Supplementary information to

Synergies of reducing greenhouse gases and atmospheric nitrogen pollutants in China

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Supplementary Note1. GHG and ANP coupling index

In order to facilitate statistical and descriptive analysis, this study coupled greenhouse gases (GHGs) and atmospheric nitrogen pollutants (ANPs) into GHG-ANPs (GNPs). To calculate emission reductions, we converted each atmospheric emission unit to integrated GHG-ANP equivalents (GNP_{eq}), a method that takes into account the environmental carrying capacity, pollution levels, and economic and social development goals of the country. This approach is consistent with the life cycle analysis methodology and has been applied in previous studies[1,2]. Table S2 provides the conversion parameters used in this study. The following is a detailed description of our conversion steps for the combined GHG and ANP emissions.

Firstly, normalize different GHGs (CH_4, N_2O, CO_2) to CO_{2eq} using 100-year Global Warming Potential (GWP) values, which provide a standardized measure of the global warming impacts of different gases over 100 years. The GWP values were initially established by the Intergovernmental Panel on Climate Change (IPCC) in 1990[3] and have since been updated multiple times, with the latest update in the IPCC's AR6 in 2021[4]. The GWP values used in this research are provided in Table S2. Here we only consider CO_2, CH_4, and N_2O as the primary GHGs, other gases such as CFCs, HFCs, and SF6 are excluded in this study due to their minimal quantities and limited association with nitrogen emissions.

Secondly, assign appropriate weights for ANPs. During this process, the chemical, physical, biological, and health effects of ANPs, as well as the pricing of pollutants and even the urgency to control them were considered. In our study, the equivalent coefficient for NH_3 and NO_x is determined by the reciprocal of the equivalent value according to the LCEPT, which has been widely used in the evaluation of regional air pollution and carbon reduction effects[5-7]. Nonetheless, since the tax law was enacted in 2015 and current socio-economic conditions and air pollution control processes in China have changed significantly, this approach may have some limitations as will be explained in SI Note. 4.

Thirdly, introduce the synergy indexes to evaluate the co-control effects. The ratio of the emission change in GHG to that in ANP was defined as S_1 and the ratio of their rates of emission change was defined as S_2, which has been applied in previous studies to estimate the magnitude of synergetic effects[8-10]. In this study, we mainly used these indicators to compare the co-benefits of emission reductions between different entities, i.e., sectors and provinces. Larger values of S_1 and S_2 indicate more efficient GHG and ANP synergistic emission reduction and better synergistic emission reduction effect. By employing these indicators, we could assess and compare the magnitude of the synergistic mitigation effects among different entities. For example, under the SSP2-45-medium scenario, the synergy of emission reductions across sectors will increase in 2030-2050, with stronger synergy in the household and industrial sectors; and this trend of progressively stronger synergies is also manifested in most provinces of China (Fig. S4 and S5).

Supplementary Note 2. Selection of co-control measures

Four aspects were considered while choosing co-control measures to reduce GHG (CO_2, CH_4, and N_2O) and ANP (NH_3 and NO_x) emissions during the scenario simulation.

1) High mitigation efficiency: measures that could significantly reduce at least two types of emissions are considered, such as deep manure placement, which has a high mitigation potential of 93-99% for NH_3 emissions with a limited trade-off to other emissions.

2) Low implementation cost: measures that are less expensive or labor-intensive are preferred, such as setting tillage or buffer zone.

3) Practical applicability: measures with limited applicability due to technical, political, or socio-economic barriers in China should be excluded. For instance, soil testing to optimize fertilizer use is considered more suitable for the US or Europe, where farms tend to be larger in scale compared to China, which has a higher prevalence of fragmented farmland.

4) Co-benefits and limited trade-offs: measures that can simultaneously reduce multiple target air pollutants emissions with a positive impact on production and life quality are prioritized, such as the use of enhanced efficiency fertilizers (EEFs) could reduce total Nr emissions by 15-40% while increasing crop yield by 9.1-20.5%; however, measures that can reduce NH_3 emissions but enhance N_2O emissions or N leaching, should be selected with caution to avoid trade-offs.

Based on the selection criteria above, a total of 26 co-control options for five sectors were summarized in this study, including structural adjustment and end-of-pipe control. Detailed descriptions of their applicability and implementation costs were listed in Table. S4.

Supplementary Note 3. Future projections under SSP-RCP scenarios

S3.1 SSP-RCP framework and scenarios setting.

To explore the long-term impacts of human-caused climate change and identify potential response strategies, O'Neill et al[11] established a group of worldwide narratives and socioeconomic trajectories, known as Shared Socioeconomic Pathways (SSPs), which can be adapted to regional contexts. They serve as benchmark scenarios, depicting feasible alternative patterns of societal and ecosystem progress over a 100-year period in the absence of climate change or climate policies. The SSPs offer five distinct trajectories (SSP1-5) for forthcoming social, economic, and environmental advancements, spanning a range of qualitative and quantitative socioeconomic dimensions[12]. Among them, population demographics, economic level, technological development, energy intensity, agricultural intensity, and environmental awareness are our primary concerns. In this paper, we selected SSP1, SSP2, and SSP5 as target baseline scenarios because they represent three representative development paths of clean and sustainable development, middle path, and high dependence on fossil energy development, respectively. The basic socioeconomic development can be seen in Fig. S8, and narrative assumptions and comparisons for the selected SSPs were listed in Table S5.

To enable further analysis by both climate models and Integrated Assessment Models (IAMs), a scenario set containing emission, concentration, and land-use trajectories was developed, known as Representative Concentration Pathways (RCPs)[13]. The RCPs provide assumptions for different levels of radiative forcing in 2100 (8.5 W/m^2, 6 W/m^2, 4.5 W/m^2, and ~3 W/m^2), and commonly served as a proxy for climate targets. To pair the RCPs with the SSPs, a set of climate policies called Shared Climate Policy Assumptions (SPAs) were imposed on the SSP baseline. Thus, the SSP-RCP framework facilitates the integration of multiple socio-economic reference pathways with climate models, enhancing the assessment of climate impacts, adaptation, and mitigation efforts[14].

Further, we applied different intensities of Nr pollutants mitigation measures (strong, medium, and weak) to the SSP-RCP scenarios. The idea to provide possible future Nr release at three distinctively different levels, also considering specific pollutant abatement, has been discussed in the literature and is conceptually comparable[15]. Thus, SSP1-REF, SSP2-REF, and SSP5-REF are regarded as the baseline scenarios which solely consider the impact of different societal choices on the world without future climate policy; and the three co-control scenarios (SSP1-26-strong, SSP2-45-medium, and SSP5-60-weak) incorporate a range of mitigation measures that address both climate change and air pollution, corresponding to the three sub-scenarios of the CMIP6 model (SSP1-26 "sustainable society", SSP2-45 "middle road", and SSP5-60 "fossil-fueled development")[16-18].

S3.2 GHG-ANP coordinated mitigation pathways.
Based on the socioeconomic and climate goals outlined in the SSP-RCP framework, we developed a portfolio of carbon and nitrogen reduction measures with varying implementation rates and intensities by sector. These co-control measures were integrated into proposed co-control scenarios. Below gives a detailed description of the sectoral adjustment under different mitigation pathways.

1) Energy. Energy structure reform is a key strategy for simultaneously reducing GHG and ANP emissions. On the supply side, this involves transitioning from carbon-intensive fossil fuels to cleaner renewable energy sources such as wind, hydropower, solar, and nuclear power. On the demand side, it includes measures to promote energy conservation, enhance efficiency, and promote electrification in sectors such as transportation, households, and industry. Under the REF and RCP6.0 scenarios, the consumption of primary energy from fossil fuels is assumed to remain high (accounting for over 80%), with a slight decline after peaking around 2030. In the SSP1-26-strong scenario, non-fossil energy is projected to account for approximately 20% of total energy consumption by 2030 and over 90% by 2050, accompanied by a sharp decrease (56–65%) in the proportion of coal[19]. While under the SSP2-45-medium scenario, the adjustment process is relatively delayed by 5-10 years, with a greater reliance on biomass and nuclear energy as non-fossil energy sources to achieve ambitious climate targets.

2) Industry. Eliminating outdated production capacity and small polluting factories, as well as upgrading industrial boilers, are critical measures for reducing emissions. For coal-fired power plants, iron and steel production (including coking), cement production, and glass production, it is recommended to replace outdated facilities with advanced ones that utilize larger boilers or cleaner energy sources, leading to energy savings attributed to energy efficiency improvement[20]. For lime production, brick production, and other industrial processes, it is not practical or cost-effective to implement end-of-pipe pollution control in small and polluting factories. Therefore, a better approach is to phase out these high-emission facilities. Under the SSP1-26-strong scenario, it is assumed that China will shut down all coal boilers with capacities smaller than 7 MW in both urban and rural areas by the end of 2020. Furthermore, the retrofitting of existing boilers to achieve ultra-low emissions will be completed by the end of 2030[21,22]. The timeframes for these actions will be delayed by 5-10 years for the SSP2-45-medium and SSP5-60-weak scenarios, respectively. However, under the REF scenarios, although the scale and structure of industries may not change significantly, adjustments will be slightly made to the energy structure to align with emission reduction goals.

3) Transportation. Retiring yellow-label and old vehicles, promoting alternative fuels, and encouraging the adoption of electric vehicles are key measures to achieve emission reduction targets. Strengthening vehicle emissions standards is also crucial in this regard[23]. Additionally, promoting sustainable transportation options such as cycling, walking, and public transportation (buses, trains, and light rail systems) can help reduce vehicle miles traveled (VMT)[24]. Under the SSP1-26-strong scenario, China has phased out more than 26.8 million yellow-label and older vehicles by the end of 2020. In the coming years, China will gradually implement the China VII emission standards for on-road traffic (to be promulgated in the mid-2020s) and the China VI emission standards for off-road traffic by 2030-2050. Moreover, It is assumed that the proportion of new energy vehicles, including battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), will exceed 50% by 2030 and 80% by 2050. Under the SSP2-45-medium scenario, the implementation of China VI emission standards for all on-road vehicles and China V for off-road transport will be further emphasized. The penetration process of new energy vehicles may be slower compared to SSP1-26-strong. As for SSP5-60-weak, policies for the introduction of alternative fuels and vehicles are not as stringent, but vehicle demand and emissions will also decline slightly due to a lower population in the future.

