Aligning Climate and Health Co-benefits through Supply-Chain Energy Intensity Coordination in China

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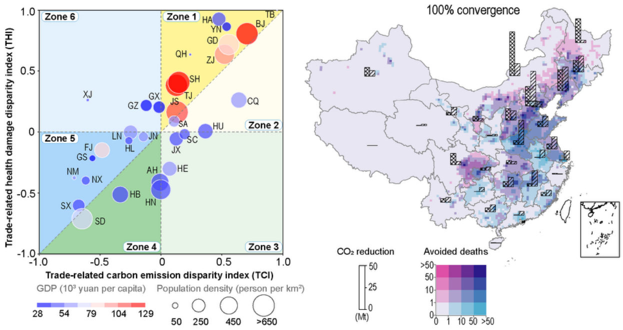
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Trade-related health damage disparity index (THI)
Trade-related carbon emission disparity index (TCI)
GDP (10³ yuan per capita)
28 54 79 104 129
Population density (person per km²)
50 250 450 >650
100% convergence
CO₂ reduction
50 25 0 (Mt)
Avoided deaths
>50 50 10 1 0
0 1 10 50 >50

Abstract

The co-mitigation of carbon emissions and air pollutants offers substantial benefits but is complicated by divergent sectoral emission profiles and spatial disparities. By integrating input-output analysis with health impact source attribution, we examine how interprovincial trade redistributes CO_2 emissions and $PM_{2.5}$-related mortality across China's supply chains. We find that demand from economically advanced provinces induces two distinct burden-shifting patterns between carbon emissions and health burdens. Carbon emissions are outsourced to sparsely populated northwestern regions through power generation, while health burdens concentrate in the densely populated industrial manufacturing belt of central and northern China. Despite production-side divergences, we identify a notable alignment at the final production level, offering opportunities to narrow the energy intensity gap through supply-chain coordination. We simulate three convergence scenarios in which upstream producers in the nonmetal, metal, and power sectors adopt energy intensities of their downstream partners. These include full convergence (100% adoption) and two partial convergence scenarios (75% and 50% adoption), with the latter constrained by national benchmark performance. Full convergence reduces trade-related CO_2 emissions by 17% (491 Mt) and averts 19% of associated mortality (3.8×10^4 deaths). Partial convergence scenarios still deliver meaningful co-benefits. This demonstrates that supply-chain coordination offers pathways to reconciling production-side disparities and more balanced climate–health co-benefits in China.

Keywords: supply-chain coordination, climate-health co-benefits, regional disparity

Synopsis Statement: Coordinating provincial supply chains provides a strategic pathway to align climate mitigation with public health benefits in China.

1. INTRODUCTION

Addressing the dual challenges of climate change and air pollution-related health impacts remains a pressing priority for China.[1–3] Both challenges stem largely from shared sources—combustion processes and industrial activities—justifying the need for integrated mitigation of carbon dioxide (CO_2) and air pollutant emissions.[4] Co-mitigation strategies offer substantial advantages by simultaneously addressing both issues more efficiently, while also delivering immediate health benefits that can help build public support—particularly given that the long-term gains of climate policies are often intangible.[4,5] As China nears the saturation point of end-of-pipe pollution control technologies, further emission reduction through conventional approaches is becoming increasingly constrained.[6,7] Consequently, strategies focusing on improvements in fuel efficiency, shifts towards renewable energy, and structural industrial upgrades are emerging as critical pathways for future air pollution control and climate mitigation.[8–10]

However, the effectiveness of co-mitigation efforts is complicated by divergent sectoral emission profiles and spatial distributions. While CO_2 emissions are predominantly concentrated in power generation and contribute to global climate impacts, air pollutants are mainly emitted by energy-intensive industries and residential sectors, exerting localized health effects that depend on population density, meteorological conditions, and atmospheric chemistry.[11–13] This spatial heterogeneity presents a significant challenge, as industrial agglomeration has concentrated polluting industries in particular regions—often densely populated—where economic development has driven the clustering of heavy industries.[14] Although large facilities in these areas are generally better equipped to implement advanced end-of-pipe controls and energy efficiency measures than smaller operations,[15] they simultaneously generate pollution hotspots that disproportionately affect local populations.[16]

This complexity is further amplified by the structure of supply chains, which effectively redistribute emissions and associated health damages across regions. Economically developed provinces often outsource their emissions and health impacts to industrial clusters in less developed areas, creating a geographical mismatch between those who consume goods and those who bear the environmental and health burdens of production.[17–19] Approximately 25% of China's $PM_{2.5}$-related deaths are linked to interprovincial trade, with emissions typically transferred from developed coastal provinces to interior regions where mitigation resources are limited.[20] This pattern not only weakens regional mitigation efforts but also exacerbates inequalities in health outcomes, thereby impeding progress toward several Sustainable Development Goals (SDGs), including reduced inequalities (SDG 10), good health and well-being (SDG 3), and climate action (SDG 13).[21]

The divergence between production-side emission patterns of carbon and air pollutants calls for greater attention to coordination at the supply-chain level in co-mitigation research. While production-oriented approaches have demonstrated considerable potential for delivering co-benefits,[13,22,23] studies focusing on co-benefits along supply chains remain limited. Recent studies have examined carbon emissions[24–26] and air pollution-related health impacts[20,27–29] embodied in interregional trade; few have provided an integrated, high-resolution assessment that captures the coupling between climate and health impacts within supply chains. Most existing health attribution studies predominantly employ scenario-based analyses or reduced-complexity models,[20,28] which either lack spatial resolution for source-specific contributions or inadequately represent atmospheric physicochemical processes. A better understanding of how carbon emissions and health impacts may exhibit different spatial and sectoral patterns along supply chains is critical to inform effective co-mitigation strategy design.

To address these complex dynamics, we integrate input-output analyses with spatially explicit health impact assessments to examine how interprovincial trade in China redistributes both CO_2 emissions and air pollution-related health damages. Our high-resolution analytical framework, which incorporates harmonized emission inventories, evaluates polarization patterns of carbon emissions and health impacts, revealing the influence of industrial agglomeration and supply chain-mediated emission relocation. Crucially, we assess the potential co-benefits of reducing the energy intensities of trade partners to levels comparable to those of outsourcing provinces, identifying strategic opportunities for synergistic mitigation. By exploring the interplay among industrial structure, trade patterns, emissions, and health outcomes, our study provides a comprehensive framework for addressing the intertwined challenges of climate change and air pollution in China, with broader implications for other countries facing similarly complex supply chain dynamics.

2. METHODS

Our integrated analytical framework combines three main components to assess climate-health co-mitigation potential in China's interprovincial supply chains (Figure S1): (1) High-resolution adjoint modeling using the Community Multiscale Air Quality (CMAQ) v5.0 to quantify how location- and species-specific emissions contribute to $PM_{2.5}$-related mortality nationwide; (2) Multi-regional input-output (MRIO) analysis using China's 2017 provincial

MRIO table to trace CO_2 emissions and health impacts through interprovincial trade flows; and (3) Scenario analysis evaluating co-benefits from aligning energy intensities across supply chain partners. This workflow enables us to identify spatial and sectoral patterns of burden redistribution and assess strategic opportunities for coordinated mitigation.

