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Who pays for whom? A bilateral carbon compensation mechanism for China's provinces

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Abstract

This study examines how responsibility attribution, regional capability and carbon valuation shape bilateral carbon compensation among Chinese provinces. Guided by the principle of Common but Differentiated Responsibilities and Respective Capabilities (CBDR-RC), the framework combines production-, consumption- and income-based accounting within a common domestic emissions boundary. The production-based share is retained locally, while consumption and income attribution determine bilateral responsibility transfers. A multidimensional Respective Capability (RC) index adjusts monetary payments according to the capabilities of both compensation parties. Using data for 30 provinces across five benchmark years from 2012 to 2020, aggregate positive responsibility transfers increase from 487.14 to 1,095.81 Mt CO_2. In 2020, 67.59% of province pairs retain their transfer direction across the full CBA–IBA weighting range. Relative to no capability adjustment, the RC specification reduces the payment share of below-median RC provinces from 39.77% to 35.60% and increases their receipt share from 34.35% to 37.64%. Relative to national-average MAC pricing, recipient-specific marginal abatement costs reverse the net compensation roles of six provinces in 2020. Joint variation in responsibility weights, capability adjustment and MAC pricing identifies four stable net payers, nine stable net recipients and seventeen provinces with switchable roles in 2020. These findings show how the implementation of CBDR-RC links responsibility allocation to the distribution and stability of inter-provincial compensation.

1. Introduction

China's commitment to peak carbon emissions before 2030 and achieve carbon neutrality before 2060 requires coordinated emission reduction efforts across provinces with highly heterogeneous economic structures, industrial functions, and mitigation capacities. As the world's largest developing country, China's growing energy demand has placed its carbon emissions among the highest globally, making the coordination of regional mitigation responsibilities a central issue in national climate governance (Guo and Feng, 2021). Meanwhile, the rapid development of logistics and inter-provincial trade has spatially decoupled production from consumption, causing carbon embodied in products to be transferred across provincial borders (Duan et al., 2018; Tian et al., 2025). Carbon emissions physically generated in one province may therefore be driven by final demand or value-chain benefits in another province. This spatial separation creates a fundamental challenge for provincial carbon governance: territorial emissions alone cannot fully identify the provinces that benefit from, induce, or bear the environmental costs of carbon-intensive production.

This challenge is particularly important in China because regional development remains highly uneven. China's provinces differ markedly in development stages, historical emissions, industrial structures, and capacities for climate action (Kanbur and Zhang, 2005). Economically advanced coastal provinces often have large final demand, stronger service sectors, and greater technological and fiscal capacity, while many central, western, and northeastern provinces undertake energy supply, raw material production, and energy-intensive manufacturing activities. For instance, wealthier consumption-oriented regions such as

Beijing and Shanghai may outsource part of their embodied emissions to inland resource-rich regions, thereby intensifying regional inequalities in environmental burdens (Yang et al., 2024). Some provinces possess more advanced technological and financial resources, while others still face stronger development constraints and weaker response capacities (Kanbur and Venables, 2007). As a result, the environmental burden associated with domestic production networks may be concentrated in production-oriented provinces, whereas part of the economic benefits and consumption welfare is captured elsewhere.

If carbon responsibility is allocated solely according to production-based accounting, production bases may bear excessive responsibility for emissions generated to satisfy external demand. Conversely, if responsibility is assigned only according to consumption-based accounting, the role of producing regions in technology choice, production organization, and local mitigation may be understated. Consequently, there is a need for a quantitative framework that allocates carbon responsibility more fairly while recognizing the heterogeneous efforts and capacities of different regions (Qin et al., 2020). A more sophisticated mechanism should not only account for the physical flow of emissions, but also reflect significant disparities in provincial capability. Capability assessment can incorporate social development, technological conditions and government response alongside economic resources (Nardo et al., 2008).

The principle of Common but Differentiated Responsibilities and Respective Capabilities (CBDR-RC) provides a useful normative basis for addressing this issue. Although CBDR-RC was originally developed in the context of international climate governance, its underlying logic is also relevant within a large country characterized by substantial regional disparities. In the provincial context, “differentiated responsibilities” require identifying how carbon responsibility is redistributed through inter-provincial trade, while “respective capabilities” require recognizing that provinces differ in their ability to bear compensation obligations.

Existing research has established bilateral carbon compensation schemes linking interregional emission transfers with responsibility allocation, carbon shadow prices and economic conditions (Han et al., 2024; Chen and Meng, 2024). Building on this work, the present study asks whether consumption and income attribution imply the same bilateral responsibility relationships, how the capabilities of both compensation parties change the distribution of payments, and which provincial net compensation roles remain stable when responsibility weights and carbon valuation vary. These questions connect the responsibility and capability components of CBDR-RC to observable differences in compensation outcomes.

To examine these questions, this study develops a bilateral inter-provincial carbon compensation mechanism for China based on a multi-regional input-output model. The framework first constructs a domestic-boundary provincial carbon flow matrix to trace emissions generated in one province to satisfy domestic final demand in another province. It then integrates PBA, CBA, and IBA to construct a bilateral net responsibility transfer matrix, denoted as TSR. In this framework, PBA is treated as locally retained responsibility, while CBA and IBA are used to identify transferable responsibility associated with domestic final demand and value-chain income benefits. The TSR matrix therefore determines the bilateral direction and physical magnitude of responsibility transfers.

Guided by the CBDR-RC principle, the framework assigns distinct functions to responsibility and capability. The bilateral net responsibility transfer matrix represents differentiated responsibility arising from domestic final demand and value-chain income. The RC index summarizes non-emission indicators of economic conditions, social development, technological innovation, and government response. It enters a bounded monetary adjustment based on the relative capabilities of the payer and recipient. By linking responsibility transfers with capability-based monetary adjustment, the proposed mechanism functions as a horizontal compensation framework that can promote synergistic regional emission reductions and more balanced development (Yu et al., 2024).

This study makes three contributions to the design of bilateral carbon compensation under CBDR-RC. First, it combines consumption- and income-based attribution within a consistent domestic emissions boundary while retaining the production-based responsibility share locally. Decomposing bilateral transfers reveals where the two forms of attribution reinforce or offset each other and identifies the responsibility weights at which payment directions change. Second, it represents respective capabilities through a multidimensional RC index and a bounded adjustment based on both compensation parties. Comparisons with no capability adjustment and a GDP-per-capita benchmark identify how this specification redistributes payments and receipts. Third, using five benchmark years for 30 Chinese provinces, it identifies stable and rule-dependent net compensation roles under joint variation in responsibility weights, capability adjustment and MAC pricing. The resulting switching thresholds connect aggregate sensitivity to the conditions under which individual provinces change compensation roles.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 presents the methodology for carbon responsibility accounting, TSR construction, RC index estimation, capability adjustment, and carbon pricing scenarios. Section 4 describes the data sources and processing procedures. Section 5 reports the empirical results. Section 6 concludes the paper and discusses policy implications.

2. Literature review

2.1. Carbon Responsibility Accounting under Alternative Principles

PBA allocates emissions to the territory where production activities and physical emissions occur. Owing to its clear territorial boundary and relatively straightforward data requirements, PBA has been widely used in official emission inventories and regional mitigation assessments (Davis et al., 2011). However, the PBA framework may assign disproportionate responsibility to production-oriented regions when emissions are generated to satisfy external demand. Such responsibility mismatches are relevant to discussions of carbon leakage (Grasso and Roberts, 2014), particularly when differences in mitigation policy stringency encourage emission-intensive production to relocate to regions with weaker constraints.

In response to this limitation, Munksgaard and Pedersen (2001) introduced the “consumer responsibility” principle, which posits that a region should be accountable for all emissions induced by its final

consumption. A study by Mi et al. (2021) that estimated China's CO_2 emission inventories from 2002 to 2018 found that while China's CO_2 emissions, after a rapid increase from 2002, began to plateau after 2012, the absolute production-based emissions remained much higher than consumption-based emissions. This indicates that China is a net exporter of embodied carbon. At the subnational level, similar producer–consumer discrepancies arise among Chinese provinces, where developed consumption-oriented regions may outsource embodied emissions to energy- and resource-intensive production bases (Yan et al., 2022).

