due to China's CN ($\Delta T_{\text{Other_CH}_4\&\text{N}_2\text{O_Leakage}}$).

$$\begin{aligned} \Delta T_{\text{CN}} = {} & \Delta T_{\text{China_CO}_2} + \Delta T_{\text{China_CH}_4\&\text{N}_2\text{O}} + \Delta T_{\text{Other_CO}_2\text{_Leakage}} \\ & + \Delta T_{\text{Other_CH}_4\&\text{N}_2\text{O_Leakage}} \end{aligned}$$

$$\Delta T_{\text{China_CO}_2} = T_{\text{China_CO}_2} - T_{\text{BAU}}$$

$$\Delta T_{\text{China_CH}_4\&\text{N}_2\text{O}} = T_{\text{China_CCN}} - T_{\text{China_CO}_2} \quad (6)$$

$$\Delta T_{\text{Other_CO}_2\text{_Leakage}} = T_{\text{World_CO}_2} - T_{\text{China_CO}_2}$$

$$\Delta T_{\text{Other_CH}_4\&\text{N}_2\text{O_Leakage}} = T_{\text{CN}} - T_{\text{China_CCN}} - (T_{\text{World_CO}_2} - T_{\text{China_CO}_2})$$

where $\triangle T_{\text{CN}}$ represents the total temperature reduction due to China's CN, and T_{BAU}, $T_{\text{China_CO}_2}$, $T_{\text{World_CO}_2}$, $T_{\text{China_CCN}}$, and T_{CN} represent the simulations of global temperature change under the BAU, China_CO_2, World_CO_2, China_CCN, and CN scenarios, respectively. Table S1 in Appendix A provides more detailed information.

3. Results

3.1. Potential carbon leakage toward CN

To investigate the risk of carbon leakage associated with China's CN, this study adjusts China's carbon emission constraint parame-

Table 1
Scenario design under different SSPs–RCPs scenarios.

Scenario	Description
SSP126-BAU	Both China and other regions follow the SSP126 emission pathway; no emission constraint
SSP126-CN	Both China and other regions follow the SSP126 emission pathway; China aims to achieve CN
SSP126-CL	Difference between SSP126-CN and SSP126-BAU
SSP245-BAU	China follows the SSP126 emission pathway, while other regions follow the SSP245 pathway; no emission constraint
SSP245-CN	China follows the SSP126 emission pathway, while other regions follow the SSP245 pathway; China aims to achieve CN
SSP245-CL	Difference between SSP245-CN and SSP245-BAU
SSP370-BAU	China follows the SSP126 emission pathway, while other regions follow the SSP370 pathway; no emission constraint
SSP370-CN	China follows the SSP126 emission pathway, while other regions follow the SSP370 pathway; China aims to achieve CN
SSP370-CL	Difference between SSP370-CN and SSP370-BAU
SSP585-BAU	China follows the SSP126 emission pathway, while other regions follow the SSP585 pathway; no emission constraint
SSP585-CN	China follows the SSP126 emission pathway, while other regions follow the SSP585 pathway; China aims to achieve CN
SSP585-CL	Difference between SSP585-CN and SSP585-BAU

The SSP126-CL to SSP585-CL scenarios are used to quantify China's domestic mitigation effects and the associated carbon leakage. More detailed information is provided in Table S4 in Appendix A.

ters within GCAM to assess the impacts on CO_2, CH_4, and N_2O emission pathways across different countries. Under the different SSPs, China's CN is estimated to result in carbon leakage ranging of 6.9% to 14.9% (196.4 to 406.2 Mt CO_2). In low-emission scenarios (SSP1), the leakage decreases by 34.3 Mt CO_2 by the end of the century. Conversely, in high-emission scenarios (SSP3), carbon leakage increases by an additional 40.9 Mt CO_2. Spatially, policy-induced carbon leakage is concentrated in developing countries and certain developed regions, with South Asia (notably India) and parts of Africa exhibiting the highest levels of leakage (orange and red regions). For example, in the SSP3 and SSP5 scenarios, carbon leakage in India reaches 58.4 and 72.2 Mt CO_2, respectively (Fig. 1).

China's CN-induced CH_4 and N_2O emissions reductions also exhibit leakage effects, amounting to 220.8–246.7 kt CH_4 and 67.6–75.3 kt N_2O in the target year under the SSP1 and SSP2 scenarios, respectively. By 2100, these values decline to 97.9–100.5 kt CH_4 and 30.9–35.6 kt N_2O. In contrast, under the SSP3 scenario, CH_4 and N_2O reductions exhibit spatial spillover benefits, with emissions in other countries reduced by 502.5 kt CH_4 and 144.3 kt N_2O by 2100. Spatially, CH_4 leakage mainly originates from shifts in agricultural and energy sector activities, occurring in regions such as Australia (1.2–171.3 kt CH_4) and South America (−10.6 to 225.7 kt CH_4). Notably, spillover benefits are most pronounced in West Africa, where reductions range from −92.1 to −228.4 kt CH_4. N_2O leakage demonstrates a more dispersed spatial distribution but particularly occurs in the United States and South America (represented by red and orange regions). Simultaneously, West Africa shows substantial co-benefits in N_2O reductions, ranging from −10.6 to −23.7 kt N_2O.

3.2. Different sensitivities to carbon leakage across countries and sectors

Changes in energy consumption patterns, energy product prices, and international trade parameters resulting from CN are also examined. Regional and sectoral variations are observed in leakage patterns. The regional biomass energy sector (Reg_Biom) is the primary contributor to carbon leakage. For instance, in India and West Africa, emissions reach 61.1–107.8 and 51.2–87.5 Mt, respectively, reflecting China's CN reliance on biomass energy imports from these regions (Fig. 2(a)). Under high-emission scenarios (SSP3 and SSP5), conventional coal (Coal_Conv) sectors show substantial carbon leakage, particularly in India (15.6–25.4 Mt) and the United States (9.1–10.3 Mt). Additionally, due to interactions among global trade, agricultural demand, and carbon markets, land-use emissions in the United States emerge as an important source of carbon leakage, with contributions ranging from 2.2 to 17.8 Mt across scenarios. Notably, the biomass power generation (Bio_Conv) and refining (Refining) sectors demonstrate carbon emission reduction spillover effects. In India, for example, these sectors achieve reductions ranging from −13.8 to −41.6 Mt and −9.0 to −39.9 Mt, respectively, underscoring their potential for mitigating emissions globally.