4) Households. In this sector, efforts will be made to reduce energy consumption for heating, cooling, and household appliances through behavioral changes and the adoption of efficient technologies. Rural electrification should be accelerated, particularly in areas where efficient technologies can be implemented. In addition, waste reduction measures are also considered, primarily focusing on solid waste landfills, as there are few cost-effective mitigation measures for the wastewater sector at present[25]. Under the SSP1-26-strong scenario, the substitution of coal with natural gas and electricity will be actively promoted. Stove upgrades will also be implemented to achieve relatively low emission levels by 2030. Additionally, coal washing will be employed as an energy-saving measure in both the SSP1-26-strong and SSP2-45-medium scenarios. By 2050, the SSP1-26 scenario aims to achieve an 85% coal-washing rate, while the SSP2-45 scenario targets a 55% rate[26]. Furthermore, in the case of waste treatment, it is roughly estimated that approximately 50% of CH_4 emissions and 20% of N_2O emissions will be reduced by 2030[27] in the SSP1-26-strong scenario.

5) Agriculture. Improving livestock and cropland management practices play a crucial role in reducing GHG and ANP emissions, particularly those associated with NH_3, N_2O, and CH_4.

Advanced livestock production strategies involve implementing scientific animal housing management techniques such as the use of adsorbents, mechanical and floor management, and additives and urease inhibitors. Additionally, enhancing feed quality and nutrition, as well as adopting better manure management practices, are important mitigation measures. Cropland management strategies focus on optimizing fertilizer types and improving utilization efficiency, implementing improved farming techniques such as crop rotation, cover cropping, and appropriate tillage methods, and adopting rational irrigation methods. The technical details and reduction efficiency of the measures in agriculture are referred to Gu et al and Ti et al[28,29]. Furthermore, the mitigation contribution of forestry is also considered within this sector. As China's NDC commitments have pledged to increase its forest coverage by 200 million hectares by 2030 compared to 2005, we assume that the SSP1-26-strong scenario will achieve this ambitious target through afforestation and silviculture. Meanwhile, China aims to increase irrigation efficiency by at least 20%, reduce animal product consumption by 30%, and achieve a comprehensive utilization rate of agricultural waste of 75% by 2030 through rapid deployment of best practice measures[30]. Under the SSP1-26-strong scenario, 70% of feasible agricultural emission reduction-related technology measures will be adopted by 2030, with priority given to low-cost, low-tech, and high-acceptance measures, and all measures adopted by 2050[15]. In the SSP2-45-medium scenario, agricultural abatement-related technology measures maintain current legislation by 2030, with 70% of feasible measures adopted by 2050 to improve nitrogen use efficiency in crop and animal farming systems. In contrast, the SSP5-60-weak scenario places less emphasis on agricultural mitigation, instead maintaining the current situation.

S3.3 Projection of GHG and ANP emissions in SSP-RCP scenarios.

In this study, the projections of GHG and ANP emissions and the analysis of costs and benefits were obtained using CHANS and GAINS models. Simultaneously, we collected data from other literature or database aligning with the SSP-RCP framework for results calibration and uncertainty analysis (Table S6). The CHANS model provides the Nr emission-related parameters such as activity data and emission factors, while the GAINS model provides information on GHG emission-related parameters and costs of abatement measures based on current policy and technology options. The SSP-RCP framework served as a reference for mapping N pollution controls in the SSPs to different levels of intensity, taking into account economic capacity and technological advancements[15]. For the baseline scenarios, we projected future activity data and combined them with the corresponding emission factors to estimate future emissions. For co-control scenarios, we set nitrogen pollutant reduction targets of three intensities and coupled synergistic reduction measures into the SSP-RCP scenarios, ultimately assessing the reduction potential, synergistic effects, implementation costs, and overall benefits under each scenario.

Below is a brief overview of the models we utilized. As these models are globally recognized, we have not included all the intricate details. For further information regarding data sources and model simulation procedures, please refer to the original studies of these models.

1) CHANS Model. Coupled Human And Natural Systems (CHANS) is a process-based model that focuses on N-flow, encompassing the intricate biogeochemical processes of N cycling[31]. By using the embedded mass balance method, the CHANS-China integrates the inputs, outputs, and accumulation of N across 14 subsystems (such as cropland, feedlot, grassland, human, industry, aquaculture, forest, pets, urban lawn, solid waste, wastewater, atmosphere, surface water, and groundwater). The CHANS-China draws on a variety of regionally-specific data sources, including (i) statistical databases that provide social-economic and agricultural activity data at the national or regional level, such as human population, GDP, land use, crop/livestock production, farm productivity, and N fertilizer use, and (ii) the latest published field experiments, literature studies, and national pollutant inventories, which offer diverse parameters (e.g., N content in crops, harvest index, manure recycling ratio) and nationally-specific emission factors (EFs) for Nr. More information about the CHANS model and its calculations can be found in the works of Gu et al[31].

2) GAINS Model. Greenhouse Gas-Air Pollution Interactions and Synergies (GAINS) is an integrated assessment model that addresses the costs and potential of air pollution control and GHG emission reductions and can be used to evaluate the interactions between policies. GAINS model describes air pollution pathways from atmospheric drivers to environmental impacts and provides information on economic, energy, and agricultural development, emission control strategies and costs, atmospheric dispersion, and source sensitivity[32]. Based on international energy and industrial statistics, emission inventories, and the data supplied by countries themselves, the GAINS model quantifies the emissions and impacts on human health, crop loss, acid deposition, and long-term radiative forcing from a multi-pollutant perspective, containing 10 air pollutants (includes SO_2, NO_x, $PM_{2.5}$, NH_3, VOC, etc.) and 6 GHGs (i.e., CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6). The GAINS model is commonly coupled with other models, such as the Global Biosphere Management Model (GLOBIOM), which covers land use activities including agriculture, forestry, and bioenergy; and Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGEix), which develops energy scenarios and identifies socio-economic and technological response strategies. A detailed description of the GAINS model framework and guidelines could be found on the website (https://iiasa.ac.at/models-tools-data/gains).

Supplementary Note 4. Limitation and uncertainty analysis

S4.1 Uncertainty analysis

There are certain uncertainties and limitations in this study. Firstly, our focus is on the coupling of GHG and Nr, considering only atmospheric components and excluding Nr in water. Future research efforts will be dedicated to developing an integrated assessment model to address the multiple interactions of GHG and Nr emissions. Another source of uncertainty arises from the weighting factors used in the emission normalization process, which rely on the current cost of pollutant treatment, including environmental taxes and carbon prices. This approach may underestimate the environmental impact of NH_3 due to the high threshold for taxable pollution equivalent to NH_3 in China[33]. Additionally, GHG indicators may fluctuate with evolving social and atmospheric governance measures due to China's active carbon trading market. Furthermore, this study concentrated solely on the interaction between GHGs and ANPs, neglecting the synergistic effects of other air pollutants like SO_2 and their long-term impacts, to isolate the influences of climate change. Future research could consider these additional pollutants through atmospheric transport models for a comprehensive understanding of air pollution dynamics.

First of all, our estimates of GHG and ANP emissions mainly rely on upgraded CHANS-China and GAINS models, specifically designed to quantify and monitor the regional-scale fluxes of Nr and GHGs. The emission factors and relative parameters derived from the models have been updated with local information including the official statistics, database, and previous studies. Recent research has suggested that most of the values employed in the GAINS model fall within the ranges reported in other studies, and the uncertainty of the CHANS model can be effectively constrained through mass balance calculations[34,35]. Thus, the overall uncertainty stemming from emission and process factors is relatively low, being kept within 15%.

Another uncertainty source is the variations in emission sources and their activity data across China. The data used in the analysis were collected from national and regional statistics, surveys, and other sources, providing average values. Given the distinct study boundaries and variations in statistical processes, it is inevitable that errors may arise in the regional activity level data. The relative uncertainty of the data, indicated by coefficients of variation (CV), was estimated based on published literature and experts' judgment (Table S1). Variables and parameters obtained from international publications were assigned higher CVs. Given that the study's scale is at the provincial level in China, any absence or errors in activity statistics can introduce uncertainty in the assessment of regional emission reduction potential.

We conducted a comparison of emissions results in the SSP-RCP scenarios with those from previous studies, and the range of variations under different scenarios was presented in Table S6. For the SSP-REF scenarios, the uncertainties in emissions of the five gases during the period 2025-2050 are relatively low, with control levels of less than 30%. However, for the SSP-RCP scenarios, the uncertainties in emission projections show a wide variation, with SSP1-26-strong>SSP2-45-medium>SSP5-60-weak. This may be attributed to the fact that we designed the ssp1 -26-strong and ssp2 -45-medium scenarios with a large number of synergistic emission reduction measures coupled in a socioeconomic context, and there is a large uncertainty in their emission reductions. This can be attributed to the design of the SSP1-26-strong and SSP2-45-medium scenarios, which incorporate more synergistic emission reduction measures within a specific socioeconomic context, introducing a larger uncertainty in predicting emission reductions. Additionally, the uncertainties associated with different air pollutant emissions are also diverse. Specifically, under the SSP1-26-strong scenario, the variation ranges in 2025-2050 are 31%-107% for NH_3, 33%-44% for NO_x, 35%-45% for N_2O, 7%-25% for CO_2, and 8%-22% for CH_4. By considering the confidence intervals of these values, the results of the emission projections and relative reductions strongly support our conclusions. However, it is undeniable that further research is needed to develop more accurate regional emission factors and improve the estimations made by the models. This will contribute to reducing the uncertainties associated with emission projections and enhance our understanding of the complex dynamics of emissions in the future.

In general, the three primary sources of uncertainty in emission assessments are the variation in data sources, spatial heterogeneity in production activities, and imperfect model parameterization. When considering the combined effects of multiple mitigation options, uncertainties can arise due to unknown practical removal efficiencies for air pollutants and unpredictable implementation levels in the future. These uncertainties are inherent and must be addressed and assessed through further bottom-up research to support the development of effective policies for coordinated management of greenhouse gas and air pollutant emissions.

S4.2 Limitations

This study has several limitations, primarily arising from parameter definition and method selection, which can be categorized into four main aspects.