2.1. Air Quality Modeling with the Adjoint Model. We employ the adjoint[30,31] model of CMAQ[32] v5.0 to quantify the contributions of location- and species-specific air pollutant emissions to $PM_{2.5}$-related premature deaths in China for the year 2017. CMAQ is a widely used chemical transport model (CTM) that simulates the transport and transformation of atmospheric pollutants and estimates their concentrations.[32] In this study, the CMAQ model is configured with the CB05 gas-phase chemistry mechanism and the AERO5 aerosol module. The adjoint model operates similarly to the CTM but in reverse, tracking the impact of a pollutant at receptor locations back to its emission sources through a cost function.[30] In our case, the cost function is the total number of premature deaths attributable to $PM_{2.5}$ exposure for China. Mortality estimates cover five major causes, including ischemic heart disease (IHD), cerebrovascular disease (stroke), chronic obstructive pulmonary disease (COPD), and lung cancer (LC) for adults over 25 years old, and acute lower respiratory illness for children under five. A single adjoint simulation provides the sensitivity of model output (e.g., $PM_{2.5}$-related mortality) to emissions at all locations and times, without the need for multiple forward simulations with perturbed inputs. The adjoint approach has been extensively applied in backward sensitivity analysis, source attribution, data assimilation, and inverse modeling.[33–35] The CMAQ adjoint implementation includes multiphase aerosol-forming processes, which allows efficient and high-resolution source attribution of health impacts.[31] Using the adjoint simulation, we quantify the contributions of emissions from seven species to $PM_{2.5}$-related mortality, including organic carbon (OC), elemental carbon (EC), other primary $PM_{2.5}$, sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), and volatile organic compounds (VOCs). The mathematical derivation of adjoint sensitivity analysis is presented in previous studies[11,19] and summarized in Text S1.

The modeling domain covers all of China with a horizontal resolution of 36 × 36 km (Figure S2) and 13 vertical layers extending up to ~16 km above the ground. Anthropogenic emissions are derived from the AiMa emission inventory (http://www.aimayubao.com/),[36] which categorizes eight sources (i.e., power generation, industry, residential, transportation, agriculture, solvent usage, fugitive dust, and fires).[37,38] The AiMa inventory provides constrained bottom-up emission data for China, integrating statistical data, ground measurements, and satellite observations. It has been extensively used and validated in previous modeling studies and air quality forecasting services in China.[11,39,40] Meteorological inputs are generated using the Weather Research Forecasting (WRF) model v3.4.1,[41] driven by global weather forecast products from the National Centres for Environmental Prediction (NCEP) Global Forecast System[42] at a spatial resolution of 0.5° × 0.5°.

To ensure robust exposure-response assessment, simulated concentrations of $PM_{2.5}$, PM_{10}, SO_2, and NO_2 are evaluated against observations from 1,504 ground-based monitoring sites across China (Figures S3 and S4). The model successfully reproduces the spatial distribution of $PM_{2.5}$ concentration with a Pearson correlation coefficient (r) of 0.63, and performance metrics for all evaluated pollutants meet or approach recommended benchmarks, indicating reliable model performance.[43,44] In addition, the adjoint sensitivities are validated against forward sensitivities derived from finite-difference and complex variable methods, showing consistent results.[31] Further details on model evaluation are provided in Text S2.

2.2. Emissions and Associated Health Impacts Embodied in the Supply Chains. While AiMa provides better constrained model-ready emission inputs, it lacks the sectoral resolution required for MRIO analysis. We therefore employ the Global Emission Modeling System (GEMS),[45,46] which provides production-based emissions disaggregated by sector and fuel combinations (Table S1). To ensure consistency with our air quality modeling, GEMS sectoral emissions are harmonized with provincial totals from AiMa. The mapping between GEMS sectors and the MRIO sectoral classification is provided in Text S3. Notably, direct household emissions from residential fossil/biomass combustion for cooking and heating, as well as emissions from private cars, are excluded from the MRIO analysis since they do not enter economic supply chains.

Second, we attribute emissions emitted in each region (i.e., direct emitter) to both final producers[47–49] (who produce the finished products using local or imported intermediate inputs) in supply chains and final consumers[47,49] (who ultimately consume the finished products). Environmentally extended MRIO models, based on input-output tables that capture exchanges within and among regions, have been widely applied to trace environmental burdens along increasingly interconnected supply chains.[26–29] In this study, we use the 2017 multiregional input-output table from the China Emission Accounts and Datasets (CEADs) database[50] to quantify emissions embodied in China's supply chains. The MRIO table covers 31 mainland provincial-level administrative divisions (excluding Macao, Hong Kong, and Taiwan) and 42 economic sectors (Table S2). Emissions embodied in international imports for domestic consumption are not considered, as this study focuses on interprovincial trade. By combining adjoint sensitivities with emissions related to economic activities (i.e., final producer or final consumer), we trace $PM_{2.5}$-related mortality along interprovincial supply chains. Further methodological details are provided in Texts S4 and S5.

A comprehensive uncertainty analysis is conducted using 10,000 Monte Carlo simulations, incorporating uncertainties from emission inventories and concentration-response functions. The associated uncertainty ranges for CO_2 emissions and $PM_{2.5}$-related premature deaths are reported throughout the study, with full details available in Text S6.

2.3. Disparities in Carbon Emissions and Health Damage. To facilitate direct interprovincial comparison of disparity in carbon emissions and health damage from the final production perspective, we introduce two normalized indices: the Trade-related carbon emission disparity index (*TCI*) and the Trade-related health damage disparity index (*THI*), which can be expressed as follows:

$$TCI^r = \frac{EEI^r - EEE^r}{EEI^r + EEE^r} \quad (1)$$

$$THI^r = \frac{MEI^r - MEE^r}{MEI^r + MEE^r} \quad (2)$$

where EEI^r and MEI^r are emissions and mortality embodied imports for province *r*, respectively, while EEE^r and MEE^r are emissions and mortality embodied in exports for province *r*, respectively. Detailed calculations are provided in Text S7. For both indices (*TCI* and *THI*), the values range from −1 (strong net receiving regions of emissions/health burdens) to 1 (strong net outsourcing regions). Throughout this study, “export” and “import” refer to interprovincial trade unless noted, whereas “international export” refers to China’s exports to the rest of the world.

2.4. Co-Mitigation via Sectoral Energy Intensity Convergence. We define potential reductions in both CO_2 emissions and $PM_{2.5}$-related health damages achievable through supply-chain coordination of energy intensities. Energy intensity is measured as energy consumption per unit of physical output, expressed in tonnes of coal equivalent (tce). To demonstrate the potential of supply-chain coordination for co-mitigation, we quantify emission and health benefits for three sectors—nonmetal, metal, and energy generation—that not only contribute most to these impacts but also have available physical output data.[20,25] Energy intensities for these sectors are measured as tce per 100 tonnes of cement, tce per 100 tonnes of steel, and tce per 10^5 kWh of electricity, respectively (Figure S5). Physical output data are obtained from the China Statistical Yearbook 2018[51] and the China Energy Statistical Yearbook 2018[52], and energy consumption data are derived from activity data underlying the GEMS inventory.