CBA makes the emissions associated with final consumption explicit and provides an accounting basis for demand-side mitigation policies. Nevertheless, the consumer responsibility principle has notable limitations. Liu (2015) contends that consumption-based accounting only indirectly influences emissions at the site of production and lacks direct constraints on manufacturing in regions with high carbon intensity. It also overlooks the "insourcing" of polluting industries by producing regions, suggesting that the ultimate responsibility for emissions reduction lies with the producers.

Given the limitations of assigning all responsibility exclusively to either producers or consumers, a growing body of research has explored shared or benefit-based responsibility accounting. These approaches attempt to distribute responsibility among multiple agents involved in production, consumption, and value creation (Lenzen et al., 2007; Cadarso et al., 2012). Shared-responsibility accounting has also been applied to energy-related mercury emissions across Chinese provinces (Guo et al., 2020). By linking emission responsibility to production, consumption, and economic benefits, these approaches provide an accounting basis for more equitable burden sharing and for designing policies to address carbon leakage. The method of allocating responsibility for pollutant emissions between countries, taking international trade flows as a reference, was first proposed by Ferng (2003). This study calculates the emissions for Taiwan in 1996 based on the consumer-benefit and producer-benefit principles, and subsequently proposes a criterion of shared responsibility that includes 50% of the two. Csutora and Vetőné Mózner (2014) decompose embodied emissions in trade and allocate emission responsibility according to the attribution of economic benefits generated during production and consumption, assigning value-added to the producer and material throughputs to the consumer. However, this division is debatable, as consumers also benefit from value-added, while producers also benefit from material throughputs, as they form the basis of their production activities. Jakob et al. (2021) allocate emission responsibility based on the proportion of benefits that producers and consumers respectively derive from emissions. Using multi-regional input-output data, they apply this method to multinational bilateral trade relationships and, on this basis, propose the "Economic Benefit Shared Responsibility" (EBSR) scheme. However, its strong dependence on external elasticity parameters and its reliance on a constructed, virtual counterfactual scenario limit its direct application in data-scarce countries and may affect the robustness of the results. More recent work extends shared responsibility to producers, consumers and investors by incorporating cross-border investment and sequential production decisions in global value chains (X. Li et al., 2026). Income-based accounting provides a complementary perspective by attributing emissions to the primary-factor suppliers whose participation in production generates income, including wages, profits and rents (Marques et al., 2012). This perspective

distinguishes income beneficiaries from final consumers and provides a basis for examining whether these two forms of attribution imply different interregional responsibility relationships.

2.2. Carbon compensation and inter-provincial equitable development

Existing studies have developed explicit bilateral compensation schemes for emissions embodied in interregional trade. Han et al. (2024) estimate inter-provincial carbon compensation using net carbon transfers and carbon shadow prices, with adjustment terms based on per capita GDP and the Engel coefficient. Chen and Meng (2024) develop a value-added-based responsibility allocation scheme for Chinese cities and derive bilateral compensation obligations from the difference between actual emissions and allocated responsibility. Their monetary calculations use the carbon shadow prices of compensation recipients. These studies provide direct foundations for identifying payer–recipient relationships and valuing compensation obligations.

The present study builds on these foundations by distinguishing consumption-based attribution from income-based attribution within a common domestic emissions boundary. Whereas Chen and Meng (2024) use value-added information to determine the producer–consumer responsibility split, this study represents income beneficiaries through a separate attribution matrix and combines it with consumption-based responsibility flows. It also specifies a bounded monetary adjustment based on the relative capabilities of both the payer and the recipient. This formulation provides a basis for examining how responsibility weights, capability adjustment and carbon valuation shape bilateral payments and provincial net compensation positions.

2.3. Respective Capability Assessment under the CBDR-RC Framework

When implementing inter-regional carbon compensation, it is necessary to distinguish responsibility allocation from capability adjustment. Responsibility determines the direction and magnitude of physical transfers, while capability affects whether and to what extent monetary obligations should be adjusted. The principle of CBDR-RC was formally established in the United Nations Framework Convention on Climate Change (UNFCCC), adopted in 1992. In the relevant literature, scholars have assessed and applied various aspects of the CBDR-RC principle. Ari and Sari (2017) developed an index for the CBDR-RC principle that included economic, social, emissions, and technological indicators estimated via Principal Component Analysis. Winkler and Rajamani (2014) explored the possibility of applying CBDR-RC, suggesting that if it were applied to all regions, it would need to involve both responsibility and capability, consider differentiation among regions, and require the construction of a differentiated model for responsibility and capability. Codal et al. (2021) selected financial, emissions, policy and legislative, and non-governmental organization perspectives as their CBDR-RC indicators. Using an equal weighting method, they conducted an empirical analysis on the G20 economies (G20).

The literature provides a basis for tracing embodied emissions, allocating shared responsibility and valuing interregional compensation. The present study connects these elements through an explicit

separation of physical responsibility and monetary capability adjustment. Its empirical focus is how consumption and income attribution interact, how multidimensional capability changes the distribution of financial obligations, and how these choices jointly affect provincial net compensation roles. This focus links the CBDR-RC framework to testable differences across alternative compensation specifications. At the international level, Hahn et al. (2024) quantify additional mitigation obligations arising from historical and prospective emissions and examine countries' economic capacity to meet them.

3. Methods

3.1. Design Framework for the Bilateral Carbon Compensation Mechanism

Guided by CBDR-RC, this study develops a bilateral carbon compensation framework linking responsibility attribution, provincial capability and carbon valuation (Fig. 1). The framework begins with a domestic multi-regional input–output model that traces the relationships between the locations of emissions and the provinces to which responsibility is attributed through final demand and value-chain income. Production-, consumption- and income-based accounting are combined within a consistent emissions boundary. The production-based responsibility share is retained locally, while consumption- and income-based attribution determine transferable responsibility. Taking the difference between opposing responsibility flows yields the bilateral net responsibility transfer matrix (TSR), which identifies the direction and physical magnitude of each compensation obligation.

The second module represents provincial capability through a multidimensional Respective Capability (RC) index. Non-emission indicators covering economic conditions, social development, technological innovation and government response are aggregated using principal component analysis. The resulting scores are normalized within each year and incorporated into a bounded monetary adjustment based on the relative capabilities of the payer and recipient. This adjustment increases payments from higher-capability to lower-capability provinces and reduces payments in the opposite capability relationship. Its strength determines how capability differences influence the monetary allocation.

The third module assigns monetary values to responsibility transfers under four pricing scenarios. A uniform carbon allowance price provides the market-price baseline. Provincial marginal abatement costs (MACs), estimated using CQR-NDDF, support both recipient-specific and national-average MAC pricing, while the social cost of carbon (SCC) provides a welfare-based reference. These scenarios connect responsibility transfers to market-based, mitigation-cost and climate-damage valuations.

Finally, responsibility transfers, capability adjustment and carbon prices are combined to construct bilateral payment matrices. Provincial receipts and payments are then aggregated to determine net compensation positions. Separate comparisons examine how capability specifications and MAC pricing rules affect the distribution of compensation. Joint variation in responsibility weights, capability-adjustment strength and MAC pricing rules identifies stable and switchable provincial net roles over the

continuous parameter domain. Capability adjustment can alter provincial net roles by changing the balance of incoming and outgoing payments while preserving individual bilateral payment directions.

3.2. Accounting for the Provincial Carbon Emission Flow Matrix

Following Leontief's input–output framework (Leontief, 1974), this study constructs a domestic MRIO system covering *R* = 30 provinces and *S* = 29 sectors, comprising *N* = *R*×*S* = 870 province–sector cells. Let z_{ij} denote intermediate deliveries from cell *i* to cell *j*, and let x_i and e_i denote gross output and direct CO_2 emissions, respectively. The technical coefficient matrix is $A = \left[z_{ij}/x_j\right]$, and the Leontief inverse is $L = (I - A)^{-1}$, where *I* is the identity matrix. Direct emission intensity is defined as $f_i = \frac{e_i}{x_i}$, with $\hat{f} = diag\,(f_1, \ldots, f_N)$.