For CH_4 leakage, agricultural sectors—particularly rice cultivation (Rice) and beef production (Beef)—are the largest contributors.

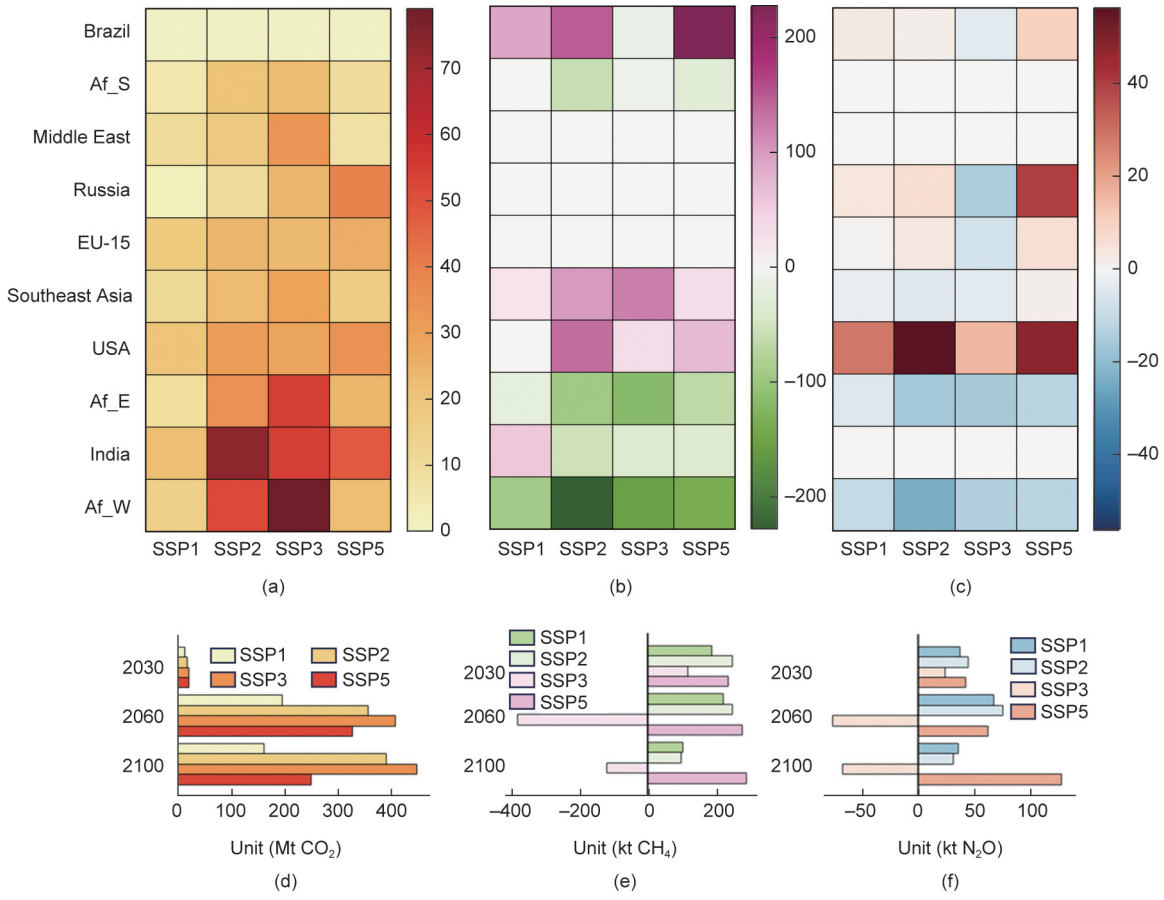

Fig. 1. Global CO_2, CH_4, and N_2O leakage induced by China's CN policies under different scenarios. (a–c) Regional variation of (a) CO_2, (b) CH_4, and (c) N_2O leakage under the SSP1, SSP2, SSP3, and SSP5 scenarios, respectively. (d–f) Temporal evolution of (d) CO_2, (e) CH_4, and (f) N_2O leakage from 2030 to 2100 across scenarios, providing insights into the dynamic trends of emissions leakage over the long term.