Emission reduction through supply-chain coordination refers to the reduction embodied in a province's imports for final production, achieved when downstream provinces with lower energy intensities influence their upstream suppliers to adopt improved performance levels. This approach preserves MRIO relationships without altering inter-sectoral technical coefficients. We calculate the supply-chain coordination potential for each province serving as a downstream final production hub across all provinces in mainland China. Emission reduction ($\Delta E^{r,s}$) and health benefits ($\Delta M^{r,s}$) in imports of goods by province *s* from province *r* are calculated as:

$$\Delta E^{r,s} = \sum_{m \in \{nonmetal,metal,power\}} E_m^{r,s} \cdot \left(1 - \frac{w'_{r,m}}{w_{r,m}}\right) \qquad (3)$$

$$\Delta M^{r,s} = \sum_{m \in \{nonmetal, metal, power\}} M_m^{r,s} \cdot \left(1 - \frac{w'_{r,m}}{w_{r,m}}\right) \quad (4)$$

where $\boldsymbol{E}_m^{r,s}$ and $M_m^{r,s}$ are emissions and associated mortality that occur in province *r* for sector *m* when producing intermediate goods consumed in province *s*, respectively. $w_{r,m}$ and $w'_{r,m}$ are the original and adjusted energy intensities of sector *m* in province *r*, respectively.

We examine three coordination scenarios, with adjusted energy intensity $w'_{r,m}$ defined as:

$$w'_{r,m} = \begin{cases} w_{s,m} & , if\ w_{s,m} < w_{r,m}, 100\%\ coordination \\ \max(w_{s,m}, q_{25}) & , if\ w_{s,m} < w_{r,m}, 75\%\ coordination \\ \max(w_{s,m}, q_{50}) & , if\ w_{s,m} < w_{r,m}, 50\%\ coordination \\ w_{r,m} & , otherwise \end{cases} \quad (5)$$

where $w_{s,m}$ is the energy intensity of sector *m* in province *s*. q_{25} and q_{50} represent the 25th and 50th percentiles of the provincial energy intensity distribution for sector *m*, respectively (Figure S6). Under full coordination, upstream provinces completely adopt the downstream province's cleaner technology when downstream provinces operate more efficiently than their upstream suppliers, representing an optimal case. Under partial coordination, technology transfer is constrained either by the downstream province's performance or national benchmarks, reflecting realistic limitations in achieving complete convergence.

3. RESULTS and DISCUSSION

3.1. Sectoral Shift in CO_2 Emissions and $PM_{2.5}$-Related Premature Deaths along Supply Chains. In 2017, China emitted 10,495 Mt (95% CI: 8,279−13,121) of anthropogenic CO_2, along with 7.8 Mt (95% CI: 3.5−15.2) of primary $PM_{2.5}$, 10.8 Mt (95% CI:5.4−19.5) of SO_2, 22.4 Mt (95% CI:17.9−27.6) of NO_x, and 11.0 Mt (95% CI: 8.6−13.9) of NH_3. Notably, 91% of China's anthropogenic CO_2 emissions and a substantial share of air pollutant emissions—

ranging from 63% for $PM_{2.5}$ to 94% for NH_3—are related to economic activities along supply chains, rather than residential direct energy consumption (Figure S7). Using an adjoint-based source attribution approach, we link these supply chain-related emissions to approximately 9.9×10^5 premature deaths (95% CI: 5.9×10^5–1.6×10^6) nationwide. For the health co-benefit assessment, we exclude the 16% contribution from NH_3 emissions and 5% contribution from VOCs (Figure S8), as NH_3 primarily originates from fertilizer application and livestock management while VOCs largely come from solvent use and fugitive emissions (Figure S9).

Mapping emissions and associated health damages across 42 economic sectors reveals substantial divergences in production-side contributions to CO_2 emissions and $PM_{2.5}$-related premature deaths. Power generation accounts for over half of production-based CO_2 emissions but contributed to less than one-third of $PM_{2.5}$-related deaths (Figure 1). This imbalance is largely due to the widespread implementation of stringent emission control technologies in power plants.[53] These controls limit power generation's contribution to only 20% of embodied primary $PM_{2.5}$ emissions and 39% of secondary precursor emissions (SO_2 and NO_x) (Figure S10). In contrast, the three major heavy industries—chemical, metal, and nonmetal production—exhibit varied contribution patterns. While chemical and metal production make relatively balanced contributions to both CO_2 emissions and $PM_{2.5}$-related premature deaths (approximately 11% and 23%, respectively), nonmetal production stands out by contributing nearly a quarter of health damages despite its relatively lower CO_2 contributions. Additionally, transportation and service sectors show higher relative contributions to health damages than to CO_2 emissions.

These sectoral imbalances present challenges for production-side co-mitigation strategies.

When shifting from a production-side to a final production-side perspective, we observe that CO_2 emissions and associated health damages driven by the same final production sector often pass through different upstream production pathways. For example, while 41% of CO_2 emissions attributed to construction demand originate from power generation, 44% of the associated premature deaths are primarily caused by emissions from nonmetal production. Similarly, for equipment and services demand, power generation is the main source of CO_2 emissions, whereas the metal and services sectors are the primary contributors to health impacts. This misalignment between sectors driving carbon emissions and those causing health damages complicates efforts to achieve balanced co-benefits through production-focused interventions alone.

Despite these production-side divergences, our analysis identifies strategic coordination opportunities at the supply-chain level. Both CO_2 emissions and $PM_{2.5}$-related premature deaths embodied in supply chains are driven by common underlying final consumption categories. Over half of these CO_2 emissions and health impacts can be attributed to a single category—capital investment—especially through construction and equipment demand. This pattern indicates the central role of China's real estate industry and infrastructure projects in driving both climate change and air pollution-related health damages.[20,25,54] Together, the top three final production sectors—construction, equipment, and services—account for 94% of embodied CO_2 emissions and premature deaths driven by capital investment. Beyond capital investment, international export also plays a significant role, contributing 36% of both CO_2 emissions and premature deaths embodied in equipment demand. This alignment between CO_2 emissions and health impacts at the final production level demonstrates how consumption-driven demand patterns ultimately shape both climate change and air pollution-related health damages, offering strategic intervention points along supply chains where co-benefits can be achieved.