Let $Y^{dom} \in \mathbb{R}^{N \times R}$ represent domestic final demand, with each column corresponding to the final demand of one province. The consumption-based carbon responsibility flow matrix at the province–sector level is:

$$Q^C = \hat{f} \cdot L \cdot Y^{dom}$$

1

Each element Q^C_{iq} measures the CO_2 emissions generated in province–sector cell *i* to satisfy the domestic final demand of province *q*. Aggregating the emitting sectors within each province gives the provincial carbon flow matrix:

$$E^C_{pq} = \sum_{i \in S_p} Q^C_{iq}$$

2

where S_p is the set of sectoral indices belonging to province *p*. In E^C, rows indicate the provinces where emissions occur, while columns indicate the provinces whose final demand induces those emissions. Diagonal elements capture emissions associated with final demand within the same province. Row sums measure domestic-demand-induced emissions occurring in each province, whereas column sums measure provincial consumption-based responsibility.

The compensation analysis uses emissions attributable to domestic final demand. International exports and the statistical discrepancy are excluded from the final-demand matrix used for compensation. Detailed matrix definitions and the accounting balance are provided in Supplementary Method S3.1–S3.2.

3.3. Calculating PBA, CBA, IBA and Bilateral Net Responsibility Transfers

Within the domestic accounting boundary, production-based responsibility is measured by the row sum of the carbon flow matrix, $PBA_p^{dom} = \sum_q E_{pq}^C$, while consumption-based responsibility is measured by its column sum, $CBA_q^{dom} = \sum_p E_{pq}^C$. These accounts distinguish the locations where emissions occur from the provinces whose final demand induces them. Income-based accounting provides a complementary perspective by attributing emissions to the provinces receiving income through production linkages (Marques et al., 2012).

Let $B = \left[z_{ij}/x_i\right]$ denote the supply-side distribution coefficient matrix and $G = (I - B)^{-1}$ the Ghosh inverse. Let va_j denote the gross value added of province–sector cell *j*, with $\widehat{VA} = \mathrm{diag}(va_1, \ldots, va_N)$. The raw income-based responsibility matrix is:

$$H^I = \hat{f}\, G^{\mathrm{T}} \widehat{VA}$$

3

Here, *G* represents the forward production linkages used for income attribution. Each element H_{ij}^I allocates emissions occurring in cell *i* to income beneficiary *j*.

To align income attribution with the domestic emissions covered by consumption-based accounting, let $\bar{e}_i^{dom} = \sum_{q=1}^{R} Q_{iq}^C$ denote the emissions generated in cell *i* to satisfy domestic final demand. The income-based allocations are rescaled within each emitting cell:

$$E_{ij}^I = H_{ij}^I \cdot \frac{\bar{e}_i^{dom}}{\sum_{j=1}^{N} H_{ij}^I}, \quad \text{if } \sum_{j=1}^{N} H_{ij}^I > 0$$

4

This adjustment preserves the relative allocation across income beneficiaries while aligning the emissions attributed under CBA and IBA at the emitting-cell level. Aggregation across the sectors of the emitting and income-receiving provinces gives:

$$E_{pq}^I = \sum_{i \in S_p} \sum_{j \in S_q} E_{ij}^I$$

5

Both E^C and the provincial E^I matrix therefore use emitting provinces as rows and responsibility-attributed provinces as columns. Provincial income-based responsibility is the column sum, $IBA_q^{dom} = \sum_p E_{pq}^I$.

The production-based responsibility share, $\alpha = 1/3$, is retained locally. The remaining share is allocated between consumption- and income-based responsibility, with $\theta \in [0, 1]$ denoting the CBA share of transferable responsibility. The bilateral net responsibility transfer is:

$$TSR_{pq}^{(\theta)} = (1-\alpha)\left[\theta\left(E_{pq}^{C} - E_{qp}^{C}\right) + (1-\theta)\left(E_{pq}^{I} - E_{qp}^{I}\right)\right]$$

6

The benchmark $\theta = 0.5$ assigns equal one-third shares to PBA, CBA and IBA. At $\theta = 1$, transferable responsibility is determined entirely by CBA; at $\theta = 0$, it is determined entirely by IBA.

A positive $TSR_{pq}^{(\theta)}$ assigns a compensation obligation from province *q* to province *p*, while a negative value indicates the reverse direction. The matrix is antisymmetric and has zero diagonal elements. Its positive component, $TSR_{pq}^{+} = \max(TSR_{pq}^{(\theta)}, 0)$, identifies the responsibility quantities to be valued as payments. An additional specification determines provincial consumption and income weights from domestic final demand and gross value added. The accounting identities, transfer derivation and alternative weighting specification are provided in Supplementary Method S3.3–S3.5.

3.4. Indicator Selection and Construction of the RC Index under the CBDR-RC Framework

The Respective Capability (RC) index represents provincial differences in the resources and conditions available to support climate action and compensation obligations. Building on multidimensional assessments under CBDR-RC (Ari and Sari, 2017), the index comprises 14 non-emission indicators covering economic conditions, social development, technological innovation and government response. Table 1 reports the indicators, their definitions, data sources, units and contribution directions.

The economic dimension captures provincial income levels, industrial structure and public-service resources. The social dimension reflects employment conditions, minimum income protection, education and healthcare provision, which characterize development conditions relevant to regional capability (Sen, 1999). The technological dimension captures accumulated knowledge, innovation commercialization and R&D investment, reflecting the technological resources available for low-carbon development (Blanford, 2009). The government-response dimension represents fiscal commitment, urban environmental infrastructure, pollution-control investment and environmental policy attention. Together, these dimensions provide a broader representation of provincial capability than income alone.

Table 1
RC Composite Index: Indicator Selection and Sources

Perspective	Objective	Indicator	Source and Explanation	Unit	Contribution Direction
economic perspective	Measure the ability of different regions to cope with climate change	GDP per capita	Data from China Statistical Yearbook	CNY/capita	
		Share of the Tertiary Industry's Value-Added in GDP	Data from Provincial Statistical Yearbooks	%	
		General public service expenditure per capita	Data from China Statistical Yearbook	CNY/capita	
social perspective	Measure differences in social development levels among regions	Urban Unemployment Rate	Data from China Statistical Yearbook	%	
		Minimum Wage Standard	The lowest tier of the monthly minimum wage standard is used.	CNY	
			Data from the Bureau of Human Resources and Social Security		
		Per Capita Years of Education	Data from Provincial Statistical Yearbooks	Years/ capita	
		Number of Hospital Beds per 1,000 people	Data from China Statistical Yearbook	Beds / 1,000 people	
technological perspective	Measure regional technological innovation and green-transition capability	Number of valid invention patents	Data from Provincial Statistical Yearbooks	Number	
		Share of new product sales revenue	Share of new product sales revenue in	%	

Perspective	Objective	Indicator	Source and Explanation	Unit	Contribution Direction
			operating revenue of industrial enterprises above designated size. Data from China Statistical Yearbook		
		R&D expenditure intensity	Data from China Statistical Yearbook	%	
government response perspective	Assessing the intensity of environmental governance efforts by different local governments	Ratio of Environmental Protection Expenditure to Public Fiscal Expenditure	Data from Provincial Statistical Yearbooks	%	
		Urban Greening Coverage Rate	The data is sourced from the China Urban Construction Statistical Yearbook	%	
		Intensity of Environmental Regulation	Investment in Industrial Pollution Control / Industrial Value Added. Data from China Statistical Yearbook	—	
		Environmental Protection Word Frequency	The number of occurrences of environmental protection terms in a provincial government work report, divided by the total word	Times / Number	

Perspective	Objective	Indicator	Source and Explanation	Unit	Contribution Direction
			count of the text. Following the methodology of Malaquias et al. (2019), We identify 125 green and environmental protection keywords from the government work reports. The metric is calculated as the total frequency of these keywords in a report, normalized by the total word count of the report.		