1) Model integration. In this study, we employed a multi-model approach to comprehensively assess reduction management, integrating various structural components such as data collection, C-N cycling model integration, emission inventory compilation, scenario simulation, and cost-benefit analysis. However, the unintended consequences or specific issues stemming from mismatch or mis-link data and analysis should be emphasized: a) simplification due to the combination of data from different spatial scales; b) simplification due to overall averaging, which may overlook non-linear parameters; and c) approximations and constraints required to maintain models adequately straightforward for results integration at a regional/provincial scale, leading in the overlooking of certain issues. Our interdisciplinary team has maximized the advantages of employing multi-model approaches, transcending methodological boundaries. However, it is worth noting that conducting such large-scale research inherently requires certain simplifications.

2) Normalized calculation. In this study, we defined a GHG-ANP coupling index based on a price system to assess coordinated management efforts. However, certain issues need to be considered when determining the weighting factors for the five atmospheric pollutants: a) the absence of information on the characteristics of certain individual pollutants during the normalization process; b) simplification due to regional variations in carbon price systems and updates in environmental tax regimes; and c) the inadequate judgment and recognition by the public and policymakers regarding the urgency of controlling nitrogen pollution. In future studies, we aim to explore a continuous iterative coefficient estimation system that takes into account the physicochemical characteristics of pollutants and their impacts on human health and ecosystem function, as well as other external factors. This would enhance the accuracy and robustness of the weighting factors used in the assessment.

3) Cost-benefit analysis. There are several potential limitations in estimating the costs and benefits of greenhouse gas and nitrogen emission reductions in China: **a)** data and parameter uncertainty. The GAINS model used to estimate costs have inherent simplifications and uncertainties around key parameters like investment cost, operating cost, technology adoption rates, and economic benefit valuations. Projecting out decades involves major uncertainties around technology development, economic and population growth, climate impacts, and more. Addressing deep uncertainties is an ongoing challenge. **b)** heterogeneity within China.

Implementation costs and benefits may differ greatly across provinces and sectors due to differences in energy systems, economic structure, and environmental impacts. However, due to data limitations, we are not able to obtain sufficient localized data. **c)** valuing benefits or impacts. Here in this study, the societal benefits were estimated to be the sum of ecosystem benefits (from a WTP perspective), human health benefits (from values of a statistical life year), and climate benefits (derived from carbon emission prices). These are three very different approaches to valuing these impacts in monetary terms. Although previous studies have used them, it is still challenging to put accurate valuations and fully quantify the health, ecosystem, climate, and economic benefits or impacts of emissions and reductions. Better valuation methods are required. **d)** feasibility constraints. The costs and benefits realized depend heavily on policy design factors like stringency, sectoral coverage, flexibility mechanisms, and more. There may be practical constraints around technical feasibility, financing, institutional capacity, political will, and social acceptance that limit realizable benefits. Integrating these constraints into modeling is difficult.

4) Social factors. The adoption of new or improved techniques is influenced by a wide range of subjective and objective factors, including social factors such as age, gender, education, and work experience, in addition to mandatory policies and incentives[36-39]. For instance, studies have shown that factors like age and experience can impact technology adoption, with older farmers being less inclined to adopt new practices due to their experience and ability to discern the importance of improved techniques[36]. Moreover, natural conditions and cultural differences across geographical areas can also affect the diffusion of abatement technologies in agriculture. To gain a deeper understanding of these social dynamics, future research should integrate social norms and risks into decision-making processes, both theoretically and empirically. Direct assessment of the effects of social factors through experiments or surveys would be valuable in exploring the impact of these variables on technology adoption. Collaboration with experts from diverse fields would also contribute to a comprehensive analysis of the social factors influencing the adoption of advanced techniques. By incorporating these perspectives, we can enhance our understanding of the complex dynamics surrounding the adoption of environmentally sustainable practices and achieve better alignment with stakeholders' needs and motivations.

In general, our findings offer stakeholders a new perspective on the synergistic carbon and nitrogen reduction, along with a comprehensive framework to assess the feasibility of co-control measures in various sectors. Nevertheless, the limitations associated with the method should be reduced by complementing other assessment methods, including more precise emission parameters and more detailed coupling process modeling. By transparently acknowledging the constraints of our methodology and the availability of data, we underscore the importance of further research in this field. It is crucial to continue exploring and refining our understanding of carbon and nitrogen reduction strategies, with a focus on overcoming the limitations of current approaches. This will ultimately contribute to more accurate and robust assessments of co-control measures, enabling stakeholders to make informed decisions and take effective action towards sustainable and integrated emission reductions in China.

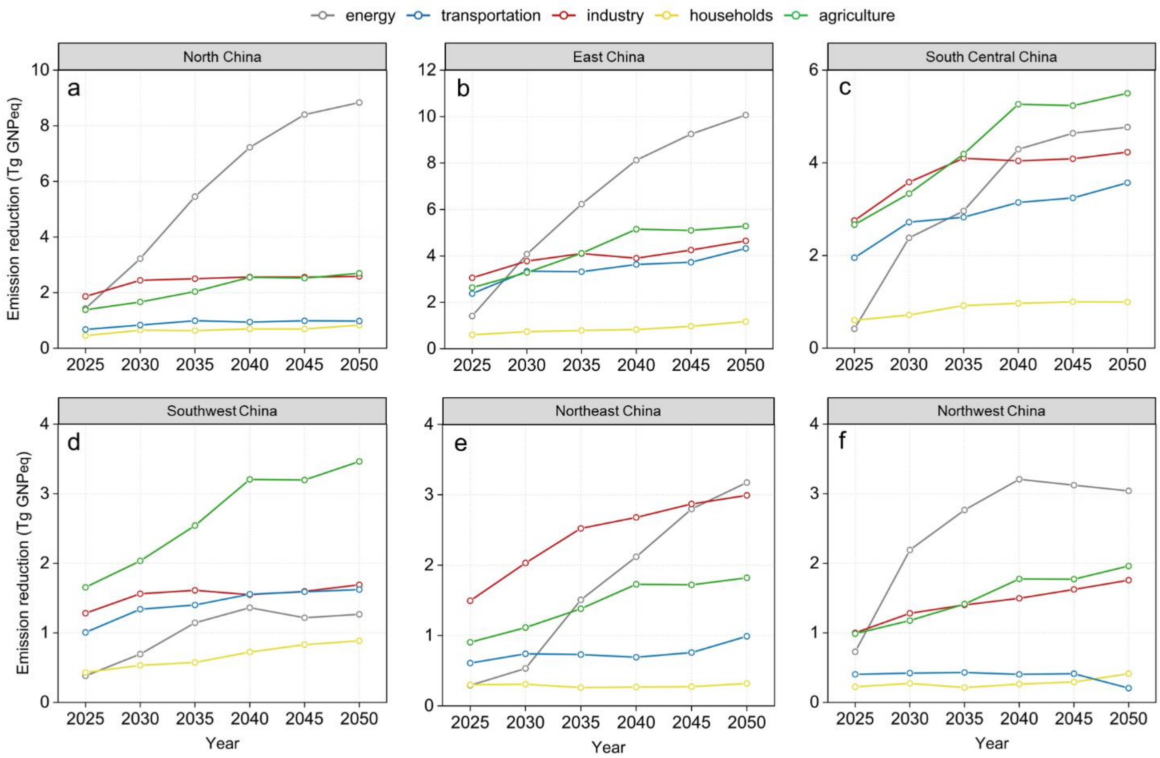

Figure S1 | Sectoral GHG-ANP reductions in China's six geographic regions under the SSP1-26-strong scenario.

The geographic divisions of China and the provinces included can be found in Table S8.

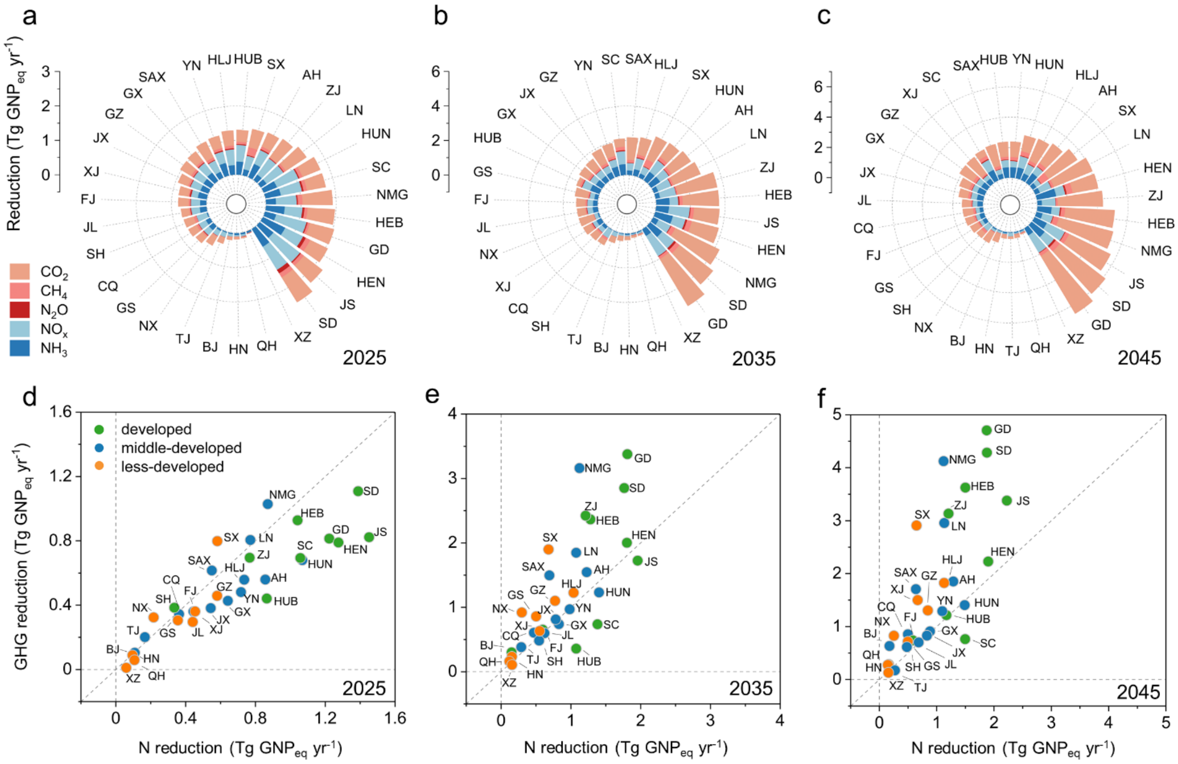

Figure S2 | Synergy mitigation effects at the regional scale in 2025, 2035, and 2045 under the SSP1-26-strong scenario.