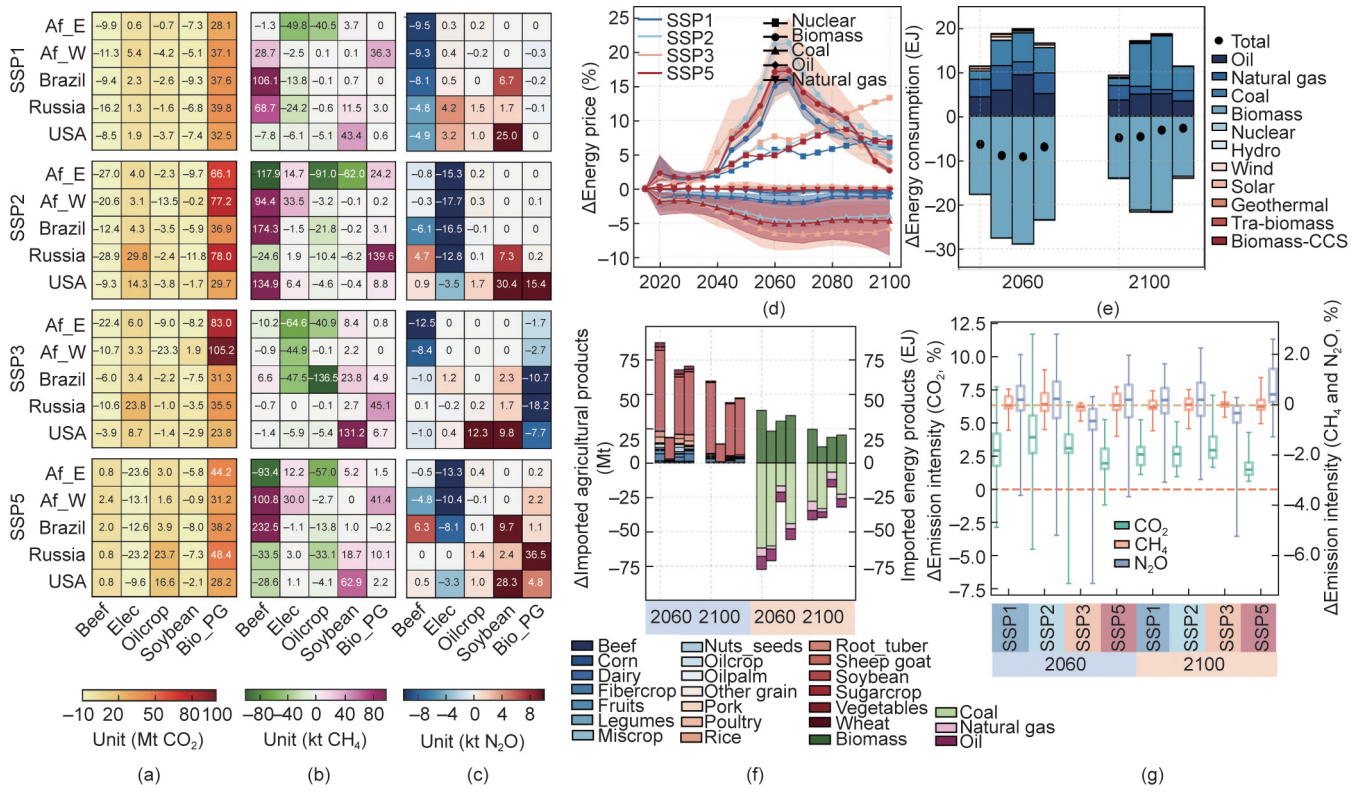

Fig. 2. Sectoral and country-level details of CO_2, CH_4, and N_2O leakage, along with associated changes in energy prices, consumption, trades, and emission intensities. (a–c) Changes in (a) CO_2, (b) CH_4, and (c) N_2O emissions across different countries and sectors under various SSP scenarios (results for 2100 are provided in Figs. S3–S5 in Appendix A, and abbreviations of country or region names are provided in Table S2). (d) Trends in energy price changes induced by China's CN in other countries. (e) Shifts in the composition of energy consumption, disaggregated by energy sources, with black dots indicating total energy consumption. (f) Changes in agricultural and energy product trade in China under different SSP scenarios. (g) Variations in CO_2, CH_4, and N_2O emission intensities over time.

For instance, CH_4 leakage from the beef production sector in Brazil reaches 93.4–138.5 Mt, while emissions in Southeast Asia (SEAsia) are primarily associated with rice cultivation, ranging from 114.7 to 140.1 Mt (Fig. 2(b)). In contrast, N_2O leakage levels are generally lower and primarily concentrated in the unmanaged land sector (Unm_Land). The United States is the main source of N_2O leakage across the scenarios, contributing 0.1–1.5 kt. Meanwhile, the power sector emerges as a beneficiary of N_2O reductions (Fig. 2(c)). Under the SSP585 scenario, Brazil achieves N_2O co-benefit reductions of 11.3 kt, while India and Southeast Asia reach reductions of 9.8 and 7.7 kt, respectively.

As shown in Fig. 2(d), China's transition toward CN drives a sharp increase in biomass energy prices, which rise by 15%–21% above the BAU level and peak between 2060 and 2065. Nuclear prices gradually increase by 6.7%–13.3%, while coal prices decline by 1.1%–5.8% by 2100. Fig. 2(e) indicates that the total energy consumption in other countries decreases by 2.7%–4.9% by 2100. Biomass consumption drops significantly 13.6%–21.5% by 2100, while coal and oil consumption rise by 2100. Fig. 2(f) shows that China's pursuit of CN is accompanied by growing imports of agricultural products—especially grains and sheep-and-goat products. Biomass imports rise by 23.0–38.3 EJ, while imports of coal, natural gas, and oil fall sharply by 44.3, 3.7, and 7.8 EJ, respectively, under SSP5. Finally, Fig. 2(g) shows that the CO_2 emission intensities of other countries increase in all scenarios, rising by more than 2.5% by 2100 under SSP1, while CH_4 and N_2O intensities fluctuate minimally (±1%). These findings underscore the interactions between China's CN policies and other countries' energy structures, resource dependencies, and emission intensities, contributing to carbon leakage.

3.3. The mitigating effect of natural carbon uptake

In the FaIR model, we focus on parameters related to global temperature anomalies relative to pre-industrial levels and CO_2 concentrations under different emission pathways. Specifically, the $IIRF_{uptake}$ parameter is analyzed to quantify the contribution of natural carbon uptake, such as forest sinks. As shown in Fig. 3, China's CN leads to a reduction in CO_2 concentrations across all scenarios, with a decline of 24.4–48.6 ppm by the end of the century (Figs. 3(a)–(d)). However, carbon leakage (dashed line) weakens this effect, especially under the high-emission scenarios (SSP370 and SSP585). In the target year, leakage-induced CO_2 concentrations increase by 2.1 ppm, and this effect amplifies to 7.7 ppm by 2100. This increases the global carbon fertilization effect, strengthening natural carbon uptake. Therefore, the carbon uptake feedback reduces the impact of carbon leakage, particularly in the high-emission scenarios. For example, under the low-emission scenarios (SSP126 and SSP245), the effect of carbon uptake mitigation ranges from 8.9% to 9.8%; in the high-emission scenarios (SSP370 and SSP585), this effect is more pronounced (10.4%–11.3%) (Figs. 3(e)–(h)).

3.4. Decomposition of the global cooling effect considering carbon leakage

Fig. 4 shows the impacts of China's carbon reductions, CH_4 and N_2O reductions, CO_2 leakage, and CH_4 and N_2O leakage on global temperature changes under different SSPs–RCPs scenarios. In the target year, China's carbon reductions—including leakage effects—mitigate global warming by 0.08 °C. By 2100, this impact