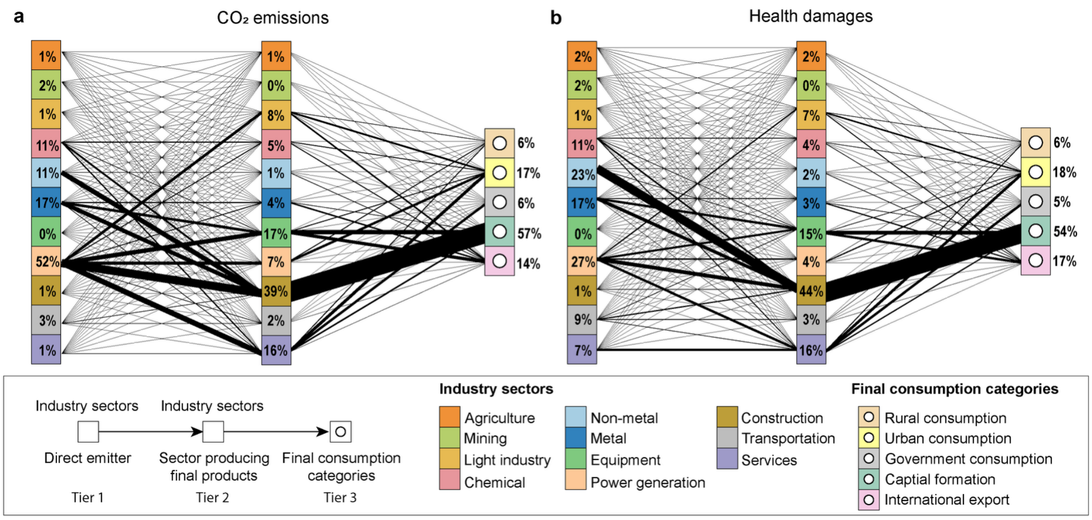

Figure 1. **Sectoral flow patterns of CO_2 emissions and health damages in 2017.** Sankey diagrams show the flows of (a) CO_2 emissions and (b) $PM_{2.5}$-related premature deaths through China's supply chains, traced from upstream production sectors (Tier 1, left), through sectors producing final goods and services (Tier 2, middle), to final demand categories (Tier 3, right). Line thickness indicates the relative magnitude of emission or premature deaths transferred between tiers. Percentages show the share of impacts attributed to each sector at each tier. "Capital formation" includes both fixed capital investment and capital inventory. For clarity, the original 44 economic sectors are aggregated into 11 broad categories (see Table S2).

3.2. Relocation of CO_2 Emissions and $PM_{2.5}$-Related Premature Deaths in Key Sectors.

Interprovincial trade between production-side regions and final production-side regions accounts for 35% of the national total CO_2 emissions (3,682 Mt, 95% CI: 2905−4603) and 20% of $PM_{2.5}$-related deaths (2.8×10^5, 95% CI: 1.6×10^5−4.9×10^5). Sector- and provincial-specific analyses reveal that these trade-embodied impacts are highly concentrated, with nearly half of both CO_2 emissions and $PM_{2.5}$-related deaths linked to just 3% of all trade flows (Figure S11), primarily involving the nonmetal, metal, and power generation sectors. Spatially, final production demand from economically advanced provinces drives distinct sectoral relocation patterns, each governed by different spatial mechanisms (Figure 2).

Proximity-driven relocation characterizes the nonmetal sector, where emission relocation is largely confined to geographically adjacent provinces due to high transport costs of bulk materials such as cement and bricks. For instance, Shanghai's demand leads to significant CO_2 emission relocation to neighboring Zhejiang, while Jiangsu's demand causes the largest health damage relocation to adjacent Anhui. Similarly, Beijing externalizes a considerable portion of nonmetal production to Hebei. This proximity-driven outsourcing has fostered industrial clusters in surrounding provinces that often enforce comparatively lenient environmental regulations relative to economic hubs like Zhejiang, Jiangsu, and Guangdong.[55] These regulatory disparities translate into lower pollution control efficiency, generating disproportionate health burdens relative to carbon footprints. Provinces such as Anhui and Hebei, which specialize in energy- and emission-intensive processes like cement clinker production, experience disproportionate health damage, with their shares of relocated $PM_{2.5}$-related mortality exceeding their shares of relocated CO_2 emissions by 60% and 73%, respectively. In contrast, Zhejiang, equipped with more advanced pollution control technologies, exhibits a 40% lower share of relocated mortality compared to its corresponding CO_2 emissions.

The metal sector displays more spatially dispersed relocation patterns while maintaining similar efficiency disparities. Zhejiang and Guangdong, as major manufacturing hubs producing final metal products, drive production in upstream regions. Together, they account for 31% of all relocated CO_2 emissions and $PM_{2.5}$-related mortality in the metal sector, with their demand influencing production across 29 of China's 30 mainland provinces. Relocated impacts concentrate in the leading iron and steel-producing provinces. These production regions exhibit significant heterogeneity in pollution control efficiency. Hebei accounts for 19% of relocated CO_2 emissions and 16% of health impacts, maintaining relatively balanced ratios. However, Henan contributes 15% of relocated mortality despite generating only 6% of relocated CO_2 emissions. This disparity reflects significant heterogeneity in pollution control technologies, particularly in the emission-intensive sintering process.[56] Weaker emission standards in Henan result in higher pollutant emissions—and consequently greater health damages—per unit of CO_2 emitted (Figure S12).

The power generation sector exhibits a resource-driven spatial pattern shaped by energy resource distribution and grid infrastructure. Final production demand spans both developed provinces (e.g., Beijing, Jiangsu, Zhejiang, and Guangdong) and industrial regions (Henan, Hebei, and Shaanxi). However, the geography of power production creates pronounced health impact disparities. Roughly 25% of CO_2 emissions (525 Mt, 95% CI: 414−656) and 33% of associated premature deaths (3.0×10^4, 95% CI: 1.7×10^4−5.3×10^4) are relocated to densely populated industrial provinces, including Hebei, Henan, Shandong, and Jiangsu. In contrast, another 25% of CO_2 emissions are externalized to energy-rich northwestern provinces—Inner Mongolia, Xinjiang, and Ningxia—but generate only 1.1×10^4 premature deaths (95% CI: 6.1×10^3−1.9×10^4). The stark contrast is primarily driven by demographic differences—the average population density in the four eastern industrial provinces exceeds that in the three northwestern provinces by a factor of 29. Our adjoint analysis confirms that the emission-weighted sensitivity of primary $PM_{2.5}$ and its precursors in Henan is 165% to 420% higher than that in Inner Mongolia and Xinjiang, respectively (Figure S13).