In Fig. d-f, the provinces are categorized into three groups based on the projected GDP under the SSP1 pathway, represented by blue, green, and orange dots, indicating developed, middle-developed, and less-developed provinces, respectively (Fig. S9).

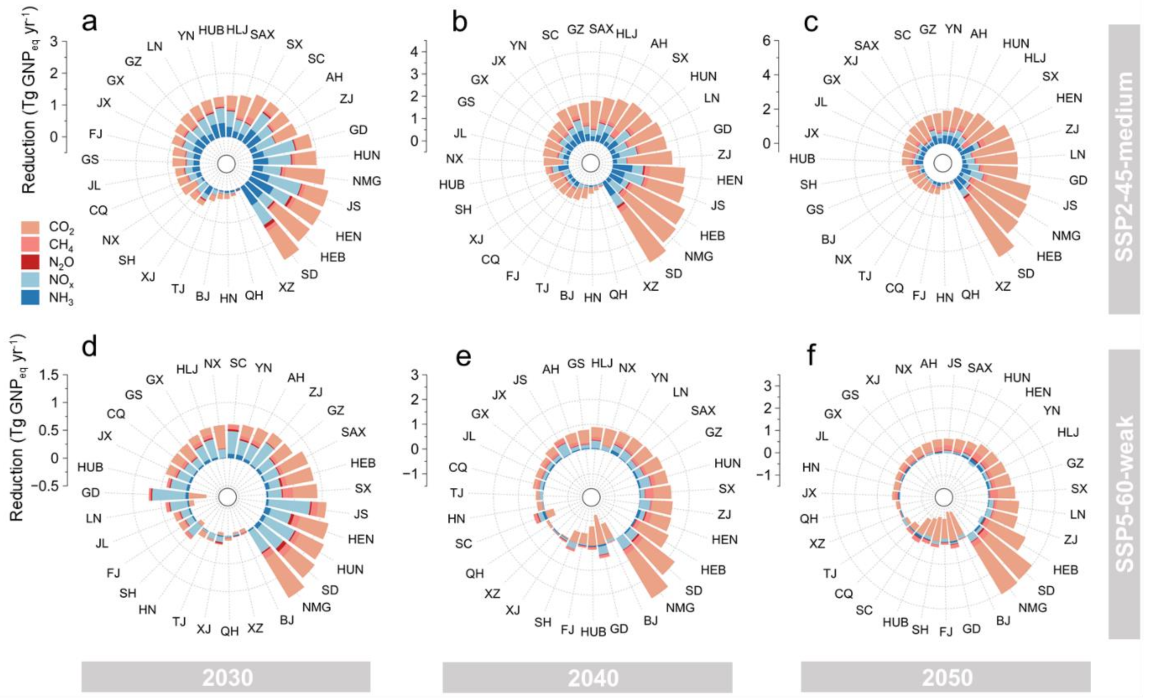

Figure S3 | Integrated reduction potential at the provincial scale in 2030, 2040, and 2050. Fig. (a-c) corresponds to the SSP2-45-medium scenario, and Fig. (d-f) corresponds to the SSP5-60-weak scenario in 2030, 2040 and 2050, respectively.

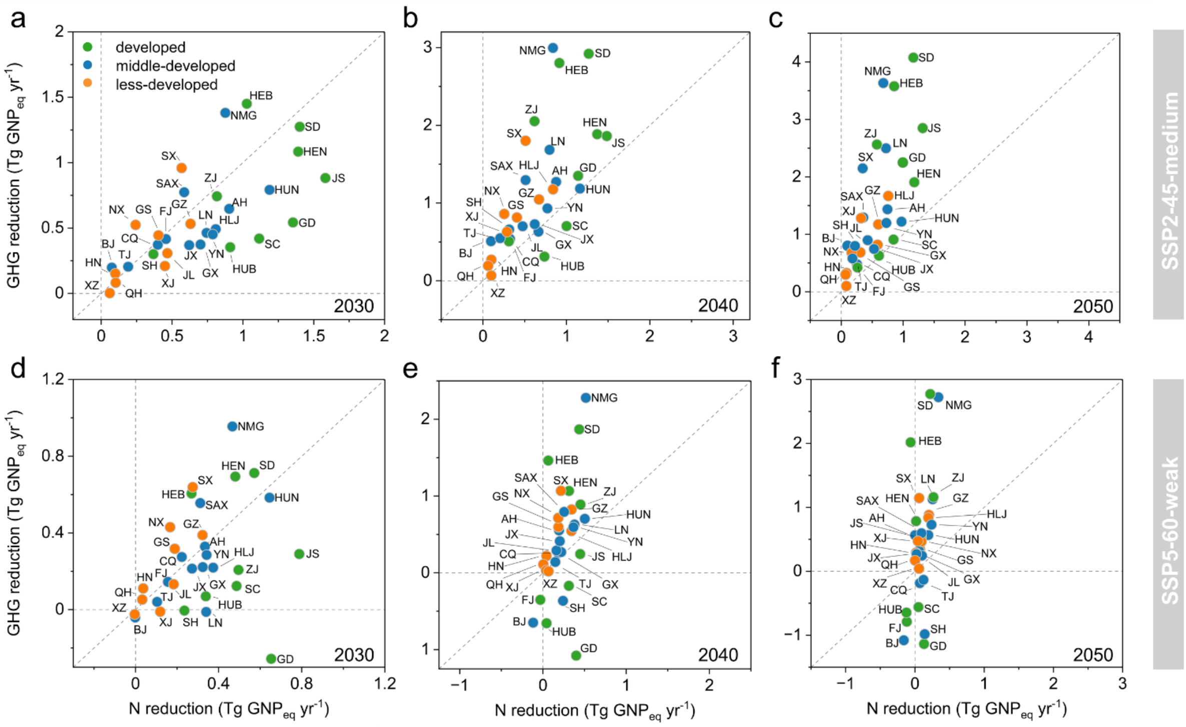

Figure S4 | Synergistic effects between GHG and ANP reductions at the provincial scale. (a-c) corresponds to the SSP2-45-medium scenario, and (d-f) corresponds to the SSP5-60-weak scenario in 2030, 2040 and 2050, respectively. The provinces are categorized into three groups based on the projected GDP, represented by blue, green, and orange dots, indicating developed, middle-developed, and less-developed provinces, respectively (Fig. S9).

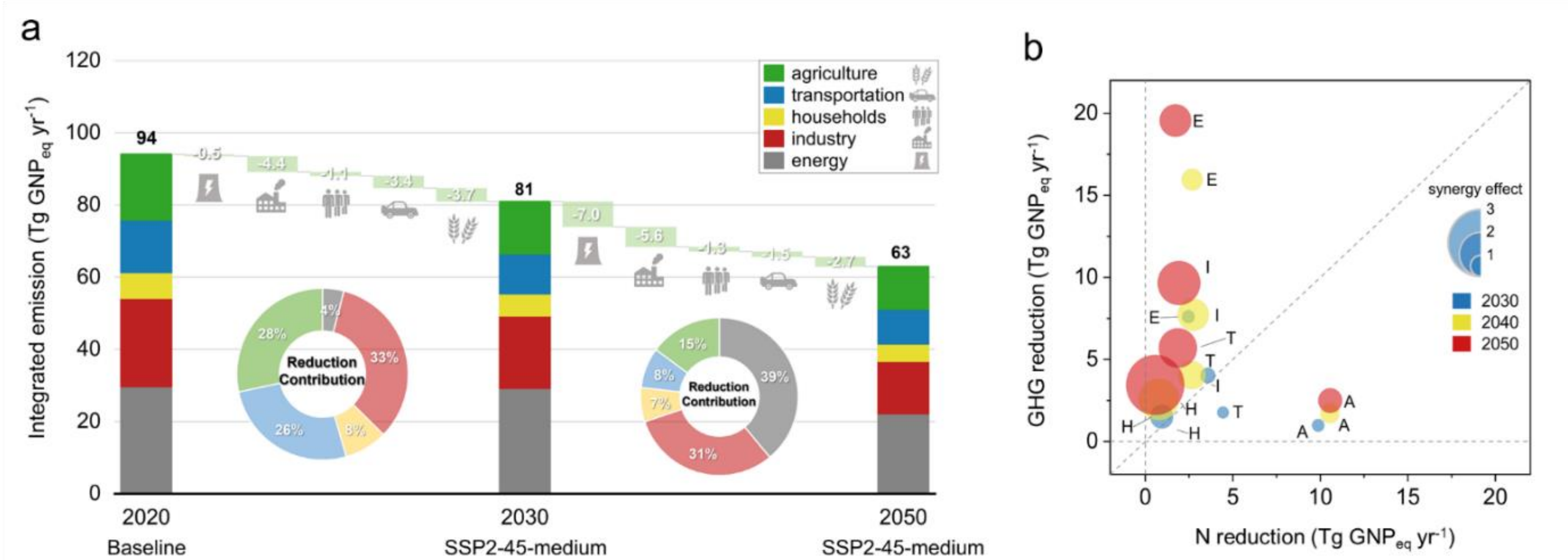

Figure S5 | Integrated reduction potential and synergistic effects by sector under the SSP2-45-medium scenario. **(a)** Emission reductions by sector in 2030 and 2050, as compared to the base year (2020). **(b)** Synergistic emission reduction effects of GHG and ANP by sector under 2030, 2040 and 2050. Here, the abbreviations correspond to energy (E), industry (I), transportation (T), agriculture (A), and households (H), respectively. The size of the dots denotes relative synergetic effects and the color denotes different years.