Principal component analysis (PCA) is used to summarize the variation shared across the indicators (Pearson, 1901). Indicators are first oriented so that higher values represent greater capability and then standardized using the pooled sample of 150 observations covering 30 provinces across the five benchmark years. The smallest number of principal components explaining at least 80% of total variance is retained. This procedure retains six components, accounting for 81.21% of the variance. Their scores are combined using weights proportional to their eigenvalues and normalized across the retained components. The resulting composite score is subsequently rescaled to [1, 10] within each year for use in the bilateral capability adjustment described in Section 3.5. The orientation, standardization and PCA calculations are detailed in Supplementary Method S4.

3.5. Constructing the Bilateral Carbon Compensation Mechanism

The bilateral compensation mechanism combines responsibility transfers, relative provincial capabilities and carbon valuation. The TSR matrix identifies the direction and physical magnitude of each bilateral obligation, while the capability adjustment and carbon price determine its monetary value.

The PCA composite capability score obtained in Section 3.4 is first rescaled to [1, 10] within each year:

$$RC_{i,t} = 1 + 9 \times \frac{CI_{i,t} - CI_{\min,t}}{CI_{\max,t} - CI_{\min,t}}$$

7

where $CI_{\min,t}$ and $CI_{\max,t}$ are the minimum and maximum composite scores across the 30 provinces in year *t*. This transformation provides a positive measure of relative provincial capability for each benchmark year.

For a payment from province *j* to province *i*, the capability adjustment factor is:

$$\Omega_{j \to i,t}(\lambda) = 1 + \lambda \left(\frac{RC_{j,t} - RC_{i,t}}{RC_{j,t} + RC_{i,t}} \right), \; 0 \leqslant \lambda \leqslant 1$$

8

Here, $RC_{j,t}$ represents the payer's capability and $RC_{i,t}$ the recipient's capability. The parameter λ controls the adjustment strength, with $\lambda = 0$ switching off capability adjustment and $\lambda = 0.5$ used in the benchmark specification. Payments increase when the payer has greater capability than the recipient and decrease when the payer has lower capability. The factor remains positive throughout the specified parameter range, so capability adjustment changes bilateral payment amounts while preserving their directions.

For a given responsibility weight θ, let $TSR_{ij,t}$ denote the bilateral responsibility balance defined in Eq. (6). The signed compensation position of province *i* relative to province *j*, under pricing scenario *k*, is:

$$CP_{ij,t}^{(k)} = \begin{cases} TSR_{ij,t} \cdot P_{ij,t}^{(k)} \cdot \Omega_{j \to i,t}(\lambda), & \text{if } TSR_{ij,t} > 0, \\ TSR_{ij,t} \cdot P_{ij,t}^{(k)} \cdot \Omega_{i \to j,t}(\lambda), & \text{if } TSR_{ij,t} < 0, \\ 0, & \text{if } TSR_{ij,t} = 0. \end{cases}$$

9

A positive $CP_{ij,t}^{(k)}$ denotes compensation received by province *i* from province *j*, whereas a negative value denotes compensation paid by province *i* to province *j*. The capability factor follows the actual payment direction. The price $P_{ij,t}^{(k)}$ is uniform across provinces under a uniform-pricing scenario and is determined by the actual recipient under recipient-specific MAC pricing.

Provincial net compensation is obtained by summing the signed bilateral positions:

$$CP_{i,t}{}^{(k)} = \sum_{j=1, j \neq i}^{30} CP_{ij,t}{}^{(k)}$$

Positive values identify net recipients and negative values identify net payers. This net position reflects the balance between all incoming and outgoing payments. Consequently, capability adjustment can change a province's net compensation role even though each bilateral payment retains its responsibility-based direction. The calculation of gross receipts, gross payments and their national shares is detailed in Supplementary Method S2.

The market-price baseline applies a uniform allowance price of 42.85 CNY/tCO_2 in all five benchmark years. This price is calculated by dividing the total transaction value by the total transaction volume of China's national carbon market in 2021 (Shanghai Environment and Energy Exchange, 2021). Holding this price fixed provides a common valuation basis for examining changes in responsibility transfers and relative capabilities across years. Alternative valuations based on recipient-specific MACs, the national-average MAC and the social cost of carbon are described in Section 3.6.

3.6. Estimating Provincial Marginal Abatement Costs and Defining Carbon-Pricing Scenarios

The marginal abatement cost (MAC) of CO_2 represents the opportunity cost of reducing one additional tonne of emissions under an environmental production technology (Färe et al., 1993, 2005; Hailu and Veeman, 2000). Previous studies have estimated provincial CO_2 abatement potential and marginal costs (Wei et al., 2012) and examined carbon shadow prices in China's secondary industry (Xue et al., 2019). Following Hu et al. (2024), this study estimates provincial MACs using convex quantile regression with a non-radial directional distance function (CQR-NDDF), providing a mitigation-cost basis for valuing bilateral responsibility transfers.

The estimation uses a pooled panel of 270 province-year observations covering 30 provinces over 2012–2020. Capital stock, employment and final energy consumption constitute the inputs; real GDP is the desirable output; and production-based CO_2, SO_2 and NO□ emissions are the undesirable outputs. Provincial MACs are estimated annually, and the compensation analysis uses the estimates corresponding to the five MRIO benchmark years: 2012, 2015, 2017, 2018 and 2020.

The model is estimated at ten quantiles from 0.05 to 0.95 in increments of 0.10 and under three directional specifications covering different combinations of input contraction, desirable-output expansion and undesirable-output contraction. For each observation and direction, a quantile frontier is selected according to the residual-based rule in Supplementary Method S1.4. Its coefficients are then used to calculate candidate MACs through labor adjustment, energy adjustment and desirable-output contraction. The final provincial MAC is the lowest available finite, non-negative estimate across these channels and directional specifications. The optimization problem, frontier-selection rule and candidate-cost calculations are presented in Supplementary Method S1.

Capital stock and real GDP are measured at 2000 constant prices. Labor and energy prices used to monetize the estimated coefficient ratios are converted to the same price level using province-year GDP

deflators. The resulting MAC estimates are expressed in CNY/tCO_2 at 2000 prices. Variable definitions, price construction and unit conversions are documented in Supplementary Method S1.1 and S1.5–S1.6.

Alongside the market-price baseline described in Section 3.5, two MAC-based pricing scenarios are constructed. Recipient-specific MAC pricing values each bilateral transfer at the estimated MAC of the actual receiving province in the corresponding year. National-average MAC pricing applies the arithmetic mean of the 30 provincial MAC estimates to every bilateral transfer within that year. The former links compensation to the recipient's estimated mitigation cost, while the latter provides a uniform cost-based benchmark. Their comparison identifies how provincial cost differences affect the allocation of compensation.

The social cost of carbon (SCC) provides an additional welfare-based valuation. This scenario applies a uniform value of 185 USD/tCO_2 at 2020 prices, using the preferred mean estimate reported by Rennert et al. (2022) for a near-term risk-free discount rate of 2%. Compensation under this scenario is reported in 2020-price USD. Together, the four pricing scenarios connect bilateral responsibility transfers to market-based, mitigation-cost and climate-damage valuations.

3.7. Comparative design and compensation-role stability

The distributional analysis compares three capability specifications at the benchmark responsibility weight and the fixed market price of 42.85 CNY/tCO_2: no capability adjustment, adjustment based on GDP per capita, and adjustment based on the multidimensional RC index. The two capability-based specifications use the same annual [1,10] normalization, the same adjustment function and $\lambda = 0.5$. Provinces with RC below the annual median form a fixed comparison group across the three specifications. Outcomes include gross payment and receipt shares, monetary amounts and provincial net compensation. An additional comparison places all three specifications on the same national funding scale by proportionately rescaling each payment matrix to the no-adjustment total.