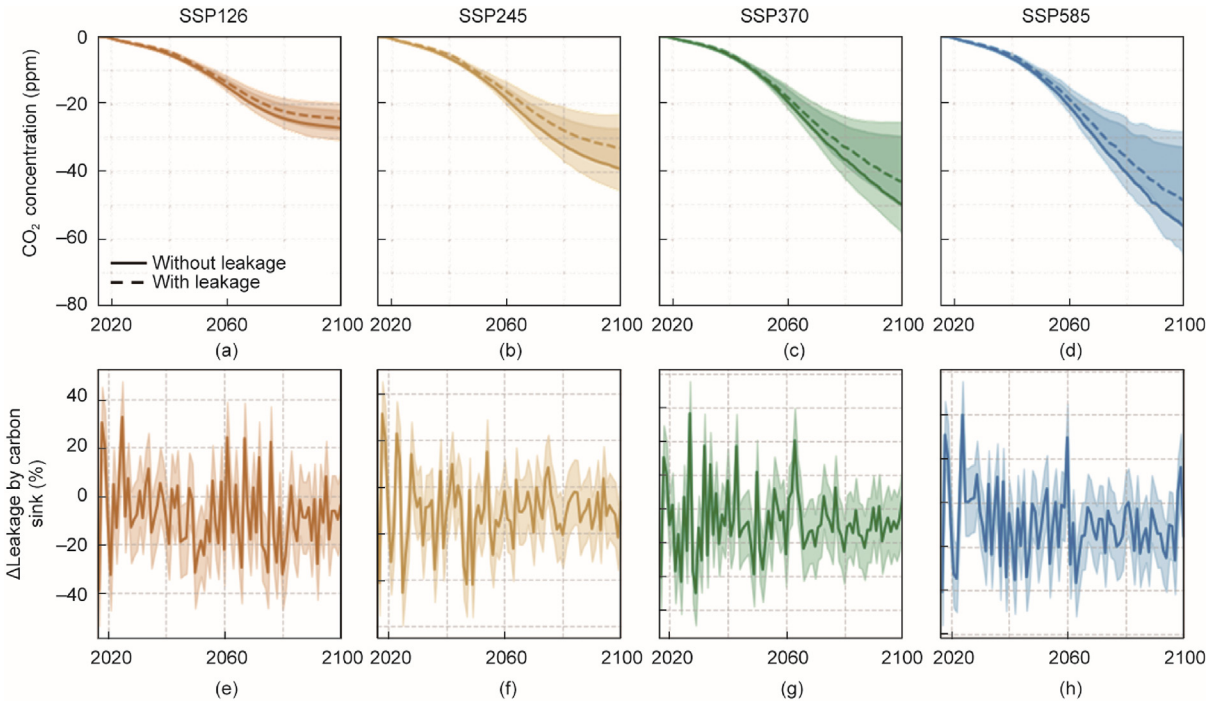

Fig. 3. Impact of carbon leakage on global CO_2 concentrations and carbon uptake. (a–d) Changes in CO_2 concentration (ppm) due to China's CN policies under (a) SSP126, (b) SSP245, (c) SSP370, and (d) SSP585. Solid lines represent the impact of China's CN without carbon leakage, while dashed lines indicate the impact with the leakage. Shaded areas show the 95% confidence interval. (e–h) Mitigating effect of natural carbon uptake on carbon leakage under (e) SSP126, (f) SSP245, (g) SSP370, and (h) SSP585. More detailed information is provided in Fig. S6 in Appendix A.

grows to 0.15–0.19 °C. Decomposing the contributions of different factors reveals that China's carbon reductions are the main driver, accounting for 92.9%–96.5% of the cooling effect in the target year and increasing to 97.8%–104.6% by 2100. CH_4 and N_2O reductions rank second, with greater contributions under the low-emission scenarios (i.e., SSP126 and SSP245), where they account for approximately 11.0%–12.5% of the cooling effect (0.02 °C by 2100).

On the other hand, carbon leakage is the main negative factor. Under the high-emission scenarios (SSP370 and SSP585), carbon leakage offsets 9.3%–14.0% (0.02–0.03 °C) by 2100. This finding indicates that, without action to limit carbon leakage, the cooling benefit of China's CN will weaken over time. CH_4 and N_2O leakage has a lesser effect, contributing less than 1.9% of warming in the target year and in some cases even cooling slightly (i.e., in SSP585). By 2100, its impact remains below 1.2%. Notably, synergy reductions in CH_4 and N_2O emissions from China offset more than 70.5% of the combined impacts of CH_4 and N_2O leakage and carbon leakage by 2100. In conclusion, improving global cooperation, and focusing on CH_4 and N_2O reductions are key to limiting temperature rise caused by carbon leakage.

4. Discussion

This research contributes to the design of China's CN pathway in three key ways: ① It quantifies the potential carbon leakage resulting from China's CN under four climate change pathways, highlighting variations across countries and sectors; ② it estimates the role of carbon uptake in mitigating leakage—an aspect largely overlooked in previous studies [5,27,28]; and ③ by incorporating this effect, it decomposes the global cooling effect induced by China's CN into four components: carbon reductions in China, CH_4 and N_2O reductions, CO_2 leakage, and CH_4 and N_2O leakage. Furthermore, it is found that CH_4 and N_2O reductions effectively offset the leakage impact in most scenarios. These findings underscore the critical role of synergistic greenhouse gas reductions and the feedback effect of carbon uptake, both of which are essential for designing decarbonization pathways that account for carbon leakage.

Carbon leakage is an issue that cannot be overlooked in the design of unilateral climate policies [8,22]. China's CN may induce carbon leakage of 6.9%–14.9% to other countries, which aligns with the previous research range of 5%–20% [5,21,23]. However, previous studies have overlooked the broader impacts on the Earth's ecosystem. The results presented here indicate that, by 2100, China's CN could mitigate global warming by 0.15–0.19 °C, which is consistent with a recent study [52]. Moreover, the impact of leakage on temperature exceeds its effect on emissions, particularly under the low-emission scenarios. For example, under the SSP126 scenario, the impact of leakage on the emissions side is 8.3%–13.5%, while it increases to 9.3%–14.0% on the temperature side. This finding indicates that earlier studies on carbon leakage have underestimated its broader impacts on ecosystems. The rise in global CO_2 concentrations caused by carbon leakage increases natural carbon uptake through the CO_2 fertilization effect [32]. Here, we found that this increase mitigates the warming effect of carbon leakage, offsetting approximately 8.9%–11.3% of its impact. This feedback mechanism highlights the potential for ecosystems to play a role in offsetting the warming effects of carbon leakage. Future studies should strengthen their analyses of Earth system feedback to carbon leakage, particularly focusing on the role of carbon uptake in mitigating leakage under long-term emission-reduction targets.