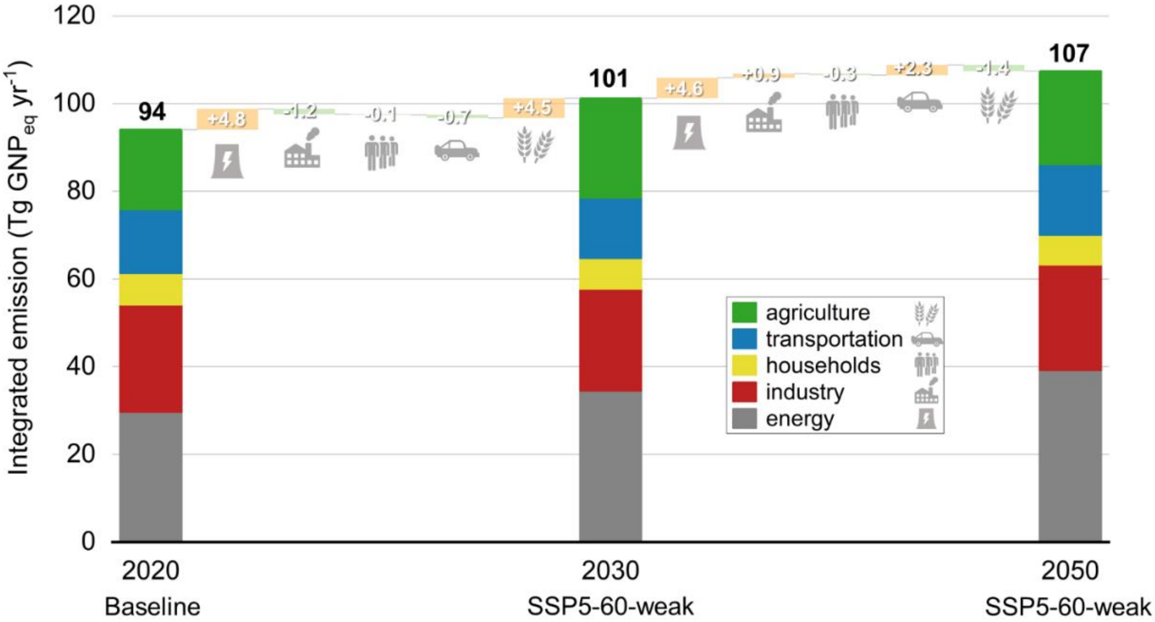

Figure S6 | Integrated emissions by sector under the SSP5-60-weak scenario.
The figure shows the integrated GHG and ANP emissions by sector in 2030 and 2050 under the SSP5-60-weak scenario compared to the base year (2020).

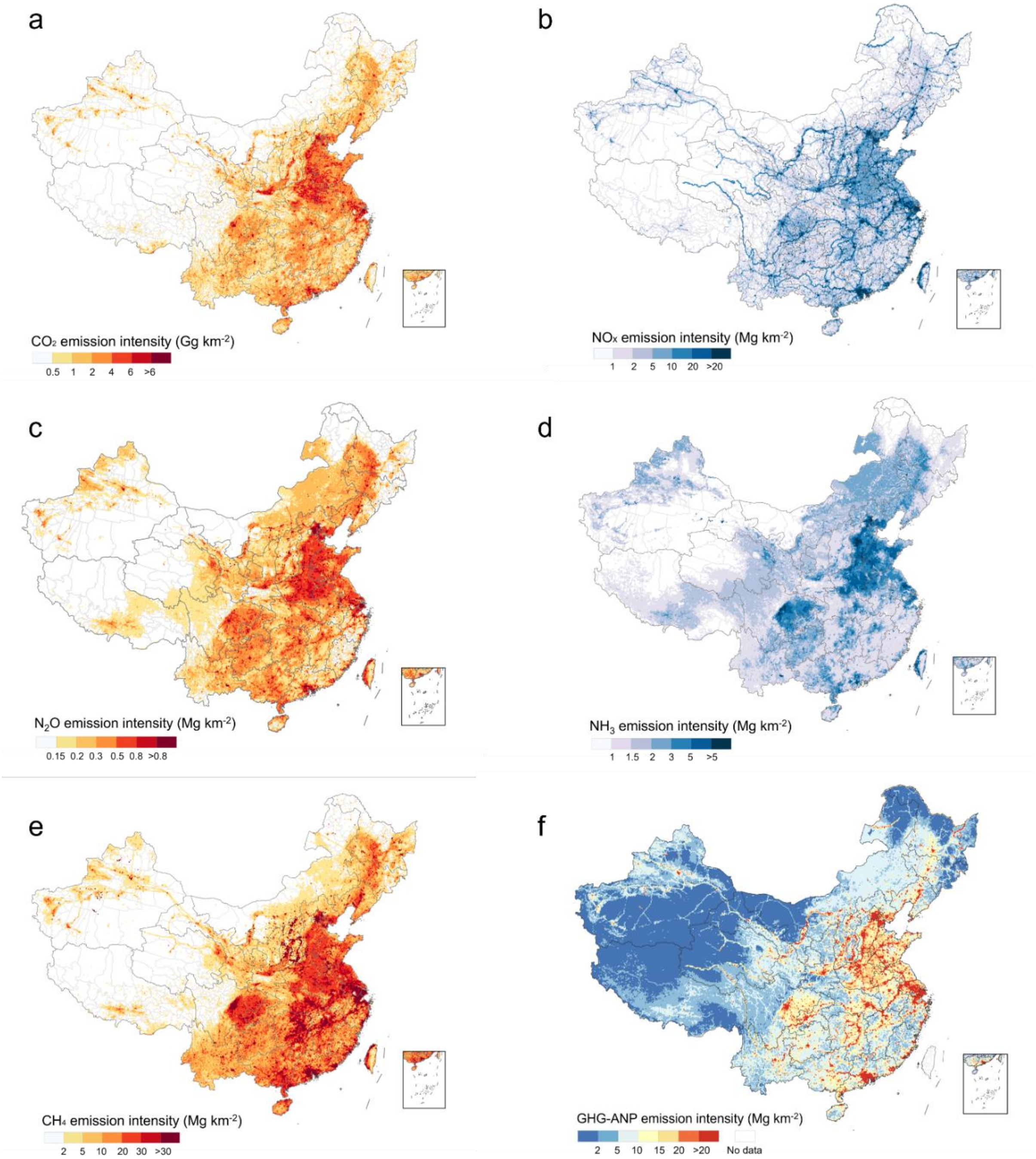

Figure S7 | Spatiotemporal pattern of GHG and ANP emissions from EDGAR.
(a) CO_2 emission intensity in 2020; (b) NO_x emission intensity in 2018; (c) N_2O emission intensity in 2020; (d) NH_3 emission intensity in 2018; (e) CH_4 emission intensity in 2020; (f) GHG-ANP integrated emission intensity. Data are presented in a 1000×1000 km spatial resolution and the original data are obtained from the latest EDGAR public database (https://edgar.jrc.ec.europa.eu/emissions_data_and_maps).

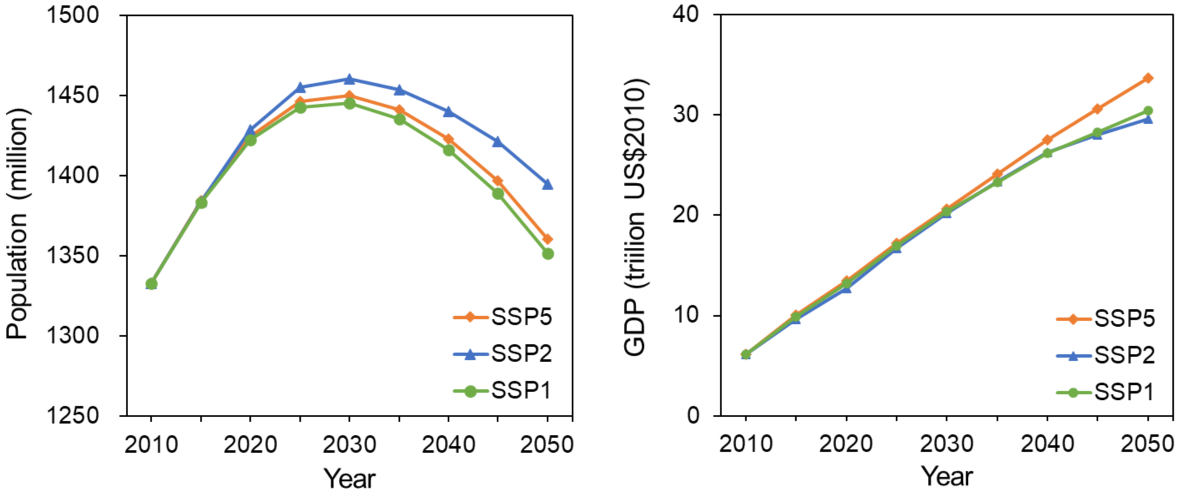

Figure S8 | Trends in population and GDP under different SSP pathways in China. **(a)** population and **(b)** GDP in China under SSPs pathways between 2010 to 2050 at 5-year intervals. The markers in green, blue, and orange depict SSP1, SSP2, and SSP5, respectively. The original data were derived from Chen et al[40] and Tong et al[41].

	GDP in SSP1 (billion USD)			GDP in SSP2 (billion USD)			GDP in SSP5 (billion USD)		
	2025	2035	2045	2030	2040	2050	2030	2040	2050
AH	453	580	775	503	672	821	508	699	937
BJ	419	483	555	454	508	549	460	525	613
CQ	336	395	432	374	419	446	379	431	473
FJ	542	890	1152	683	1037	1232	703	1104	1426
GS	132	192	261	163	224	291	164	229	305
GD	1503	2176	2750	1805	2401	2617	1838	2559	3101
GX	285	329	374	302	342	378	310	367	469
GZ	193	200	219	196	205	217	199	215	248
HN	84	113	138	102	126	147	103	130	160
HEB	767	1106	1347	940	1252	1410	950	1295	1562
HLJ	283	324	361	298	336	358	303	351	424
HEN	1175	1656	2082	1392	2011	2428	1412	2088	2525
HUB	715	918	1106	804	986	1149	829	1050	1286
HUN	559	750	1000	648	868	1046	648	897	1154
NMG	432	542	558	479	553	572	491	586	675
JS	2339	2821	3015	2610	3012	3040	2674	3211	3582
JX	366	492	587	416	552	572	427	601	740
JL	249	328	394	287	361	435	290	371	479
LN	564	711	845	637	788	946	645	795	976
NX	54	77	106	64	91	108	65	96	121
QH	46	57	70	54	63	74	55	64	79
SAX	303	403	545	342	459	593	344	478	638
SD	1621	2732	3587	2242	3444	3890	2324	3620	4533
SH	584	785	948	727	876	1030	738	893	1069
SX	226	295	364	256	324	381	261	345	434
SC	775	1029	1141	934	1107	1161	945	1129	1258
TJ	332	450	527	408	499	571	410	509	596
XZ	21	23	26	22	24	26	23	25	29
XJ	165	222	285	193	258	334	194	261	348
YN	324	401	447	359	425	440	368	448	493
ZJ	1100	1794	2266	1509	2009	2345	1533	2120	2889

Figure S9 | GDP by the province under the SSP1, SSP2, and SSP5 scenario. This figure contains the years 2025, 2035 and 2045 for SSP1; 2030, 2040 and 2050 for SSP2 and SSP5, respectively. Here, the GDP top 30% of provinces in China are considered as developed regions, the last 30% or so are considered as less-developed regions and the rest are medium-developed regions. The original data were referred to Tong et al[41] in 2010 RMB purchasing power parity, and we assumed a constant dollar exchange rate at the 2010 level to convert the data into USD values.