The pricing analysis compares the national-average MAC with recipient-specific MACs, both expressed at 2000 prices. Changes in provincial net compensation are decomposed into changes in receipts minus changes in payments. This decomposition identifies how local mitigation costs and the costs of compensation counterparties contribute to a change in net position.

The joint analysis combines eleven CBA weights, θ= 0, 0.1,..., 1, with three capability-adjustment strengths, λ= 0, 0.5 and 1, and the two MAC price structures. Across the five benchmark years, this produces 330 scenarios. Continuous stability is then evaluated over θ and λ in [0,1] using all bilateral direction breakpoints. Provinces are classified as stable net recipients or payers when net compensation remains positive or negative, respectively, throughout the parameter domain under both pricing rules. Roles are classified as switchable when both positive and negative net positions occur within the combined set of specifications, subject to the numerical tolerance defined in Supplementary Method S2.

4. Data

This study uses the Chinese provincial multi-regional input–output (MRIO) tables for 2012, 2015 and 2017 (Zheng et al., 2021) and for 2018 and 2020 (J. Li et al., 2026). Each table covers 31 provincial-level units in mainland China and 42 sectors within each province. Provincial sectoral CO_2 emissions are obtained from the inventories published by China Emissions Accounts and Datasets (CEADs), which cover 30 provinces and 47 sectors. These inventories account for CO_2 emissions from the combustion of 17 fossil fuels and cement production processes.

The sectoral classifications of the MRIO tables and emissions inventories are harmonized with reference to the Industrial Classification for National Economic Activities (GB/T 4754–2017), retaining the original sectoral detail wherever possible. The geographical coverage is aligned to the 30 provinces included in the emissions inventories, excluding Tibet. The resulting dataset comprises MRIO tables and corresponding production-based CO_2 emissions for 30 provinces and 29 sectors in each benchmark year. The 29 sectors are listed in Appendix 1. Direct emissions from urban and rural household fuel use are excluded from the sectoral production-emissions vector, while household consumption remains included in domestic final demand. Data sources for the indicators used to construct the RC index are summarized in Table 1.

Provincial MACs used in the sensitivity analysis are estimated using the CQR-NDDF approach developed by Hu et al. (2024). For this estimation, a continuous province-year panel is constructed for the same 30 provinces over 2012–2020, yielding 270 observations. The three inputs are capital stock, employment and final energy consumption. Capital stock is estimated using the perpetual inventory method following Zhang, Wu and Zhang (2004) and is expressed at 2000 constant prices. Employment is measured by the number of employed persons, using data from the China Labour Statistical Yearbook and provincial employment statistics. Final energy consumption is constructed by aggregating the final consumption of coal, petroleum products, natural gas and electricity, after converting the individual energy products into standard coal equivalents. Energy-consumption data and conversion coefficients are obtained from the China Energy Statistical Yearbook. The desirable output is provincial real GDP at 2000 constant prices, reconstructed from regional GDP and regional GDP indices reported in the China Statistical Yearbook. The undesirable outputs comprise production-based CO_2 emissions, SO_2 emissions and NO□ emissions. SO_2 and NO□ data are obtained from the China Environmental Statistical Yearbook.

Two province-year input-price proxies are constructed for the MAC calculation. The nominal labor-price proxy is calculated as the employment-share-weighted average of urban and rural residents' per capita wage income, using urban and rural employment shares as weights. The wage-income data are obtained from the China Labour Statistical Yearbook.

The nominal composite energy-price proxy is constructed from gasoline, diesel, natural-gas and industrial-electricity prices obtained from CEIC and the Price Monitoring Center of the National Development and Reform Commission. Monthly observations are converted into annual averages, and the component prices are expressed in CNY per tonne of standard coal. Within each province and year, the composite price is calculated using each component's share in the combined standard-coal-equivalent consumption of these four energy forms. Thus, coal contributes to the final energy input, while the energy-price basket comprises gasoline, diesel, natural gas and electricity.

To maintain consistency with capital stock and real GDP, both nominal input-price proxies are deflated to the 2000 price level using province-year GDP deflators. Each deflator is calculated as the ratio of nominal GDP to GDP at 2000 constant prices, with both GDP series expressed in the same monetary units. The nominal labor-price and composite energy-price proxies are then divided by the corresponding deflator. The resulting annual labor-price proxy is expressed in 2000-price CNY per person, and the composite energy-price proxy is expressed in 2000-price CNY per tonne of standard coal. The MAC estimates are consequently expressed in 2000-price CNY per tonne of CO_2. Variable definitions, estimation units and the construction of the price variables are documented in Supplementary Method S1, including Table S1.

5. Results

5.1. Provincial Carbon Responsibility and Bilateral Net Responsibility Transfers

Figure 2 presents provincial responsibilities under PBA, CBA and IBA within the domestic final-demand boundary. Aggregate emissions increased by 16.5%, from 7,481.45 Mt CO_2 in 2012 to 8,715.68 Mt CO_2 in 2020. The accounting principles produce distinct provincial profiles. In 2020, Beijing's consumption-based responsibility was 210.40 Mt, compared with production-based responsibility of 54.70 Mt. Inner Mongolia showed the reverse pattern, with PBA of 704.81 Mt and CBA of 222.43 Mt. In Shanxi, income-based responsibility reached 493.04 Mt, compared with CBA of 190.92 Mt. Shandong ranked first under IBA in all five years, and the five

largest IBA responsibilities accounted for 34.37–36.08% of the domestic total.

Figure 2. The comparison of carbon responsibility under PBA/CBA/IBA in 2012, 2015, 2017, 2018, and 2020. Unit: Mt

The bilateral TSR matrix translates these attribution differences into responsibility claims and obligations. Aggregate positive TSR increased from 487.14 Mt in 2012 to 1,095.81 Mt in 2020, an increase of approximately 125% (Fig. 3a). In 2020, Inner Mongolia and Hebei had the largest net responsibility claims, at 198.00 and 167.29 Mt, respectively. Guangdong and Jiangsu had the largest net obligations, at 169.71 and 96.19 Mt. The consumption and income contributions in Fig. 3b show how these positions emerge from the two attribution components.

Consumption and income attribution reinforce each other for some province pairs and offset each other for others. For the Jiangsu–Shanxi relationship, the CBA component assigns a net transfer of 11.17 Mt from Jiangsu to Shanxi under the benchmark weights, while the IBA component offsets this by 1.03 Mt. Their combined transfer is 10.14 Mt. The direction changes at θ= 0.0845: weights above this threshold assign the obligation to Jiangsu, whereas lower weights assign it to Shanxi. The Guangdong–Liaoning and Jiangsu–Liaoning relationships provide two further examples of opposing consumption and income attribution. These cases show how the responsibility principle enters the identification of compensation parties.

Figure 3. Responsibility transfers, attribution components, and bilateral direction stability.

(a) Aggregate positive bilateral TSR in the five benchmark years, counted once. (b) CBA and IBA contributions to provincial net responsibility in 2020 under equal weighting. Black markers indicate their sum; positive values denote net responsibility claims. (c) Percentage shares of the 435 unique province pairs with stable or switching responsibility directions as θ varies from 0 to 1 within each benchmark year. Stable directions remain unchanged throughout this range, whereas switching directions reverse at an interior threshold. The PBA share is fixed at one third, and θ represents the CBA share of the remaining two thirds.

Across the five benchmark years, 48.28–67.59% of province pairs retain the same transfer direction throughout $\theta \in [0,1]$ (Fig. 3c). In 2020, 294 of the 435 pairs retain their direction and account for 81.91% of benchmark positive TSR. Aggregate positive TSR ranges from 503.52 to 1,871.73 Mt as the transferable share shifts from income to consumption attribution, compared with 1,095.81 Mt under equal weighting. The alternative weights therefore affect both the scale of inter-provincial responsibility and the direction of a subset of bilateral relationships.