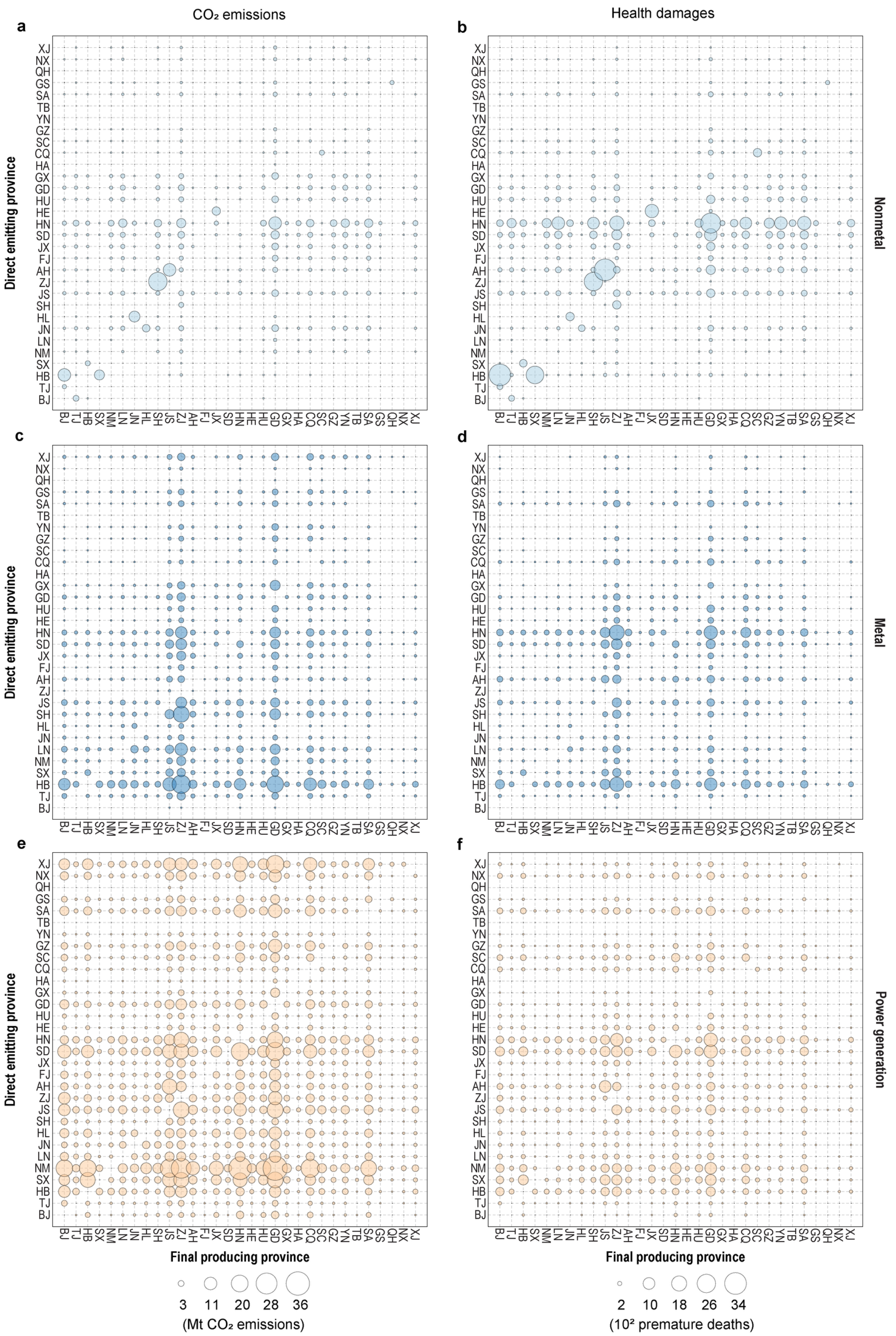

Figure 2. Relocation of CO_2 emissions and health damages driven by interprovincial trade across key industrial sectors. Bubble plots illustrate the relocation of impacts across provinces, with each panel representing a specific sector: (a−b) nonmental, (c−d) metal, and (e−f) power generation. Left panels (a, c, e) show CO_2 emissions, while right panels (b, d, f) show $PM_{2.5}$-related premature deaths. Each circle represents the impacts that occurred in the producing province (*y*-axis), induced by demand from the

final producing province (x-axis). Circle size is proportional to the magnitude of transferred impact, as indicated in the legends below. Local consumption impacts (i.e., those on the diagonal from lower left to upper right) are set as zeros and not displayed. Province abbreviations: BJ, Beijing; TJ, Tianjin; HB, Hebei; SX, Shanxi; NM, Inner Mongolia; LN, Liaoning; JL, Jilin; HL, Heilongjiang; SH, Shanghai; JS, Jiangsu; ZJ, Zhejiang; AH, Anhui; FJ, Fujian; JX, Jiangxi; SD, Shandong; HN, Henan; HE, Hubei; HU, Hunan; GD, Guangdong; GX, Guangxi; HA, Hainan; CQ, Chongqing; SC, Sichuan; GZ, Guizhou; YN, Yunnan; TB, Tibet; SA, Shaanxi; GS, Gansu; QH, Qinghai; NX, Ningxia; XJ, Xinjiang.

3.3. Divergent Polarization of CO_2 Emissions and $PM_{2.5}$-Related Premature Deaths. To systematically assess how sectoral emission relocations translate into broader provincial disparities, we developed two complementary metrics: the trade-related carbon emission disparity index (TCI) and the trade-related health damage disparity index (THI). These indices evaluate whether a province is a net importer or exporter of environmental burdens, normalized from −1 (strong exporter) to 1 (strong importer), allowing for direct cross-provincial comparison.

By plotting provinces based on their TCI and THI scores (Figure 3a), we identified six distinct zones characterizing the spatial distribution of carbon and health burden transfer. Most provinces cluster in the upper-right and lower-left quadrants (Zones 1, 2, 4, and 5), indicating a systematic pattern of burden relocation through interprovincial trade. Provinces that function as final production hubs in our sectoral analysis—Beijing, Shanghai, Zhejiang, and Guangdong—cluster in Zone 1 along the 1:1 line, reflecting high TCI and THI scores. These provinces capture high added value through final goods production while driving demand for raw materials and intermediate goods from other regions. Their supply-chain networks generate comparable relocations of both carbon emissions and health impacts, indicating aligned burden transfer patterns. Interestingly, several less-developed provinces—including Hainan, Yunnan, and Tibet—also fall within Zone 1, despite their relatively minor contributions to national totals (Figure S14). These provinces exhibit high dependence on imports due to increasing consumption and limited local production capacity.[20,25] Given their import dependence, development-oriented policies are needed to promote sustainable local production and reduce reliance on emission-intensive imports.

Zone 2 comprises provinces with decoupled carbon and health burden profiles. These provinces typically import electricity and raw materials while exporting manufactured goods,[20,25] creating asymmetric environmental burden patterns. Though their TCI scores are positive, their THI scores are comparatively lower, as local manufacturing emissions offset the health gains achieved through outsourcing. Chongqing exemplifies this trend, with a TCI of 0.6 but a THI of only 0.2, reflecting how local topography and population density intensify health impacts from its industrial activities.[57]

Burden-bearing provinces exhibit diverging patterns, rather than aligning along the 1:1 line. Zone 4 provinces—concentrated in North and Central China (Figure 3b)—form a densely populated industrial manufacturing corridor shaped by historical infrastructure development, market accessibility, and labor availability.[58] Provinces with manufacturing specialization and less stringent pollution controls—particularly Henan and Anhui—fall into this zone with THI scores around −0.5 but TCI scores near zero. This pattern indicates these provinces shoulder disproportionate health burdens relative to their net carbon emissions, consistent with the pollution control efficiency disparities previously discussed. In contrast, Zone 5 includes sparsely populated northwestern regions, showing significant carbon leakage but minimal health burden spillover, largely due to low population exposure.