Table S1. Coefficients of variation (CVs) for the main activity data.

Category	Activity data	Uncertainty type	Distribution	CVs (%)	Refs
Energy	Coal production	A	U	10	
	Petroleum production	A	U	10	
	Natural gas production	A	U	10	
	Coke production	A	U	10	
	Crude oil production	A	U	10	
	Gasoline production	A	U	10	
	Diesel production	A	U	10	42-44
	Fuel oil production	A	U	10	
	Coal-fired power generation	A	U	10	
	Hydroelectric power generation	A	U	10	
	Nuclear power generation	A	U	10	
	Wind power generation	A	U	10	
	Biomass power generation	A	U	10	
	Solar power generation	A	U	10	
Industry	Industrial coal combustion	A	U	30	
	Industrial oil combustion	A	U	20	
	Industrial gas combustion	A	U	20	44-46
	N fertilizer production	A	U	5	
	Synthetic ammonia production	A	U	5	
	Other industrial products*	A	U	5	
Transportation	Light-duty gasoline vehicles	A	U	5	
	Heavy-duty gasoline vehicles	A	U	5	
	Light-duty diesel vehicles	A	U	5	34,45
	Heavy-duty diesel vehicles	A	U	5	
	Motorcycles	A	U	5	
Households	Domestic coal combustion	A	U	20	
	Domestic oil combustion	A	U	20	
	Domestic gas combustion	A	U	20	
	Domestic biomass burning	A	U	30	
	Urban population	A	U	5	
	Rural population	A	U	5	31,34,42,45,47
	Food consumption	A	U	10	
	Goods consumption	A	U	10	
	Waste landfill	A	U	10	
	Waste compost	A	U	10	
	Waste incinerates	A	U	5	
	Amount of treated wastewater	A	U	20	
Agriculture	Fertilizer applied	A	U	5	
	Fertilizer type	B	U	10	31,34,45,47,48
	Cultivated areas	A	U	10	
	Crop yield	A	U	5	

Crop residue	A	U	10
Areas of N-fixing crops	A	U	5
Effective irrigated areas	A	U	10
Confined animal population	A	U	10
Grazing animal population	A	U	10
Area of grassland	A	U	5
Grassland area affected by fires	A	U	10
Area of forests	A	U	5
Forest area affected by fires	A	U	50

* Other industrial products include clinker, lime, glass, chemical products, and metal products.

Note: A and B stand for Type A and Type B uncertainty, respectively. Type A uncertainty is based on valid statistical method for treating data, type B uncertainty is based on scientific judgment using all of the relevant information available. U and N represent the Uniform distribution and Normal distribution, respectively.

Table S2. Parameters of GHG-ANP equivalent (*GNP_{eq}*) calculation.

Indicator	Parameters			Description
W_{ANP}	NH_3	1.25 GNP_{eq}/kg NH_3		According to the Law of China Environmental Protection Tax (LCEPT)[49], the tax rate for air pollutants varies between 1.2 and 12[c] CNY kg^{-1}. However, due to a lack of research on NH_3, we have used an average tax rate of 6 CNY kg^{-1} for it. Besides, since the conversion factor from NH_3 to ANP_{eq} is assumed to be 1, we have assigned a relative weight of 1.25 to NH_3.
	NO_x	1.5 GNP_{eq}/kg NO_x		Based on China's latest local tax law[50], we used 8.55[c] CNY kg^{-1} as the environmental tax rate for NO_x in this study, so the relative weight of NO_x was set to 1.5.
W_{GHG}	0.0037 GNP_{eq}/kg CO_{2eq}			The average carbon price of China’s carbon trading pilots since 2013 was 0.0223[a,c] CNY kg^{-1}. As the weight of ANP_{eq} is 1, the relative weight of CO_{2eq} was set to 0.0037.
ANP	NH_3	α	1/0.8	Referring to the LCEPT[49], per unit of ANP_{eq} equals 0.8[b] kg NH_3 or 0.95 kg NO_x.
	NO_x	β	1/0.95	
GHG	CH_4	γ	28	To calculate CO_2 equivalent (CO_{2eq}) for each GHG category, the Global Warming Potential-100 (GWP_{100}) values from the IPCC's Sixth Assessment Report (AR6)[4] were used, following the formula CO_{2eq} = GHG emissions × GWP_{100}.
	N_2O	δ	273	
	CO_2	ε	1	

Note:

[a] Carbon trading prices in China vary with region, policy and market, but this study assumed that the national average carbon trading value remains unchanged.

[b] Since the pollutant taxable equivalents of atmospheric NH_3 may be grossly underestimated, the pollutant taxable equivalents of ammonia nitrogen (NH_4^+-N) were used here instead.

[c] The data here is denoted in Chinese Yuan (CNY). According to China's National Bureau of Statistics, the exchange rate for the U.S. dollar to RMB in 2020 is 6.897.

Table S3. Source categories of GHG and ANP emissions in China.

Category	Subcategory	Species				
		NH_3	NO_x	CO_2	CH_4	N_2O
1. Agriculture*	Fertilizer application	√	√			√
	Irrigation	√			√	
	Agricultural soil	√	√			
	Compost of crop residues	√				√
	Livestock production	√			√	
	Manure storage	√			√	
	Manure spreading	√			√	√
	Grassland (grazing etc.)	√			√	
	Forest	√	√	√	√	√
	Biomass burning (fielding burning)	√	√	√	√	√
	Agricultural machinery			√	√	
2. Households	Domestic coal combustion		√	√		
	Domestic oil combustion		√	√		
	Domestic gas combustion		√	√		
	Biomass burning (crop residues, firewood, manure, etc.)	√	√		√	√
	Wastewater disposal	√			√	√
	Solid waste landfill	√			√	
	Solid waste incineration	√	√	√		
	Solid waste composting	√	√			
3. Transportation	Light duty diesel vehicles	√	√	√	√	√
	Light duty gasoline vehicles	√	√	√	√	√
	Heavy-duty diesel vehicle	√	√	√	√	√
	Heavy-duty gasoline vehicle	√	√	√	√	√
	Motorcycles	√	√	√	√	√
	Non-road machinery	√	√	√	√	√
4. Energy	Power and heating plants	√	√	√		√
	Fuel production and distribution		√	√		
	Fuel conversion		√	√		
	coal mining			√	√	
	Petroleum refining			√	√	
5. Industry	Industrial coal combustion		√	√		
	Industrial oil combustion		√	√		
	Industrial gas combustion		√	√		
	Industrial processes (metal, cement, lime, fertilizer, etc.)	√	√	√		
	Construction			√		
	Solvents (Nitric acid, adipic acid, etc.)			√		√

* Note: In this study, agriculture is broadly defined to encompass cropland, forestry, pasture, grassland, and other land use, which is commonly referred to as Agriculture, Forestry, and Other Land Use (AFOLU).

Table S4. Detailed description of the selected mitigation options for GHG and ANP co-control.

Category	Mitigation strategy	Mitigation measure	Species					Implementation cost
			CH_4	CO_2	N_2O	NH_3	NO_x	
Energy	Reduce CH_4 from coal mining	Upgrading or modifying ventilation systems in coal mines; Installing methane drainage systems in coal mines and capturing the released methane for use or destruction; Sealing off abandoned mine areas and actively degasifying coal seams.	+++	+				The cost can range from thousands to millions of dollars, depending on the complexity and size of the mine. while implementing these measures can incur initial costs, they can also lead to long-term financial savings through increased energy efficiency and reduced greenhouse gas emissions. Additionally, technological advancements and economies of scale may contribute to cost reductions over time.
Energy	Improve oil and gas extraction	Improving venting and containment systems, and infrastructure for capturing and utilizing methane, such as cost-effective pipelines or equipment for conversion to usable energy.	++	+			+	The implementation cost varies depending on the characteristics of the well and the technology used. It can range from thousands to tens of thousands of dollars per well completion. The implementation cost varies depending on the characteristics of the well and the technology used. It can range from thousands to tens of thousands of dollars per well completion.
Energy	Apply ultra-low technologies	Applying Carbon Capture and Storage (CCS) technologies on broiler and promoting the ultra-low emission transformation.	++	+++			+++	The cost of carbon capture can vary based on the size and complexity of the broiler operation, the chosen CCS technology, and the specific emission sources targeted. Generally, CCS costs can range from tens to hundreds of dollars per metric ton of captured CO_2. Technological Advancements and Scale: The cost of CCS technologies has been decreasing over time as technological advancements are made and economies of scale are achieved. It is expected that future innovations and wider adoption of CCS could further contribute to cost reductions in the long run.
Energy	Improve fuel quality and efficiency	Coal Washing, blending and sorting, upgrading combustion systems, turbines, boilers, and generators to	++	+++			+++	The cost of fuel quality upgrades depends on factors like the type of fuel, production processes, and availability of alternative sources. It can involve investments in refining infrastructure, blending facilities, and distribution networks, which can range

		newer models that have better fuel efficiency ratings.					from millions to billions of dollars. The long-term benefits, such as reduced fuel consumption and emissions, can outweigh the initial implementation costs for many of these measures.
Industry	Adoption of renewable energy	Integrating renewable energy sources, such as solar power or wind energy, into industrial processes.	++			++	The cost of installing renewable energy generation systems, such as solar panels, wind turbines, or biomass facilities, can depend on the installed capacity and technology chosen. Costs may include equipment procurement, engineering and design, construction, and installation expenses. It's important to note that the costs of renewable energy technologies have been decreasing over time.
Industry	Switch to cleaner fuels	Transitioning from fossil fuels to cleaner alternatives, such as natural gas or biofuels, can significantly reduce both GHG and nitrogen emissions.	+++	+	+	+++	Switching to cleaner alternatives may require establishing or modifying fuel infrastructure within the industrial facility, such as pipelines, storage tanks, or dispensing systems. The costs will depend on the size of the operation, proximity to existing infrastructure, and the specific requirements of the chosen alternative fuel.
Industry	Improve energy efficiency	Improve energy efficiency in industrial processes by implementing technologies such as cogeneration, heat recovery, and efficient equipment.	++		+	++	Implementing energy efficiency technologies may require modifications to existing infrastructure, such as upgrading electrical systems, optimizing heat distribution networks, or installing control systems. The cost will depend on the scale of modifications needed and the compatibility of the existing infrastructure with the new technologies.
Industry	Process optimization and waste reduction	Recycling and reusing materials, reducing water usage, and implementing advanced manufacturing technologies to reduce waste and improve resource management.	+++	+++	+	++	Implementing process optimization and waste reduction often requires upgrading or retrofitting existing equipment or investing in new technologies. The cost will depend on the scale of the industrial operation and the specific technologies chosen, such as sensors, automation systems, or advanced control systems.