Province-specific weights based on domestic final-demand absorption and value added produce smaller changes around the benchmark. They preserve 97.24–99.31% of bilateral directions across the five years, with changes in aggregate positive TSR ranging from − 1.66% to 2.10%. At most one provincial net responsibility role changes in any year. Together, the two exercises distinguish the effects of economic-structure-based weighting from the wider redistribution associated with alternative responsibility principles. Detailed results are provided in Supplementary Data S1.

5.2. Bilateral Carbon Compensation Flows and Provincial Net Positions

Building on the TSR results in Section 5.1, this section examines bilateral compensation under the market-price baseline. Each positive bilateral responsibility transfer is valued at 42.85 CNY/tCO_2 and adjusted by the RC-based capability factor with $\lambda = 0.5$. Aggregate bilateral payments increase from 23.09 billion CNY in 2012 to 49.78 billion CNY in 2020. With the allowance price held constant across years, this increase reflects changes in the underlying responsibility transfers and relative provincial capabilities. It therefore represents an expansion of the financial transfers generated by the compensation rule under a common valuation basis.

Figure 4. Directed bilateral carbon compensation flows among the ten provinces with the largest total compensation involvement in each benchmark year under the market-price baseline.

Note

Arc and ribbon widths are scaled separately within each year. “Shown flows” reports payments among the selected provinces; links involving other provinces are omitted.

Figure 4 presents the links among the ten provinces with the largest total receipts plus payments in each benchmark year. Arrowheads identify recipients, and ribbon widths indicate bilateral payment amounts. Major links connect provinces with substantial demand- and income-based responsibility to provinces carrying production-side responsibility within the domestic production network. In 2020, the largest bilateral payments include Jiangsu to Inner Mongolia, Guangdong to Hebei, and Guangdong to Inner Mongolia, at 1,064.71, 1,064.64 and 1,050.35 million CNY, respectively. These links illustrate how the compensation rule translates the separation between the location of emissions and the attribution of economic responsibility into specific financial relationships between provinces.

The provincial net positions further clarify this pattern. Guangdong has the largest net payment in 2020, at 8.44 billion CNY, followed by Jiangsu, Zhejiang, Beijing and Sichuan. Inner Mongolia and Hebei have the largest net receipts, at 8.65 and 7.34 billion CNY, followed by Xinjiang, Shanxi and Liaoning. For Beijing and Guangdong, both consumption-based and income-based responsibility exceed production-based responsibility within the domestic emissions boundary, generating net payment obligations under the benchmark allocation. Hebei and Inner Mongolia exhibit the reverse relationship and consequently hold substantial net responsibility claims. The compensation mechanism thus links financial obligations to the balance between locally generated emissions and responsibility attributed through final demand and value-chain income, with relative capability adjusting the monetary amounts.

Table 2
Main net payers, recipients, and concentration of bilateral carbon compensation

Year	Major net payers	Major net recipients	Share of selected payers in total payments (%)	Share of selected recipients in total receipts (%)
2012	Beijing; Guangdong; Shanghai; Tianjin; Shaanxi	Hebei; Inner Mongolia; Anhui; Henan; Shandong	61.88	48.2
2015	Beijing; Guangdong; Chongqing; Zhejiang; Tianjin	Hebei; Inner Mongolia; Anhui; Xinjiang; Liaoning	49.73	47.77
2017	Guangdong; Beijing; Tianjin; Anhui; Zhejiang	Inner Mongolia; Hebei; Jiangsu; Ningxia; Liaoning	43.73	51.75
2018	Guangdong; Beijing; Zhejiang; Henan; Shaanxi	Hebei; Inner Mongolia; Liaoning; Shandong; Xinjiang	55.36	52.41
2020	Guangdong; Jiangsu; Zhejiang; Beijing; Sichuan	Inner Mongolia; Hebei; Xinjiang; Shanxi; Liaoning	50.91	55.99

Note: Provinces are ranked by net compensation, defined as receipts minus payments. The concentration measures use the gross payments or receipts of the five selected provinces as a share of the corresponding national total.

Table 2 shows both persistence and change in provincial compensation positions. Beijing and Guangdong rank among the five largest net payers in every benchmark year, while Hebei and Inner Mongolia consistently rank among the five largest net recipients. Jiangsu provides a clear example of a changing position: it moves from the third-largest net recipient in 2017, receiving a net 1.96 billion CNY, to the second-largest net payer in 2020, paying a net 4.88 billion CNY. This change accompanies a reversal in its underlying responsibility balance. In 2017, Jiangsu's production-based responsibility exceeds both its consumption-based and income-based responsibility; by 2020, both attributed measures exceed its production-based responsibility. The shift demonstrates how a province's compensation position can change as its production emissions and attributed demand and income responsibilities evolve.

Financial transfers are also concentrated among a limited group of provinces. Table 2 ranks provinces by net compensation and reports the selected groups' shares of gross national payments and receipts. The five largest net payers account for 61.88% of total payments in 2012, falling to 43.73% in 2017 before reaching 50.91% in 2020. The corresponding share of the five largest net recipients increases from 48.20% in 2012 to 55.99% in 2020. These results indicate that the persistent presence of several leading provinces coexists with changes in the distribution of payment obligations and compensation receipts across the wider network.

The recurring positions of the leading payers and recipients provide a basis for sustained inter-provincial coordination, while changes such as Jiangsu's highlight the value of periodically updating responsibility accounts and compensation positions. The concentration of financial transfers also makes the treatment of provincial capability consequential for the allocation of payment obligations and receipts. Section 5.3 therefore examines how alternative capability specifications redistribute these amounts across provinces.

5.3. Provincial Capability and Its Effects on Compensation Payments and Receipts

Figure 5 shows substantial differences in the PCA composite capability scores across provinces. Beijing has the highest score in each benchmark year, while several coastal provinces also occupy relatively high positions. The composite scores summarize economic conditions, social development, technological innovation and government response, and are transformed into the annual RC index used in the compensation rule. These differences provide the capability basis for adjusting bilateral payments under CBDR-RC. Figure S1 presents the joint distribution of responsibility and capability in 2020, linking provincial capability positions to their involvement in responsibility transfers.

The adjustment operates through the relative capabilities of both compensation parties. A payment is increased when the payer has greater capability than the recipient and reduced when the payer has lower capability. Its effect on a province therefore depends on the capabilities of the provinces connected to it through outgoing and incoming compensation links. To examine these effects, the following comparisons hold the responsibility matrix and carbon price fixed and consider three specifications: no capability adjustment, adjustment using GDP per capita, and adjustment using the multidimensional RC index. The latter two use the same annual normalization and adjustment strength of $\lambda = 0.5$.

Table 3 shows that capability adjustment changes both the aggregate scale and the provincial allocation of compensation. In 2020, total payments are 46.96 billion CNY without adjustment, 52.59 billion CNY under GDP per capita, and 49.78 billion CNY under multidimensional RC. Under RC adjustment, payments by provinces below the annual RC median decline from 18.68 to 17.72 billion CNY, a reduction of 5.09%, while national payments increase by 6.02%. This group's share of payments falls from 39.77% to 35.60%, and its share of receipts rises from 34.35% to 37.64%. Holding group membership fixed across the three specifications, these changes show that RC adjustment reduces the group's payment obligations while increasing its share of compensation receipts.

Table 3
Aggregate and distributional effects of capability adjustment in 2020

Capability specification	National payments	Payments by below-median RC group	Receipts of below-median RC group	Group payment share (%)	Group receipt share (%)
No capability adjustment	46.955	18.675	16.131	39.77	34.35
GDP per capita	52.587	19.236	18.802	36.58	35.76
Multidimensional RC	49.782	17.724	18.74	35.6	37.64

Note: Monetary amounts are expressed in billion CNY, valued at the fixed allowance price of 42.85 CNY/tCO_2. The below-median RC group contains the same 15 provinces across all three specifications.