Chord diagrams (Figure 3c,d) further visualize this divergence. The dominant carbon flow runs from Zone 5 to Zone 1, with approximately 530 Mt (95% CI: 418−662) of CO_2 (17% of total interprovincial flows). In terms of health impacts, the primary flow is from Zone 4 to Zone 1, transferring approximately 6.3×10^4 premature deaths (95% CI: 3.5×10^4−1.1×10^5), or 27% of trade-related mortality. This single pathway accounts for more than twice the number of deaths exported from Zone 5 to Zone 1. Although CO_2 emissions and health impacts stem from different burden-bearing zones, they converge at a common outsourcing destination—Zone 1. These patterns reveal how final production activity in economically advanced provinces creates distinct spatial footprints for carbon and health burdens, with important implications for understanding coordination opportunities across China's supply-chain networks.

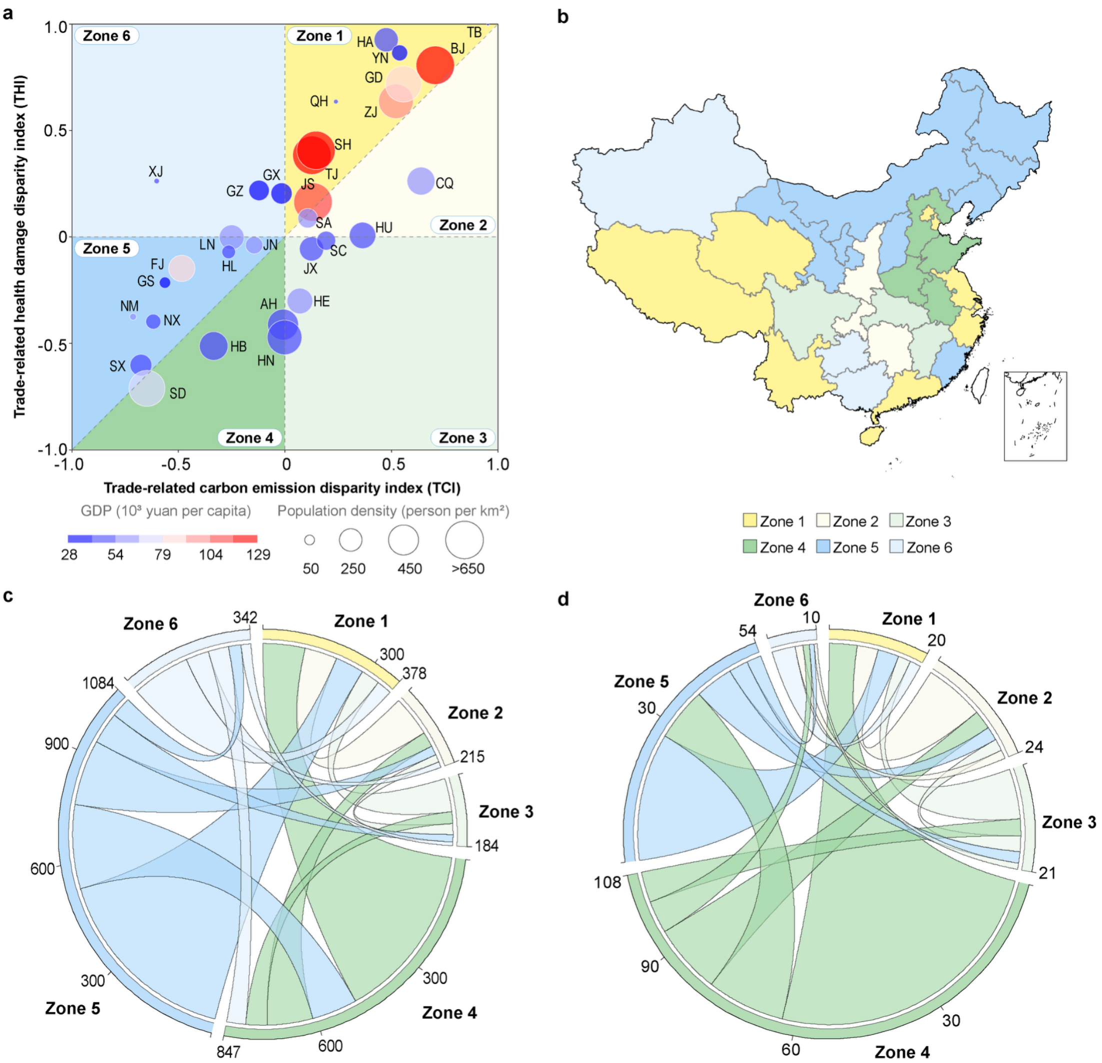

Figure 3. **Polarization patterns in CO_2 emissions and health damages in China**. (a) Province-level classification based on the trade-related carbon emission disparity index (TCI; *x*-axis) and the trade-related health damage disparity index (THI; *y*-axis). TCI and THI represent normalized differences between emissions (or health impacts) embodied in imports and exports. Circle size indicates population density; circle color indicates GDP per capita (from dark blue for less developed to dark red for more developed provinces). Province abbreviations follow Figure 2. (b) Spatial distribution of provinces by zone classifications corresponding to panel (a). (c) Chord diagram showing major interregional CO_2 emission transfers between zones. Line color represents the exporting zone, and line width indicates transferred volume (in Mt CO_2). (d) same as (c), but for $PM_{2.5}$-related premature deaths (in thousands).

3.4. Co-mitigation Opportunities through Supply-Chain Energy Intensity Coordination. Disparities in energy intensity are a key driver of the geographic and sectoral polarization of carbon emissions and associated health burdens.[59,60] Provincial energy intensities range from roughly twofold differences in power generation to more than 50-fold gaps in the metal sector (Figure S5). Power generation shows relatively smaller variation but still follows a regional divide, with provinces within the Northeast China Power Grid (Liaoning, Jilin, and Heilongjiang) exhibiting notably higher intensities. Developed coastal provinces consistently exhibit lower energy intensities compared to less-developed inland provinces. Major producers, such as Hebei for steel, Anhui for cement, and Inner Mongolia for electricity, exhibit intermediate energy intensity levels. These intensity gaps between final production hubs and their upstream supplier regions amplify trade-driven emission relocation and associated health burdens, revealing substantial potential for targeted intervention.

To quantify these opportunities, we simulate scenarios in which upstream producers adopt cleaner technologies through supply-chain coordination with the advanced provinces they serve. This reflects documented mechanisms of technology diffusion and knowledge spillovers when production regions are integrated into supply networks anchored by economically developed hubs.[61–63] We examine three convergence scenarios with varying degrees of adoption. Full convergence (100%) assumes complete alignment with downstream partners, while partial convergence (75% and 50%) imposes limits based on national benchmark performance (see Section 2.4).