Industry	Carbon capture and utilization (CCU)	Implement carbon capture and utilization techniques to capture and store CO2 emissions from industrial processes.	+	+++	++	+	+++	Costs can include installing capture equipment, retrofitting existing plants, and integrating the capture process into the overall system. The choice of technology will depend on factors such as the type of industrial process, emission concentration, and energy requirements. the cost of storing and transporting captured CO_2 involves establishing or modifying pipelines, compression systems, and storage facilities.
Industry	Advanced emission control technologies	Install and utilize advanced emission control technologies, such as selective catalytic reduction (SCR) or flue gas desulfurization (FGD) systems during industrial processes.		++	+++			Installing the advanced emission control equipment involves costs related to equipment procurement, engineering design, and installation. This may include purchasing catalysts, reactors, absorption towers, scrubbers, and other necessary components. The complexity of the installation process, the scale of the industrial operation, and site-specific conditions can influence the installation cost.
Transportation	Enhance Public Transportation	Expanding and improving public transportation systems can reduce the number of private vehicles on the road, thereby decreasing emissions. Investments in high-capacity buses, metro systems, and rail networks can provide more sustainable transportation options, leading to lower GHG, NO_x, and NH_3 emissions.	+	++	+		+++	Expanding public transportation systems typically requires significant investments in infrastructure. This includes the construction or expansion of stations, tracks, depots, terminals, and maintenance facilities. The cost will depend on the length and complexity of new lines or routes, the number of stations, and the type of transportation mode being implemented.
Transportation	Upgrade Vehicle Emission Standards	Implementing stricter regulations on vehicle emissions, especially for heavy-duty vehicles and diesel engines, can contribute to significant emission reductions.		++	+	++	+++	Implementing upgraded emission standards requires investments in incorporating new technologies into vehicle manufacturing processes. This includes retooling production lines, modifying assembly processes, and integrating emission control systems into vehicles. The cost will depend on the number of vehicles affected by the upgrade and the complexity of the required modifications. In some cases, existing vehicles may need to be

								retrofitted with emission control technologies to comply with upgraded standards. This involves installing additional equipment or modifying existing components. Retrofitting can be a significant cost for fleet owners or vehicle operators, especially if there is a large number of vehicles involved.
Transportation	Promote Electric Vehicles (EVs)	Encouraging the adoption of EVs can significantly reduce GHG emissions from transportation. China has already been promoting electric mobility, continued support for EV infrastructure development, and incentives for EV purchases.	+	+++	+	+	+++	Promoting EVs often requires significant investments in charging infrastructure. This includes establishing charging stations, both public and private, and deploying charging infrastructures in residential areas, workplaces, and public spaces. The cost will depend on the number of charging stations needed, their types (e.g., slow, fast, ultra-fast), and the desired coverage area.
Transportation	Improve Fuel Efficiency	Implementing stricter fuel efficiency standards for vehicles can reduce both GHG emissions and fuel consumption. Encouraging the use of hybrid vehicles and promoting advanced technologies like stop-start systems and lightweight materials can improve the overall fuel efficiency of the transportation fleet.	+	+++	+	+	++	The specific costs associated with the use of hybrid vehicles and promoting advanced technologies for fuel efficiency in China will vary based on factors such as market conditions, regional differences, government policies, and availability of incentives. Advancements in technology and increasing market demand for hybrids may contribute to a decrease in their relative costs over time.
Households	Renewable energy sources	Promote the installation of renewable energy systems like solar panels or small wind turbines for household electricity generation. Utilizing clean energy sources reduces reliance on fossil fuels and decreases GHG emissions.	++	+	+	++	++	The specific costs associated with promoting the installation of renewable energy systems for household electricity generation in China will vary based on factors such as regional differences, system size, local regulations, and market conditions.

Households	Energy-efficient appliances	Encourage the use of energy-efficient appliances, such as refrigerators, air conditioners, washing machines, and light bulbs. These appliances consume less energy and therefore reduce GHG emissions.	+	+		+	++	Energy-efficient appliances may have a slightly higher upfront cost compared to standard appliances, but they can result in long-term energy savings. The specific costs associated with using energy-efficient appliances in China will vary based on factors such as regional differences, suppliers, availability of models, and any ongoing energy-saving initiatives.
Households	Enhance building insulation	Enhance the insulation of buildings by insulating roofs, walls, and windows. This can greatly reduce the need for heating and cooling, leading to lower energy consumption and GHG emissions.	+	+		+	++	The cost of insulation materials and labor will depend on market prices, availability, and local conditions. It is essential to consider the quality and performance of the materials to ensure long-term energy efficiency and durability.
Households	Waste management	Implement proper waste management practices, including recycling, composting, and reducing food waste. Landfills emit significant amounts of methane, a potent GHG, so reducing waste sent to landfills can help mitigate emissions.	++	+		++		Establishing or improving recycling infrastructure, such as recycling centers or collection points for recyclable materials, may require investment in infrastructure development, equipment (such as collection trucks, balers, or compactors), and personnel. Setting up composting systems for organic waste disposal can involve costs for purchasing compost bins or containers and composting materials.
Households	Water management	Promote water-saving practices and improve wastewater treatment ratio in households.	++	+	+++	++	++	Installing water-saving fixtures such as low-flow faucets, showerheads, and toilets can help reduce water consumption. Expanding or upgrading wastewater treatment infrastructure to improve treatment ratios requires substantial investment.
Agriculture	Soil management	Reducing tillage intensity and frequency; Using cover crops; Applying organic amendments.	+		++	++	+	The costs associated with soil management practices can vary depending on factors such as the specific agricultural system, soil type, climate, and local conditions. The availability of financial incentives, government support programs, and carbon markets can help offset some of the implementation costs and provide economic incentives for farmers to adopt sustainable soil management practices.

Agriculture	4R fertilization	The 4R stands for the right source, right rate, right time, and right place of fertilizer application, which enhances nutrient use efficiency, reduces fertilizer waste and supports crop productivity while minimizing the negative consequences of excessive application.	+		+++	+++	++	Implementation costs of 4R fertilization can vary significantly depending on the farm size, location, crop types, and existing infrastructure. Implementation costs of 4R fertilization can vary significantly depending on the farm size, location, crop types, and existing infrastructure. Implementing the right rate and right-place aspects of 4R fertilization may involve the use of specialized application equipment and technology. This can include precision farming tools, such as variable rate applicators, GPS guidance systems, or drones.
Agriculture	Improved irrigation	Upgrading irrigation systems with more efficient technologies, such as drip irrigation or precision sprinklers, can help optimize water use and reduce emissions. Adopting water management practices such as proper scheduling, soil moisture monitoring, and improved drainage can reduce GHG and NH_3 emissions.	+++		++	++		The cost of upgrading irrigation systems will depend on the scale of the operation, the existing infrastructure, and the specific technology chosen. The cost of adopting water management practices will depend on the level of monitoring required, any necessary infrastructure modifications, and the adoption of new practices.
Agriculture	Manure management	Solid-liquid separation; manure cover storage; acidifying slurry by additives; promoting feces composting and anaerobic digestion to convert feces into organic fertilizers; Promoting the fermentation of feces to produce biogas.	+++		+++	+++	+	Implementing solid-liquid separation techniques involves installing equipment such as separators or screens to remove solids from the liquid fraction of manure. The cost will depend on the scale of the operation, the size and type of equipment required, and any necessary modifications to existing infrastructure. Constructing manure storage facilities that are covered to reduce emissions can involve upfront costs for materials, labor, and engineering design. Implementing anaerobic digestion systems requires the installation of specialized digesters to break down organic matter and produce biogas.

Agriculture	Feeding and Housing adaptation	Implementing a low-Crude protein diet and use of additives can improve feed efficiency and reduce methane emissions from enteric fermentation; improved ventilation systems, proper insulation, and optimized space utilization can help minimize GHG and NH_3 emissions from animal housing.	+++		++	+++		Adjusting feed formulations to incorporate a low-crude protein diet and additives may require changes in manufacturing processes, equipment, and quality control procedures. This can include modifying production lines, testing protocols, and compliance with safety standards. The cost will depend on the extent of modifications needed and the scale of feed production.
Agriculture	Grazing management	Rotational grazing, rest periods for vegetation recovery, and promoting diverse plant species can improve carbon sequestration and enhance the overall health of grasslands, leading to potential reductions in GHG emissions.	++		+	++		Implementing rotational grazing systems may require investments in infrastructure such as fencing, water supply systems (e.g., troughs, pipelines), and shade structures. The cost will depend on the size of the grazing area, the number of paddocks or pastures needed, and the specific infrastructure requirements.
Agriculture	Regulate biomass burning	Promoting sustainable biomass utilization and cleaner biomass-burning practices while enforcing emission limits can help minimize GHG and ANP emissions.	+	+	+	+	++	Ensuring compliance with sustainable biomass utilization and cleaner burning practices may require monitoring systems and enforcement mechanisms. This can involve establishing monitoring programs, conducting emissions testing, and implementing penalties for non-compliance. The cost will depend on the extent of monitoring and compliance measures implemented.

Note: "+" denote the mitigation efficiency to the specific gas emissions, "+", <30%, "++" 30-60%, "+++", >60%.

Table S5. Comparison of key parameters under different scenarios.