By analyzing emission sources separately, we can better quantify the mitigation potential of each greenhouse gas. Previous studies have shown that the global warming potentials (GWPs) of CH_4 and N_2O are 84–87 times and 298 times that of CO_2, respectively

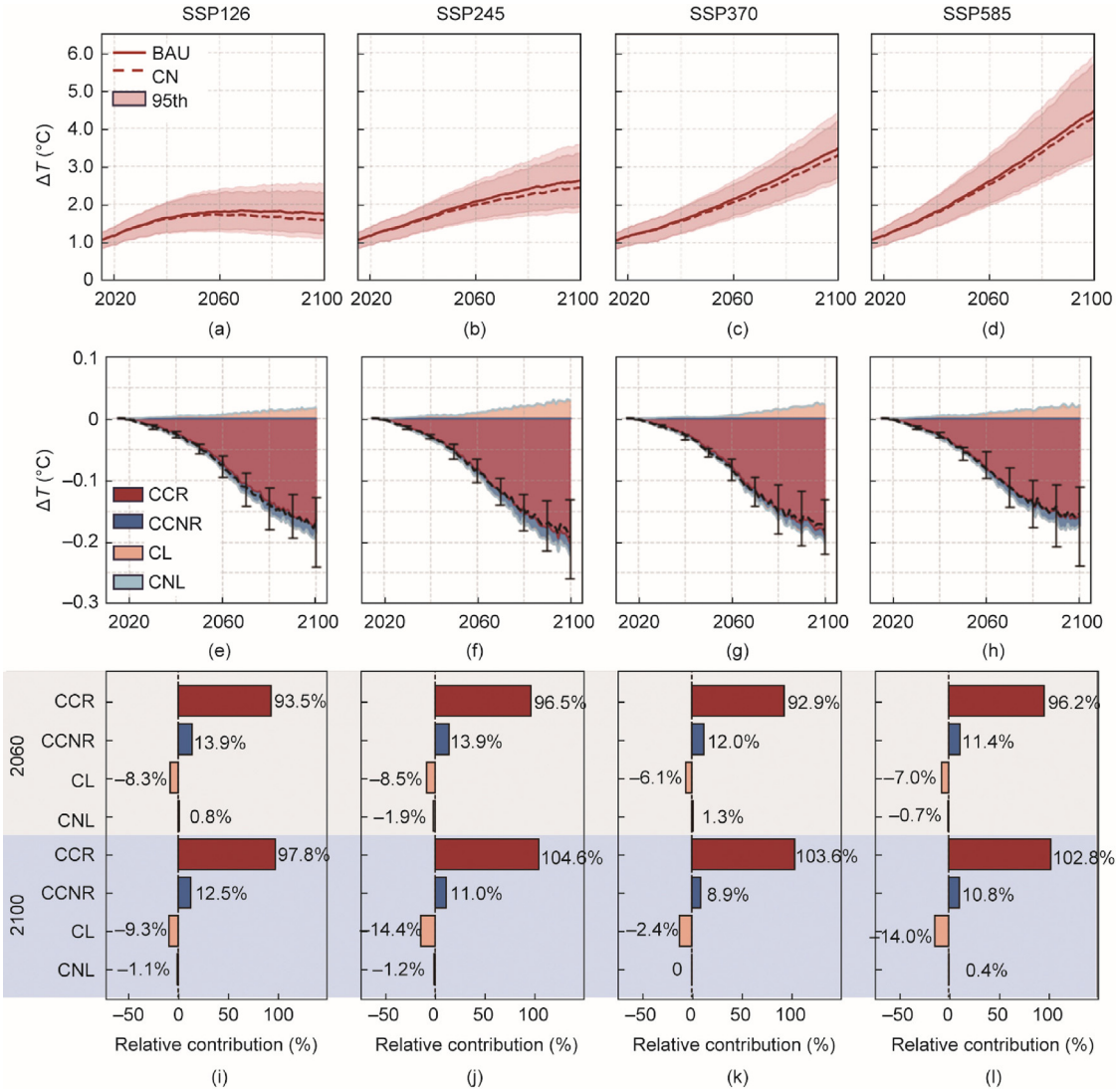

Fig. 4. Impacts of China's emission reductions and leakage on global temperature. (a–d) Trends in global temperature change (ΔT, °C) under (a) SSP126, (b) SSP245, (c) SSP370, and (d) SSP585 with and without China's CN. Solid red lines represent scenarios without CN, while dashed red lines show scenarios with CN. Shaded areas represent the 95% confidence interval, indicating model uncertainty. (e–h) Contributions of China's carbon reductions (CCR), CH_4 and N_2O reductions (CCNR), CO_2 leakage (CL), and CH_4 and N_2O leakage (CNL) to temperature changes under (e) SSP126, (f) SSP245, (g) SSP370, and (h) SSP585. (i–l) Relative contributions or offsets of each factor to temperature reduction under (i) SSP126, (j) SSP245, (k) SSP370, and (l) SSP585. More detailed information is provided in Fig. S7 in Appendix A.

[53]. Despite the relatively modest synergistic reductions in CH_4 (2.9–4.1 Mt) and N_2O (0.4–0.5 Mt) emissions under China's CN efforts, there are leakages of 97.9–100.5 kt CH_4 and 30.9–35.6 kt N_2O to other regions. However, these reductions remain critical in mitigating the negative impacts of leakage. Our findings reveal that the offset effect can exceed 70.5%, highlighting the pivotal role of CH_4 and N_2O in increasing cooling effects and mitigating carbon leakage impacts. Expanding the scope of climate policies can significantly increase the overall cooling effect of policies and improve the efficiency of achieving long-term climate targets.

Carbon leakage arises due to asymmetry in the scope and enforcement of climate policies across regions [4,5,22]. To address this challenge, traditional measures such as border carbon adjustments (BCAs), free allocation of emission allowances, and subsidies for low-carbon technologies have been proposed [54–56]. Table 2 [28,58,61–65] synthesizes the effects and limitations of key carbon leakage mitigation tools. BCAs are intended to equalize carbon costs across countries by imposing tariffs on imports and offering rebates on exports [28]. Nonetheless, recent evidence indicates that they have limited effectiveness in preventing carbon leakage and result in welfare losses [28,57]. Moreover, as the global trade environment deteriorates, the risk of ineffective policy tools increases, particularly due to the tariffs imposed by the Trump administration. Here, we conducted additional simulations by adjusting the Sino–US trade parameters to evaluate the impact of disruptions in Sino–US trade through 2030 on carbon leakage. The results indicate that such disruptions can reduce fossil-fuel-related carbon leakage by at least 11.4% under various climate scenarios, in line with previous findings [57–59]. However, for carbon leakage driven by land-use change, trade policies tend to amplify the risks, which is overlooked in most BCA studies (Table 3). The United States' unilateral tariffs prompt trade partners to adopt retaliatory measures, which have contributed to the restructuring of global supply chains [60]. In this context, China's import demand has shifted toward more carbon-intensive countries. For example, disruptions in the Sino–US trade of biomass energy and food could lead China to increase its imports of fossil fuels and use alternative food sources, thereby exacerbating carbon leakage

Table 2
Synthesized evaluation of major carbon-leakage mitigation tools.