Full convergence reduces trade-related CO_2 emissions from nonmetal, metal, and power generation sectors by 17% (491 Mt), and avoids 19% of the associated premature deaths (3.8 ×

10^4) (Figure 4a). Critically, partial convergence scenarios still deliver meaningful gains, with 75% convergence achieving 364 Mt CO_2 reduction and 2.8×10^4 avoided deaths, while 50% convergence yielding 213 Mt CO_2 reduction and 1.3×10^4 avoided deaths, respectively. These findings demonstrate that supply-chain coordination offers viable pathways to co-benefits, even when technology transfer faces realistic constraints.

The spatial distribution of benefits reflects the burden-shifting patterns documented in Section 3.3 and remains broadly consistent across scenarios (Figures 4b and S15). CO_2 reduction concentrates in northwestern and northeastern energy-supplying regions (Zone 5), while health benefits concentrate in densely populated central and northern provinces (Zone 4). This geographic divergence underscores how supply-chain coordination can simultaneously address carbon leakage to remote regions and health burden concentration in industrial corridors.

Sectoral priorities vary by coordination relationship, informing targeted technology transfer strategies. In Xinjiang, Ningxia, and Inner Mongolia—the major northwestern provinces supplying electricity to advanced coastal hubs—power sector improvements dominate potential co-benefits. For instance, reducing energy intensity in Inner Mongolia's power generation could yield CO_2 reduction more than three times greater than that from industrial upgrades (nonmetal and metal). Conversely, in densely populated industrial provinces such as Hebei, improvements in the nonmetal and metal sectors deliver greater combined climate-health benefits due to higher exposure levels. Across most southern provinces, industrial sector improvements contribute more to CO_2 reduction than power-sector interventions, reflecting regional differences in industrial structure and electricity sourcing.

A small number of provinces can leverage their supply-chain influence to generate disproportionate co-benefits nationwide. Zhejiang and Guangdong emerge as the two most influential final production hubs, together accounting for about 44% of total achievable co-benefits under full convergence and about one-third under partial convergence (Figure 4a). Their pathways to impact, however, show notable differences (Figure 4c,d). Zhejiang-driven coordination primarily reduces CO_2 emissions through nonmetal and metal sector improvements in proximate regions (Shanghai and Jiangsu) within the Yangtze River Delta and northern industrial provinces (e.g., Hebei and Liaoning). Guangdong, while achieving smaller reductions in these nearby regions, exerts broader geographical influence through long-distance supply chains. For example, Guangdong-driven collaboration yields substantial CO_2 reduction in Inner Mongolia and health benefits in Sichuan Basin and Ningxia, predominantly via power sector pathways. These complementary patterns suggest that effective strategies should capitalize on the different geographic and sectoral reach of these final production hubs.

Spatially explicit analysis at the grid level reveals that even within provinces, strategically targeted interventions can maximize efficiency of technology transfer investments. In Inner Mongolia, energy intensity reduction in eastern and central areas near population centers provides far greater health benefits than comparable actions in the sparsely populated western region. Similarly, in Hebei, southern industrial cities, such as Handan, Xingtai, and Shijiazhuang, emerge as high-priority intervention targets. Moreover, collaboration through different sectoral pathways produces spatially distinct benefit distribution patterns within provinces. In Shandong, for example, Guangdong-driven coordination generates greater health benefits in the southwestern region through power sector improvement, but produces larger gains in other parts of the province through industrial improvements.

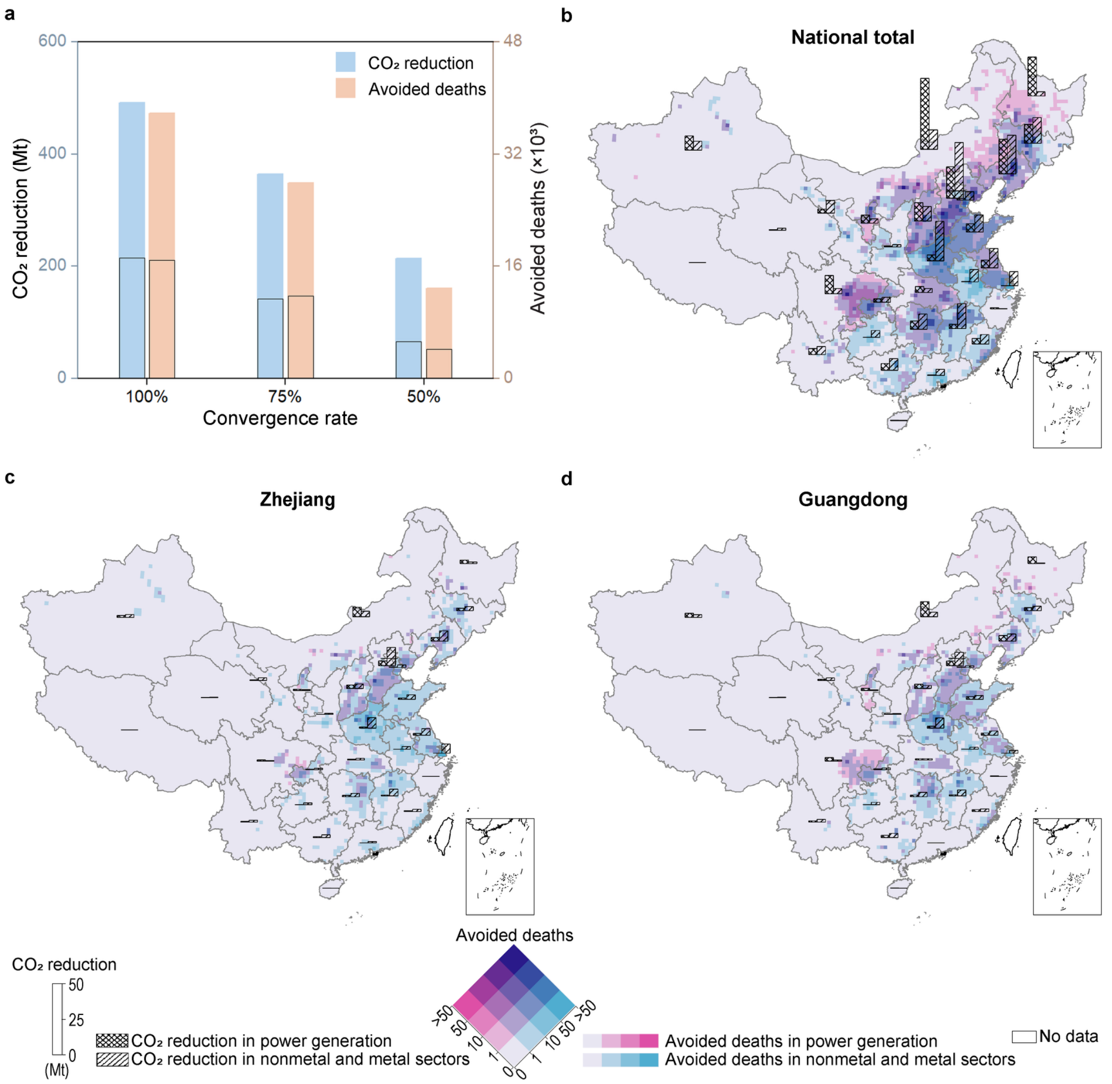

Figure 4. Co-mitigation potential from narrowing sectoral energy intensity gaps along provincial supply chains in China. (a) National total co-benefits under three convergence scenarios (100%, 75%, and 50%), in which upstream provinces are assumed to improve their sectoral energy intensity toward convergence benchmarks. Contributions from Zhejiang and Guangdong, the top two influential final production hubs, are highlighted with black boxes. (b–d) Reduction in CO_2 emissions (Mt, vertical bars) and avoided $PM_{2.5}$-related premature deaths (colored background) for supply chains driven by the national total (b) and the top two provinces—Zhejiang (c) and Guangdong (d)—under the 100% convergence scenario. Results are shown by two sectoral categories: power generation and the industrial sectors of nonmetal and metal.