Factor	Key input parameters	SSPs comparison
Macro-variables		
Population	Total population	SSP1<SSP5<SSP2
	Rural population	SSP1<SSP2<SSP5
Economy	GDP	SSP5>SSP1>SSP2
	Agricultural value-added /person	SSP1>SSP5>SSP2
	Industrial value-added /person	SSP1>SSP5>SSP2
	Service value-added /person	SSP1>SSP5>SSP2
	Per capita consumption	SSP1>SSP5>SSP2
Social Features	Energy intensity	SSP1<SSP2<SSP5
	Resource intensity	SSP1<SSP2<SSP5
	Learning rate to improve technical efficiency	SSP1< SSP2<SSP5
	Energy efficiency payback period	SSP1<SSP2<SSP5
	Fuel preference-dislike of coal	SSP1>SSP2>SSP5
	Secondary energy tax	SSP1>SSP2>SSP5
Energy demands		
Energy-intensive industry	Clinker/cement ratio	SSP1<SSP2<SSP5
	Cement demand	SSP1<SSP2<SSP5
	Cement production-fossil fuel preference	SSP1<SSP2<SSP5
	Barriers to cement trade	SSP1=SSP2=SSP5
	Steel material efficiency	SSP1>SSP2>SSP5
	Steel production-scrap share	SSP1>SSP2>SSP5
	Steel demand	SSP1<SSP2<SSP5
	Steel production-fossil fuel preference	SSP1<SSP2<SSP5
	Barriers to steel trade	SSP1=SSP2=SSP5
	Production mode preference (environmentally friendly)	SSP1>SSP2>SSP5
Transportation	Minimum travel time/year/person	SSP1<SSP2<SSP5
	Travelable cost	SSP1<SSP2<SSP5
	Green emergence cost to total cost ratio	SSP1>SSP2>SSP5
	Luxury transportation revenue elasticity	SSP1<SSP2<SSP5
	Preference for green transportation	SSP1>SSP2>SSP5
	Energy efficiency for freight and passenger transportation	SSP1>SSP2>SSP5
	Prefer electric vehicles (<150 km)	SSP1>SSP2>SSP5
	Future transport technology costs	SSP1<SSP2<SSP5
	Biofuel tax	SSP1>SSP2>SSP5
Households	Cooking efficiency	SSP1>SSP2>SSP5
	Appliance efficiency	SSP1=SSP2=SSP5
	Secondary fuel efficiency	SSP1>SSP2>SSP5
	Feasibility of microfinance	SSP1 considered
	Fuel subsidies for poor households	SSP1 considered
	Growth rate of building area	SSP1=SSP2=SSP5
	Income inequality (Gini coefficient)	SSP1<SSP2<SSP5
	Home appliance ownership rate	SSP1<SSP2<SSP5

	Share of solid fuel consumption	SSP1<SSP2<SSP5
	Appliance energy efficiency	SSP1>SSP2>SSP5
Non-energy sector	Maximum demand for chemical products	SSP1<SSP2<SSP5
	Conversion efficiency (feedstock: intermediate chemicals)	SSP1>SSP2>SSP5
	Conversion efficiency (feedstock: finished chemicals)	SSP1>SSP2>SSP5
	Coal utilization rate (feedstock)	SSP1>SSP2>SSP5
	Biomass utilization rate (feedstock)	SSP1<SSP2<SSP5
Energy supply		
Fossil energy	Coal/Oil/Natural gas transport distance (transport barriers)	SSP1<SSP2<SSP5
	Learning rate to improve energy efficiency	SSP1<SSP2<SSP5
	Energy transportation costs	SSP1<SSP2<SSP5
Natural gas production industry	Natural gas replacing liquefied natural gas (LNG)	SSP1=SSP2=SSP5
Bioenergy industry	Minimum bioenergy target	SSP1>SSP2>SSP5
	Learning barriers to biofuel use	SSP1<SSP2<SSP5
	Transport distance (transport barriers)	SSP1<SSP2<SSP5
	Bio-crop management level	SSP1>SSP2>SSP5
	Biofuel conversion efficiency	SSP1>SSP2>SSP5
Power industry	Minimum installed capacity of PV or wind power	SSP1>SSP2>SSP5
	Learning barriers to PV or wind power use	SSP1<SSP2<SSP5
	Transmission and distribution costs of solar, and PV power	SSP1<SSP2<SSP5
Hydrogen production industry	Fixed investment in hydrogen production technology	SSP1>SSP2>SSP5
	Hydrogen energy production efficiency	SSP1>SSP2>SSP5
	Hydrogen energy-related infrastructure barriers	SSP1<SSP2<SSP5
	Hydrogen-based clean fuel preference	SSP1>SSP2>SSP5
	Transportation costs	SSP1<SSP2<SSP5
Agricultural production		
Agricultural production	Crop nitrogen use efficiency (NUE)	SSP1>SSP2>SSP5
	Cropping area	SSP1<SSP2<SSP5
	Fertilizer use	SSP1<SSP2<SSP5
	Livestock population	SSP1<SSP2<SSP5
	Livestock NUE	SSP1>SSP2>SSP5
	Manure recycling ratio	SSP1>SSP2>SSP5
	Crop residues retention	SSP1>SSP2>SSP5

Table S6. Uncertainty of future emissions in different scenarios (unit: %).

Species	Scenarios	2025	2030	2035	2040	2045	2050
NH_3	SSP1-REF	19	20	23	25	26	28
	SSP2-REF	18	19	20	20	23	26
	SSP5-REF	17	14	14	14	14	15
	SSP1-26-strong	31	38	49	80	82	107
	SSP2-45-medium	29	36	42	49	55	62
	SSP5-60-weak	17	17	20	23	26	28
NO_x	SSP1-REF	20	20	22	25	27	30
	SSP2-REF	19	20	22	22	24	30
	SSP5-REF	18	18	19	20	21	21
	SSP1-26-strong	33	41	42	44	42	41
	SSP2-45-medium	22	37	34	31	34	38
	SSP5-60-weak	11	17	20	23	26	29
N_2O	SSP1-REF	24	25	27	30	30	32
	SSP2-REF	20	23	26	27	30	30
	SSP5-REF	18	18	20	21	22	22
	SSP1-26-strong	44	45	40	35	38	41
	SSP2-45-medium	35	36	33	31	32	32
	SSP5-60-weak	13	18	17	16	18	19
CO_2	SSP1-REF	20	20	23	27	30	32
	SSP2-REF	20	20	23	25	27	30
	SSP5-REF	16	18	22	24	26	28
	SSP1-26-strong	10	15	22	30	34	39
	SSP2-45-medium	10	16	26	35	35	36
	SSP5-60-weak	7	10	11	12	18	25
CH_4	SSP1-REF	21	21	26	28	30	31
	SSP2-REF	21	21	24	27	28	29
	SSP5-REF	18	19	20	22	22	23
	SSP1-26-strong	12	16	22	28	29	30
	SSP2-45-medium	8	8	9	10	15	22
	SSP5-60-weak	9	11	14	16	14	12

Reference:

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Table S7. Uncertainty of sectoral emission reduction in different scenarios.

Year	Energy	Industry	Households	Transportation	Agriculture
SSP1-26-strong					
2025	10%	10%	13%	17%	8%
2030	14%	15%	18%	20%	9%
2035	15%	16%	21%	21%	11%
2040	17%	21%	24%	22%	14%
2045	20%	22%	25%	24%	18%
2050	22%	23%	32%	27%	19%
SSP2-45-medium					
2025	10%	11%	11%	10%	11%
2030	12%	14%	13%	13%	13%
2035	15%	16%	14%	15%	15%
2040	18%	16%	15%	17%	16%
2045	19%	17%	17%	19%	18%
2050	22%	19%	19%	21%	20%
SSP5-60-weak					
2025	6%	5%	8%	6%	7%
2030	9%	7%	10%	6%	9%
2035	13%	8%	11%	9%	10%
2040	13%	10%	14%	11%	11%
2045	17%	18%	16%	19%	12%
2050	25%	42%	17%	33%	14%

Table S8. Geographical divisions of China and abbreviations of provinces.

Geographic divisions	Province	Abbreviation
North China	Beijing	BJ
	Hebei	HEB
	Inner Mongolia	NMG
	Shanxi	SX
	Tianjin	TJ
East China	Anhui	AH
	Fujian	FJ
	Jiangsu	JS
	Jiangxi	JX
	Shandong	SD
	Shanghai	SH
	Zhejiang	ZJ
South Central China	Guangdong	GD
	Guangxi	GX
	Hainan	HN
	Henan	HEN
	Hubei	HUB
	Hunan	HUN
Southwest China	Chongqing	CQ
	Guizhou	GZ
	Sichuan	SC
	Tibet	XZ
	Yunnan	YN
Northeast China	Heilongjiang	HLJ
	Jilin	JL
	Liaoning	LN
Northwest China	Gansu	GS
	Ningxia	NX
	Qinghai	QH
	Shaanxi	SAX
	Xinjiang	XJ

Table S9. Willingness to pay (WTP) for ecosystem services in China.

Province	GDP (billion USD, 2020)	Population (10 thousand, 2020)	PGDP (USD, 2020)	WTP (considering inflation*; USD, 2020)	Ref
Beijing	523	2189	23905	24.62	60
Tianjin	204	1387	14732	11.34	61
Hebei	525	7464	7041	14.41	
Shanxi	256	3490	7325	18.34	
Inner Mongolia	252	2403	10447	22.27	61
Liaoning	364	4255	8535	31.00	
Jilin	178	2399	7365	18.34	
Heilongjiang	199	3171	6181	14.95	62
Shanghai	561	2488	22583	34.84	63
Jiangsu	1489	8477	17576	5.81	64
Zhejiang	937	6468	14588	22.48	65
Anhui	561	6105	9195	16.87	65
Fujian	637	4161	15341	2.00	66
Jiangxi	372	4519	8245	39.11	67
Shandong	1060	10165	10460	12.96	68
Henan	797	9941	8037	15.79	
Hubei	630	5745	10792	28.00	67
Hunan	606	6645	9119	23.65	68
Guangdong	1606	12624	12789	30.31	69
Guangxi	321	5019	6424	14.41	70
Hainan	80	1012	7993	15.79	71
Chongqing	362	3209	11333	28.00	
Sichuan	705	8371	8427	31.00	72
Guizhou	258	3858	6708	14.41	
Yunnan	356	4722	7535	61.24	73
Tibet	28	366	7589	50.61	71
Shaanxi	380	3955	9611	13.33	74
Gansu	131	2501	5218	18.34	75
Qinghai	44	593	7368	18.34	75
Ningxia	57	721	7905	18.34	
Xinjiang	200	2590	7770	17.97	71

*WTP takes into account 2% annual average inflation over 10 years.

Note: Due to the lack of literature for the underlined provinces, data from provinces with similar PGDP were taken based on expert judgment.

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