Tools	Type	Definition	Leakage-mitigation effect	Limitations
Border carbon adjustments	Market-based	A trade-linked carbon charge: Imports pay a tariff equal to domestic carbon price; exports receive rebates	6.0%–33.3% leakage reduction [58,61]	World Trade Organization (WTO) compliance risk, calculating the embodied emissions and trade retaliation potential [28]
Free allowance allocation	Market-based	Free permits to industries based on historic output benchmarks	Above 13.6% leakage reduction [62,63]	Weak output-price signal and weak marginal abatement incentive [62]
Optimal tax–subsidy mix	Market-based	Calibrated mix of sector-specific taxes/subsidies to minimize global leakage and maximize welfare	First-best simulations even yield negative leakage [64]	Likely to deviate from the theoretical optimum due to administrative barriers, lack of information, and political economy factors [64]
Low-carbon technology subsidies	Subsidy-based	Grants or tax credits for low-carbon technologies	Around 15% leakage reduction [65]	High budget cost; efficacy hinges on tech maturity

Table 3
Impact of the Sino–US trade shutdown on CO_2 leakage (CL).

Scenarios	Description	△Fossil fuel-related CL (FF-CL)	Regions with increased FF-CL	△Land use-related CL (LU-CL)	Regions with increased LU-CL
SSP126_CN_notrade	As a supplemental scenario to SSP1-2.6_CN, a suspension of bilateral Sino–US trade is imposed	−74.6 Mt C	36.7%	353.0 Mt C	77.4%
SSP245_CN_notrade	As a supplemental scenario to SSP2-4.5_CN, a suspension of bilateral Sino–US trade is imposed	−166.9 Mt C	35.5%	462.7 Mt C	90.3%
SSP370_CN_notrade	As a supplemental scenario to SSP3-7.0_CN, a suspension of bilateral Sino–US trade is imposed	−446.5 Mt C	22.6%	612.0 Mt C	90.3%
SSP585_CN_notrade	As a supplemental scenario to SSP5-8.5_CN, a suspension of bilateral Sino–US trade is imposed	−37.2 Mt C	45.2%	258.1 Mt C	80.6%

More detailed information is provided in Note S3 in Appendix A.

risks, particularly through increases in land-use emissions from regions such as Russia, Canada, and Brazil. Future policies targeting carbon leakage should focus more on mitigating the impact of warming, rather than solely focusing on reducing emissions. Furthermore, fostering international cooperation in technological innovation is essential [57] and could involve coordinated greenhouse gas reductions and increases in natural carbon sinks to offset the warming effects of leakage.

The limitations of this study are threefold. First, by applying a total carbon constraint within the GCAM framework, we ignore uncertainties arising from alternative technologies and pathway choices. Variations in biomass energy deployment, power generation technologies, and other choices within CN pathways can significantly influence the scale and regional disparities of carbon leakage [36,66]. Second, our assessment of Earth system impacts excludes important carbon sources, such as emissions from glacier melt and wildfires [67,68]. This omission likely leads to an underestimation of the net effect of leakage on atmospheric CO_2 levels. Third, although GCAM v6.0 models international trade flows endogenously by adjusting for relative prices, production costs, and policy constraints, it provides a relatively coarse representation of global trade patterns. Consequently, the model cannot fully capture changes in trade network topology or their impacts on cross-border carbon flows and associated leakage effects. Despite these limitations, our findings highlight the critical importance of integrating carbon leakage considerations into the design of future climate-adaptive decarbonization pathways.

5. Conclusions

This study integrates GCAM and the FaIR model to quantify the carbon leakage associated with China's CN by 2100 and assess its impact on global warming. First, GCAM was employed to evaluate the scale of carbon leakage induced by China's CN policies. Then, the FaIR model was used to estimate the mitigation effects of natural carbon uptake on leakage. Finally, simulation experiments were conducted to trace four key sources contributing to the global cooling effects of China's CN: China's carbon reductions, CH_4 and N_2O reductions, CO_2 leakage, and CH_4 and N_2O leakage. There are four key conclusions:

(1) By the end of this century, while China's CN results in carbon leakage equivalent to 6.9%–14.8% of emissions, Earth system feedback amplifies the warming impacts of leakage from a global warming perspective (SSP126, change from 6.9% to 9.3%).

(2) Carbon leakage primarily occurs through mechanisms such as changes in energy product prices, energy consumption structures, trade dynamics, and emission intensities. The biomass sectors in India, the European Union, and West Africa are the most sensitive to carbon leakage.

(3) Natural carbon uptake, increased by leakage through the carbon fertilization effect, mitigates 8.9%–11.3% of the global warming impact of carbon leakage.

(4) Synergistic reductions in CH_4 and N_2O emissions, induced by China's CN, offset over 70.5% of the warming caused by leakage.

Given the deteriorating global trade environment, we recommend that future research incorporate trade-network-based approaches into GCAM to capture the impacts of changes in bilateral trade relationships and network topology. Additionally, due to the limited effectiveness of emission-side policy tools, future policy design should place greater emphasis on mitigating the warming effects of carbon leakage. For example, moving toward CN through CO_2 removal holds potential for reducing carbon leakage. Furthermore, integrating GCAM with high-resolution Earth system models would enable simulations of the broader impacts of carbon leakage on ecosystems, supporting the exploration of nature-based

solutions. These efforts would build upon this study and contribute to the development of resilient, climate-adaptive decarbonization pathways.

CRediT authorship contribution statement

Rui Su: Writing – original draft, Visualization, Data curation, Conceptualization. **Cuncun Duan:** Writing – review & editing, Validation, Conceptualization. **Bin Chen:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2025.08.027.