3.5. Discussion and Environmental Implications. Our integrated framework reveals the pivotal role of final producers in achieving climate-health co-mitigation. While production-side emissions are spatially and sectorally dispersed, the final production demand driving these impacts is highly concentrated. This convergence pattern, obscured in previously separated analyses,[20,25,26] establishes final producers as critical coordination nodes. Furthermore, our high-resolution adjoint modeling shows that health impacts of these relationships vary substantially by location, depending on population exposure and regulation stringency. Hence, sourcing decisions directly determine both emission volumes and associated health impacts. This leverage can be exercised through strategic supplier selection and improvement initiatives, for which precedents already exist.

Evidence of final producers' coordination capacity spans multiple governance contexts. Apple's Supplier Clean Energy Program requires manufacturing partners to procure 100% renewable electricity and facilitate joint clean energy investments through mechanisms like the China Clean Energy Fund.[64] Under the Clean Development Mechanism, multinational companies have promoted energy efficiency among upstream partners in emerging economies by offering financial and technological support in exchange for carbon reduction credits.[65] Final producers have also coordinated technology diffusion by establishing common standards. Zhejiang's ISO 50001 supplier certification program exemplifies how final producers can standardize efficiency practices across upstream partners, achieving an estimated 26% reduction in energy intensity.[66] Cross-firm R&D consortia enable collaborative development of technologies such as hydrogen-based direct reduction for iron ore processing, projected to reduce energy intensity by about 40% at marginal abatement costs below near-term carbon price forecasts.[67] At the regional level, the Beijing-Tianjin-Hebei coordination framework illustrates how final production hubs can drive upstream industrial transformation.[68] Beijing and Tianjin coordinate emission reduction in Hebei through technical assistance and ecological compensation programs, facilitating large-scale phaseout of outdated crude steel capacity.[69–71] These examples demonstrate coordination feasibility across corporate, sectoral, and regional scales. Achieving the 17% emission and 19% mortality reduction identified in our full convergence scenario would require systematically scaling such approaches, though our partial convergence scenarios may represent more realistic near-term targets given institutional constraints.

Scaling coordination mechanisms requires institutional frameworks aligned with existing governance structures. China's national carbon market, covering power and industrial sectors since 2021, provides such a platform.[72] Incorporating supply-chain emission credits would require mechanisms for allocating reductions between final producers and suppliers alongside verification protocols for upstream improvements. While detailed policy design remains for future development, the concentration of impacts offers practical entry points. With 3% of trade flows, primarily in the nonmetal, metal, and power sectors, accounting for 50% of emission burdens, targeted pilot programs could deliver substantial co-benefits before broader expansion.

Significant barriers remain despite these opportunities. Provincial governments often prioritize local GDP growth over cross-regional environmental objectives, while fragmented authority between environmental and economic agencies hampers coordination.[73] The absence of standardized mechanisms for cross-provincial technology transfer and benefit-sharing raises transaction costs, discouraging voluntary coordination.[74,75] These institutional constraints, combined with resource availability limitations, form key barriers to realizing identified co-benefits. Moreover, infrastructure lock-in embedded in existing energy and technological systems further constrains the pace and scope of energy intensity improvements.[76] Our estimates, therefore, represent achievable benefits under reformed governance and gradual infrastructure adjustment, rather than outcomes expected under current institutional and technological arrangements.

Several limitations affect interpretation. First, the use of 2017 MRIO data does not capture recent supply chain restructuring under China's dual circulation strategy, likely underestimating current trade-embodied impacts. Second, VOC-related health impacts are not fully quantified. This study adopts a combustion-based energy intensity framework. Electrification-related mitigation strategies, which offer more comprehensive co-mitigation prospects by simultaneously reducing CO_2 and VOC emissions, require fundamental restructuring of Input-Output relationships for accurate representation. Additionally, CMAQ v5.0 lacks several critical secondary organic aerosol formation pathways for VOCs, potentially underestimating their contribution to $PM_{2.5}$-related health impacts.[77] Third, our convergence scenarios assume static MRIO relationships, not accounting for how energy intensity improvements could reshape supply chain structures through price and substitution effects, alongside simplified treatment of technological and institutional path dependencies. Essential research directions include dynamic modeling of final producer responses to carbon pricing to clarify policy effectiveness under different market conditions, sectoral analysis of coordination capacity variations to identify where final producer leverage is strongest, integration of electrification pathways into supply-chain co-mitigation frameworks, and assessment of how spatial redistribution of final production activities affects co-benefit distribution as China's industrial transformation continues. Extending this framework internationally could guide supply chain governance as climate policies expand globally, particularly for countries with pronounced production-consumption separations.[18,78]

ASSOCIATED CONTENT

Data Availability Statement

Meteorological fields were generated using WRF v3.8.1 with grid nudging, driven by Global Forecast System (GFS) surface data from the National Centers for Environmental Prediction (NCEP), available at https://www.nco.ncep.noaa.gov/pmb/products/gfs/#GFS. The CMAQ Adjoint v5.0 model code can be accessed from the U.S. EPA GitHub repository (https://github.com/USEPA/CMAQ_ADJOINT) and its Zenodo archive (https://zenodo.org/records/3780216). The 2017 AiMa emission dataset used in this study can be accessed at https://doi.org/10.5281/zenodo.17199169. The Global Emission Modeling System (GEMS) inventory can be accessed at https://gems.sustech.edu.cn/home. The 2017 Chinese Multi-regional Input-Output table is available from the CEADs database (https://www.ceads.net/data/input_output_tables/). Source attribution analysis was performed using MATLAB R2021a.

Supporting Information. Supplementary figures 1−15; supplementary tables 1−4; Supplementary texts 1−7, including methodological framework, emissions and health impacts embodied in the supply chains, GEMS inventory source information, MRIO sector classification, fitted parameters for IER model, model evaluation, health impact attribution analysis, mapping of GEMS emissions to the MRIO table, and uncertainty analysis.

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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AUTHOR CONTRIBUTIONS

Y.C. conceived and supervised the study. J.D. and Y.C. processed and analyzed the data. H.S., J.M.M., and S.T. contributed to the development of the model framework. D.J. and Y.C. drafted the manuscript. H.S., G.S., and S.T. participated in the result discussions. J.M., J.M.M., A.G.R., S.Z., and A.H. provided critical revisions.

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