The GDP-per-capita comparison highlights the distinction between changes in funding scale and changes in allocation. Although the below-median RC group's payment share falls under GDP-per-capita adjustment, its total payments rise to 19.24 billion CNY as the national compensation total expands. Rescaling each adjusted payment matrix to the unadjusted national total of 46.96 billion CNY isolates the allocation effect. At this common funding scale, the group pays 17.18 billion CNY under GDP per capita and 16.72 billion CNY under multidimensional RC, compared with 18.68 billion CNY without adjustment. The RC specification therefore assigns a smaller proportion of payment obligations to the below-median RC group under an equal aggregate funding requirement.

Figure 6 compares changes in provincial payment and receipt shares under GDP-per-capita and multidimensional RC adjustment. Changes are measured in percentage points relative to no capability adjustment, with each share calculated using the national payment or receipt total under its respective scenario. Guangdong's share of national payments increases by 1.47 percentage points under RC, compared with 0.26 percentage points under GDP per capita. Fujian's payment share decreases by 0.22 percentage points under RC but increases by 0.38 percentage points under GDP per capita. These differences reflect changes in each province's capability relative to its compensation counterparties, which alter the adjustments applied to incoming and outgoing bilateral payments. The multidimensional specification therefore produces a distinct allocation of payment obligations by incorporating economic

conditions, social development, technological innovation and government response into the assessment of relative capability.

Figure 6. Effects of capability adjustment on provincial payment and receipt shares in 2020. (a) Changes in payment shares. (b) Changes in receipt shares.

Yunnan illustrates how these bilateral adjustments can alter a province's net compensation position. Without adjustment, it receives 613.69 million CNY and pays 892.61 million CNY, leaving a net payment of 278.92 million CNY. Under RC adjustment, its receipts increase to 788.86 million CNY and its payments decline to 703.57 million CNY, producing a net receipt of 85.30 million CNY. Under GDP-per-capita adjustment, it remains a net payer of 145.74 million CNY. Yunnan's position at the lower end of the RC distribution increases its incoming payments from higher-capability provinces and reduces its outgoing payments to higher-capability provinces. The combined adjustment of these two sets of flows changes its aggregate net position while preserving the direction of each bilateral responsibility link.

Together, these results demonstrate how the capability component of CBDR-RC enters the financial allocation of compensation. Responsibility attribution establishes the bilateral obligations, while relative capability determines how those obligations translate into payments and receipts. In the 2020 comparison, the multidimensional RC specification shifts payment shares away from the below-median RC group and increases its share of compensation receipts. Detailed provincial comparisons and the common-funding-scale results are reported in Supplementary Data S2.

5.4. Sensitivity to Alternative Carbon-Pricing Scenarios

This section examines the sensitivity of compensation outcomes to carbon pricing while holding responsibility weights and capability adjustment fixed at $\theta = \lambda = 0.5$. Table 4 summarizes the four valuation scenarios and their aggregate payments in 2020. The market-price scenario provides an allowance-based benchmark, the two MAC scenarios represent mitigation-cost valuations, and the SCC scenario provides a welfare-based reference. Under uniform positive pricing, all bilateral payments change proportionately, preserving provincial payment shares, receipt shares and net compensation identities. The comparison between national-average and recipient-specific MACs therefore identifies how provincial cost differences affect compensation outcomes.

Table 4
Carbon-pricing scenarios and aggregate bilateral compensation payments in 2020

Scenario	Price setting	Currency and valuation basis	Aggregate payments in 2020
Market price	42.85 CNY/tCO_2	CNY valued at the fixed 2021 allowance price	49.78 billion CNY
Recipient-specific MAC	Estimated MAC of the receiving province	CNY at 2000 constant prices	231.00 billion CNY
National-average MAC	484.21 CNY/tCO_2	CNY at 2000 constant prices	562.54 billion CNY
SCC	185 USD/tCO_2	USD at 2020 prices	214.93 billion USD

Notes: Aggregate payments sum bilateral transfers once. All scenarios use the same 2020 responsibility matrix and RC adjustment. The national-average MAC is the arithmetic mean of the 30 provincial MAC estimates. Monetary amounts retain the currency and valuation basis specified for each scenario. The SCC value of 185 USD/tCO_2 at 2020 prices is taken from Rennert et al. (2022).

The two MAC scenarios produce substantially different compensation totals. At 2000 constant prices, aggregate payments amount to 562.54 billion CNY under the national-average MAC and 231.00 billion CNY under recipient-specific MACs. This difference reflects how responsibility transfers are distributed across provinces with different mitigation costs. Weighting recipient MACs by their incoming capability-adjusted responsibility transfers gives an average of 198.83 CNY/tCO_2, below the unweighted provincial average of 484.21 CNY/tCO_2. The lower weighted value indicates that lower-cost recipients carry substantial weight in the compensation network. Applying recipient-specific prices consequently reduces the valuation of these transfers and the aggregate compensation total.

Provincial cost differences also change the balance of receipts and payments. Under recipient-specific pricing, a province's incoming transfers are valued at its own MAC, while its outgoing transfers are valued at the MACs of the provinces receiving its payments. The resulting adjustment therefore depends on both local mitigation costs and the composition of compensation counterparties. In 2020, six provinces change their net compensation identities relative to uniform national-average MAC pricing (Fig. 7a and 7b). Tianjin, Anhui, Jiangxi, Henan and Hubei move from net payers to net recipients, while Qinghai moves from a net recipient to a net payer. The remaining 24 provinces retain their net signs.

The decomposition in Fig. 7c illustrates the different receipt–payment adjustments underlying these transitions. In Henan, receipts increase by 3.38 billion CNY and payments decline by 23.19 billion CNY, jointly moving its net position from a payment of 25.00 billion CNY to a receipt of 1.57 billion CNY. Tianjin becomes a net recipient even though its receipts decline: the reduction in payments, at 5.20 billion CNY, exceeds the 3.64 billion CNY reduction in receipts. Qinghai experiences the reverse balance, with the loss of receipts exceeding the reduction in payments. These cases show how recipient-specific pricing interacts with both sides of a province's compensation account, allowing changes in net identity even as the underlying bilateral responsibility directions remain fixed.

(a) Net payer–recipient transitions from national-average to recipient-specific MAC pricing. (b) Net compensation under both pricing rules and the corresponding changes for all 30 provinces. (c) Decomposition of net compensation changes for the six provinces with role reversals. Band widths in (a) represent province counts. All monetary amounts are expressed in billion CNY at 2000 prices.

Figure 9. Provincial net compensation under recipient-specific MAC pricing, 2020.

Note

Solid lines show net compensation at λ= 0.5, and shaded bands cover λ in [0,1] at each θ. Diamonds mark the benchmark θ=λ=0.5; open circles and labels indicate switching thresholds on the solid lines. P, S and R denote stable net payers, switchable roles and stable net recipients, respectively, over θ,λ in [0,1] under the indicated pricing rule. Vertical scales vary across provinces but match for each province between the two figures.

This section examines whether provincial net compensation roles persist as responsibility weights and capability adjustment vary. The CBA share of transferable responsibility, θ, and capability-adjustment strength, λ, vary continuously over [0,1], while the production-based responsibility share remains fixed at one third. Figures 8 and 9 present the 2020 results under national-average and recipient-specific MAC pricing, respectively. A province is classified as a stable net payer or recipient when its net compensation retains the same sign throughout the parameter domain.

Under national-average MAC pricing, nine provinces are stable net payers, nine are stable net recipients, and twelve have switchable roles. Under recipient-specific MAC pricing, the corresponding counts are six, twelve and twelve. Ten provinces change their full-domain stability classification between the two pricing rules. The identical number of switchable provinces therefore conceals a change in their composition: the valuation rule changes which provinces have persistent financial roles and which depend on the selected responsibility and capability parameters.

The response curves show how responsibility attribution affects both compensation amounts and provincial roles. Under national-average MAC pricing, increasing the CBA weight deepens net payments in Guangdong and Jiangsu while increasing net receipts in Hebei and Inner Mongolia. These provinces retain their respective roles throughout the parameter domain, although their compensation amounts vary substantially. For other provinces, changing the responsibility weight can reverse the balance between receipts and payments. At λ= 0.5, the curves cross zero for eleven provinces under national-average MAC pricing and nine under recipient-specific MAC pricing.