References

[1] CAT net zero target evaluations. Report. Cologne: Climate Action Tracker; 2023.
[2] Aichele R, Felbermayr G. Kyoto and carbon leakage: an empirical analysis of the carbon content of bilateral trade. Rev Econ Stat 2015;97:104–15.
[3] Grubb M, Jordan ND, Hertwich E, Neuhoff K, Das K, Bandyopadhyay KR, et al. Carbon leakage, consumption, and trade. Annu Rev Env Resour 2022;47:753–95.
[4] Yu B, Zhao Q, Wei YM. Review of carbon leakage under regionally differentiated climate policies. Sci Total Environ 2021;782:146765.
[5] Jakob M. Why carbon leakage matters and what can be done against it. One Earth 2021;4:609–14.
[6] Nielsen T, Baumert N, Kander A, Jiborn M, Kulionis V. The risk of carbon leakage in global climate agreements. Int Environ Agreements 2021;21:147–63.
[7] Solomon S. IPCC (2007): climate change the physical science basis. Reprort. Washington, DC: American Geophysical Union; 2007.
[8] Babiker MH. Climate change policy, market structure, and carbon leakage. J Int Econ 2005;65:421–45.
[9] Marcu A, Egenhofer C, Roth S, Stoefs W. Carbon leakage: an overview. Report. Brussels: Centre for European Policy Studies; 2013.
[10] Meng J, Huo J, Zhang Z, Liu Y, Mi Z, Guan D, et al. The narrowing gap in developed and developing country emission intensities reduces global trade's carbon leakage. Nat Commun 2023;14:3775.
[11] King LC, Van Den Bergh JCJM. Potential carbon leakage under the Paris Agreement. Clim Change 2021;165:52.
[12] Kuik O, Hofkes M. Border adjustment for European emissions trading: competitiveness and carbon leakage. Energy Policy 2010;38:1741–8.
[13] Dechezleprêtre A, Gennaioli C, Martin R, Muûls M, Stoerk T. Searching for carbon leaks in multinational companies. J Environ Econ Manage 2022;112:102601.
[14] Yarlagadda B, Zhao X, Iyer G, Wild T, Hultman N, Lamontagne J. Emissions leakage and economic losses may undermine deforestation-linked oil crop import restrictions. Nat Commun 2025;16:1520.
[15] Wang S, Wang X, Chen S. Global value chains and carbon emission reduction in developing countries: does industrial upgrading matter? Environ Impact Assess Rev 2022;97:106895.
[16] Lei T, Wang D, Yu X, Ma S, Zhao W, Cui C, et al. Global iron and steel plant CO_2 emissions and carbon-neutrality pathways. Nature 2023;622:514–20.
[17] Tan X, Liu Y, Cui J, Su B. Assessment of carbon leakage by channels: an approach combining CGE model and decomposition analysis. Energy Econ 2018;74:535–45.
[18] Jiang J, Ye B, Zeng Z, Yang X, Sun Z, Shao S, et al. Carbon abatement and leakage in China's regional carbon emission trading. Environ Sci Technol 2024;58:17661–73.
[19] He LY, Chen KX. Does China's regional emission trading scheme lead to carbon leakage? Evidence from conglomerates. Energy Policy 2023;175:113481.
[20] Yu Z, Wang Z, Ma M, Ma L. The impact of carbon leakage from energy-saving targets: a moderating effect based on new-energy model cities. Appl Energy 2024;375:124113.
[21] Gerlagh R, Kuik O. Spill or leak? Carbon leakage with international technology spillovers: a CGE analysis. Energy Econ 2014;45:381–8.
[22] Misch F, Wingender P. Revisiting carbon leakage. Energy Econ 2024;140:107786.
[23] Wu L, Zhou Y, Qian H. Global actions under the Paris Agreement: tracing the carbon leakage flow and pursuing countermeasures. Energy Econ 2022;106:105804.
[24] Pan Da, Tao L, Sun K, Golston LM, Miller DJ, Zhu T, et al. Methane emissions from natural gas vehicles in China. Nat Commun 2020;11:4588.
[25] Wang Y, Zhu Z, Dong H, Zhang X, Wang S, Gu B. Mitigation potential of methane emissions in China's livestock sector can reach one-third by 2030 at low cost. Nat Food 2024;5:603–14.
[26] Xu P, Houlton BZ, Zheng Y, Zhou F, Ma L, Li B, et al. Policy-enabled stabilization of nitrous oxide emissions from livestock production in China over 1978–2017. Nat Food 2022;3:356–66.
[27] Davis SJ, Caldeira K. Consumption-based accounting of CO_2 emissions. Proc Natl Acad Sci USA 2010;107:5687–92.
[28] Böhringer C, Fischer C, Rosendahl KE, Rutherford TF. Potential impacts and challenges of border carbon adjustments. Nat Clim Chang 2022;12:22–9.
[29] Matthews HD, Wynes S. Current global efforts are insufficient to limit warming to 1.5 °C. Science 2022;376:1404–9.
[30] Wang S, Zhang Y, Ju W, Chen JM, Ciais P, Cescatti A, et al. Recent global decline of CO_2 fertilization effects on vegetation photosynthesis. Science 2020;370:1295–300.
[31] Matthews HD. Implications of CO_2 fertilization for future climate change in a coupled climate–carbon model. Glob Chang Biol 2007;13:1068–78.
[32] Fernández-Martínez M, Sardans J, Chevallier F, Ciais P, Obersteiner M, Vicca S, et al. Global trends in carbon sinks and their relationships with CO_2 and temperature. Nat Clim Chang 2019;9:73–9.
[33] Hall A. The role of surface Albedo feedback in climate. J Clim 2004;17:1550–68.
[34] Schmale J, Zieger P, Ekman AML. Aerosols in current and future Arctic climate. Nat Clim Chang 2021;11:95–105.
[35] Zhang Y, Wang X, Lian X, Li S, Li Y, Chen C, et al. Asymmetric impacts of forest gain and loss on tropical land surface temperature. Nat Geosci 2024;17:426–32.
[36] Calvin K, Patel P, Clarke L, Asrar G, Bond-Lamberty B, Cui RY, et al. GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems. Geosci Model Dev 2019;12:677–98.
[37] Ou Y, Roney C, Alsalam J, Calvin K, Creason J, Edmonds J, et al. Deep mitigation of CO_2 and non-CO_2 greenhouse gases toward 1.5 °C and 2 °C futures. Nat Commun 2021;12:6245.
[38] Hong C, Zhao H, Qin Y, Burney JA, Pongratz J, Hartung K, et al. Land-use emissions embodied in international trade. Science 2022;376:597–603.
[39] Boden T, Andres B. National CO_2 emissions from fossil-fuel burning, cement manufacture, and gas flaring: 1751–2014. Report. Oak Ridge: Oak Ridge National Laboratory; 2014.
[40] Global non-CO_2 greenhouse gas emission projections & mitigation 2015–2050. Report. Washington, DC: United States Environmental Protection Agency; 2019.
[41] Harmsen M, Fricko O, Hilaire J, Van Vuuren DP, Drouet L, Durand-Lasserve O, et al. Taking some heat off the NDCs? The limited potential of additional short-lived climate forcers' mitigation. Clim Change 2020;163:1443–61.
[42] Leach NJ, Jenkins S, Nicholls Z, Smith CJ, Lynch J, Cain M, et al. FaIRv2.0.0: a generalized impulse response model for climate uncertainty and future scenario exploration. Geosci Model Dev 2021;14:3007–36.
[43] Forster P, Storelvmo T, Armour K, Collins W, Dufresne JL, Frame D, et al. Chapter 7: the Earth's energy budget, climate feedbacks, and climate sensitivity 2021. Report. Geneva: Intergovernmental Panel on Climate Change; 2021.
[44] Smith C, Cummins DP, Fredriksen HB, Nicholls Z, Meinshausen M, Allen M, et al. Fair-calibrate v1.4.1: calibration, constraining and validation of the FaIR simple climate model for reliable future climate projections. Geosci Model Dev 2024;17:8569–92.
[45] Smith C. FaIR calibration data 2024. Database. Geneva: Zenodo; 2024.
[46] Thornhill G, Collins W, Olivié D, Skeie RB, Archibald A, Bauer S, et al. Climate-driven chemistry and aerosol feedbacks in CMIP6 Earth system models. Atmos Chem Phys 2021;21:1105–26.
[47] O'Neill BC, Tebaldi C, Van Vuuren DP, Eyring V, Friedlingstein P, Hurtt G, et al. The scenario model intercomparison project (ScenarioMIP) for CMIP6. Geosci Model Dev 2016;9:3461–82.
[48] Climate change 2023: synthesis report. Report. Geneva: Intergovernmental Panel on Climate Change; 2023.
[49] Cheng J, Tong D, Liu Y, Geng G, Davis SJ, He K, et al. A synergistic approach to air pollution control and carbon neutrality in China can avoid millions of premature deaths annually by 2060. One Earth 2023;6:978–89.
[50] Riahi K, Van Vuuren DP, Kriegler E, Edmonds J, O'Neill BC, Fujimori S, et al. The shared socioeconomic pathways and their energy, land use, and greenhouse

gas emissions implications: an overview. Glob Environ Change 2017;42:153–68.
[51] Sun Y, Jiang Y, Xing J, Ou Y, Wang S, Loughlin DH, et al. Air quality, health, and equity benefits of carbon neutrality and clean air pathways in China. Environ Sci Technol 2024;58(34):15027–37.
[52] Li L, Zhang Y, Zhou T, Wang K, Wang C, Wang T, et al. Mitigation of China's carbon neutrality to global warming. Nat Commun 2022;13:5315.
[53] Climate change 2014: synthesis report. Report. Geneva: Intergovernmental Panel on Climate Change; 2015.
[54] Sakai M, Barrett J. Border carbon adjustments: addressing emissions embodied in trade. Energy Policy 2016;92:102–10.
[55] Kruse-Andersen PK, Sørensen PB. Optimal energy taxes and subsidies under a cost-effective unilateral climate policy: addressing carbon leakage. Energy Econ 2022;109:105928.
[56] Ambec S, Esposito F, Pacelli A. The economics of carbon leakage mitigation policies. J Environ Econ Manage 2024;125:102973.
[57] Sun X, Mi Z, Cheng L, Coffman D, Liu Y. The carbon border adjustment mechanism is inefficient in addressing carbon leakage and results in unfair welfare losses. Fundam Res 2024;4:660–70.
[58] Böhringer C, Balistreri EJ, Rutherford TF. The role of border carbon adjustment in unilateral climate policy: overview of an energy modeling forum study (EMF 29). Energy Econ 2012;34:S97–110.
[59] Mörsdorf G. A simple fix for carbon leakage? Assessing the environmental effectiveness of the EU carbon border adjustment. Energy Policy 2022;161:112596.
[60] Hu L, Chen S, Zhang C, Zhou L, Li A. Understanding the heterogeneous roles of China's sectors under the shock of second trump administration's new tariffs: a novel method of shock-based input–output data envelopment analysis. Energy 2025;324:135687.
[61] Branger F, Quirion P. Would border carbon adjustments prevent carbon leakage and heavy industry competitiveness losses? Insights from a meta-analysis of recent economic studies. Ecol Econ 2014;99:29–39.
[62] Meunier G, Ponssard JP, Quirion P. Carbon leakage and capacity-based allocations: is the EU right? J Environ Econ Manage 2014;68:262–79.
[63] Monjon S, Quirion P. Addressing leakage in the EU ETS: border adjustment or output-based allocation? Ecol Econ 2011;70:1957–71.
[64] Kruse-Andersen PK, Sørensen PB. Optimal unilateral climate policy with carbon leakage at the extensive and the intensive margins. Scand J Econ 2025;127:427–59.
[65] Fischer C, Greaker M, Rosendahl KE. Robust technology policy against emission leakage: the case of upstream subsidies. J Environ Econ Manage 2017;84:44–61.
[66] Zhang S, An K, Li J, Weng Y, Zhang S, Wang S, et al. Incorporating health co-benefits into technology pathways to achieve China's 2060 carbon neutrality goal: a modelling study. Lancet Planet Health 2021;5:e808–17.
[67] Schleussner CF, Ganti G, Lejeune Q, Zhu B, Pfleiderer P, Prütz R, et al. Overconfidence in climate overshoot. Nature 2024;634:366–73.
[68] Hudiburg T, Mathias J, Bartowitz K, Berardi DM, Bryant K, Graham E, et al. Terrestrial carbon dynamics in an era of increasing wildfire. Nat Clim Chang 2023;13:1306–16.