Capability adjustment provides an additional route to role conversion. Under recipient-specific MAC pricing, the curves for Jiangsu, Hubei and Sichuan retain a single sign at λ= 0.5, but their shaded ranges extend across zero at some responsibility weights. Their classification therefore depends on the joint specification of responsibility and capability parameters. A conditional threshold further illustrates this interaction: at θ= 0.5, Yunnan changes from a net payer to a net recipient when λ exceeds 0.3829 under national-average MAC pricing. Under recipient-specific MAC pricing, it remains a net recipient throughout

the full parameter domain. The role-changing effect of capability adjustment thus depends on the responsibility allocation and pricing rule within which it operates.

Considering both pricing rules and the full parameter domain together, four provinces remain net payers and nine remain net recipients in 2020, while the remaining seventeen have switchable roles. Applying this joint criterion across the five benchmark years identifies between seventeen and twenty-three provinces with switchable roles in each year. Beijing remains a stable net payer and Hebei a stable net recipient throughout all five years. These results identify persistent provincial compensation positions alongside a larger group whose financial roles depend on policy design. For this latter group, assigning payment and receipt obligations requires the responsibility weights, capability-adjustment strength and valuation rule to be specified together.

6. Conclusion

Based on a multi-regional input-output framework, this study develops a bilateral inter-provincial carbon compensation mechanism for China. The proposed framework integrates three components: a tripartite responsibility accounting system based on production-based responsibility (PBA), consumption-based responsibility (CBA), and income-based responsibility (IBA); a bilateral net responsibility transfer matrix (TSR); and a Respective Capability (RC) index used to adjust monetary compensation according to provincial ability to pay. Unlike single-perspective responsibility accounting, the proposed mechanism identifies not only the aggregate responsibility attributed to each province, but also the bilateral direction and magnitude of responsibility transfers embedded in inter-provincial trade. In this framework, the TSR matrix determines who should compensate whom, while the RC-based capability adjustment factor modifies the monetary scale of compensation according to the relative capability of the payer and the recipient.

Under the 2020 market-price baseline, Guangdong, Jiangsu, Zhejiang, Beijing and Sichuan are the largest net payers, while Inner Mongolia, Hebei, Xinjiang, Shanxi and Liaoning are the largest net recipients. Beijing and Guangdong remain among the five largest net payers in every benchmark year, and Hebei and Inner Mongolia remain among the five largest net recipients. These results suggest that China's inter-provincial carbon responsibility is not simply a matter of territorial emissions, but is shaped by domestic final demand, industrial division, and value-chain income distribution. The bilateral compensation matrix therefore provides a more precise basis for identifying responsibility relationships than provincial aggregate emissions alone.

The capability comparison shows how multidimensional capability changes the distribution of compensation. Relative to no capability adjustment, the RC specification reduces the payment share of provinces below the annual RC median from 39.77% to 35.60% and increases their receipt share from 34.35% to 37.64% in 2020. Differences from the GDP-per-capita benchmark show that the capability measure affects the allocation of financial obligations even when the adjustment function is held fixed. The RC adjustment preserves each bilateral payment direction while changing the amounts assigned to

incoming and outgoing transfers, which can alter a province's net compensation role. This gives the capability component of CBDR-RC a distinct role in the monetary allocation.

Carbon valuation affects both the scale and distribution of compensation. With responsibility and capability adjustment held fixed, uniform positive prices proportionately scale payments while preserving provincial net roles. Relative to national-average MAC pricing, recipient-specific MAC pricing moves Tianjin, Anhui, Jiangxi, Henan and Hubei from net payers to net recipients in 2020, while Qinghai changes in the opposite direction. Joint variation in responsibility weights, capability adjustment and the two MAC pricing rules identifies four stable net payers, nine stable net recipients and seventeen provinces with switchable roles in 2020. Across the five benchmark years, Beijing remains a stable net payer and Hebei a stable net recipient. These findings show that provincial compensation roles depend on the interaction between responsibility attribution, relative capability and the valuation of bilateral obligations.

These findings have several policy implications. First, China should gradually establish a bilateral carbon compensation mechanism that is linked to inter-provincial responsibility transfers. Such a mechanism should not be understood merely as a fiscal transfer scheme, but as an institutional tool for coordinating regional decarbonization, industrial upgrading, and equitable development. Compensation funds could be directed toward low-carbon technology adoption, energy-efficiency improvement, clean-energy infrastructure, and transition support in major recipient provinces. This would help transform carbon compensation from a passive redistribution mechanism into an active instrument for green development.

Second, differentiated policy instruments should be designed according to provinces' positions in the responsibility–capability framework. For high-capability net payers, policies should emphasize green consumption, supply-chain decarbonization, circular economy development, and the use of green procurement to transmit low-carbon incentives along domestic value chains. For major recipient provinces with resource-intensive production structures, compensation should be combined with targeted support for industrial decarbonization, energy transition, and technological upgrading. For provinces with relatively high responsibility but limited capability, compensation obligations should be introduced gradually and accompanied by green investment offsets or transition assistance to avoid imposing excessive short-run burdens.

Third, the market-price scenario should remain the primary policy benchmark because its pricing rule is observable and linked to China's carbon market. The national-average MAC scenario provides a uniform cost-based sensitivity benchmark, while receiver-specific MAC pricing reveals how provincial mitigation-cost heterogeneity affects net compensation positions. The SCC scenario provides a welfare-based reference. Any use of these alternative valuations in fiscal transfer design would require a common monetary basis and a separate assessment of affordability.

Finally, the proposed compensation mechanism should be updated dynamically. As China's inter-provincial production networks, carbon market institutions, mitigation technologies, and regional development conditions continue to evolve, the key parameters of the mechanism—including MRIO tables, provincial emission inventories, RC indicators, capability adjustment parameters, and carbon prices—

should be reviewed regularly. A periodic updating process would help maintain the fairness, feasibility, and policy relevance of the compensation mechanism over time. Beyond China, the framework of combining bilateral net responsibility transfers with capability-based monetary adjustment also offers a transferable approach for other large emerging economies facing regional inequality in climate governance.

Declarations

Author Contribution

A was responsible for study design, methodology, data collection and curation, software, formal analysis, visualization, and writing the original manuscript. B contributed substantially to reviewing and editing the manuscript. C and D reviewed the manuscript and provided comments. All authors read and approved the final manuscript.

References

1. Ari I, Sari R (2017) Developing CBDR-RC indices for fair allocation of emission reduction responsibilities and capabilities across countries. Cogent Environ Sci. 3https://doi.org/10.1080/23311843.2017.1420365
2. Bai J, Zhou J, Zhao C, Chang IS, Wu J (2025) The role of carbon sinks and renewable energy in the allocation of China's provincial carbon emissions allowance: From the perspectives of equity, efficiency, and continuity. Environ Impact Assess Rev 115:108058. https://doi.org/10.1016/j.eiar.2025.108058
3. Blanford GJ (2009) R&D investment strategy for climate change. Energy Econ 31(S1):S27–S36. https://doi.org/10.1016/j.eneco.2008.03.010
4. Cadarso MÁ, López LA, Gómez N, Tobarra MÁ (2012) International trade and shared environmental responsibility by sector. An application to the Spanish economy. Ecol Econ 83:221–235. https://doi.org/10.1016/j.ecolecon.2012.05.009
5. Chen W, Meng Y (2024) Intercity carbon compensation mechanism based on value-added captured responsibility allocation. J Environ Manage 371:123091. https://doi.org/10.1016/j.jenvman.2024.123091
6. Codal KS, Ari I, Codal A (2021) Multidimensional perspective for performance assessment on climate change actions of G20 countries. Environ Dev 39:100639. https://doi.org/10.1016/j.envdev.2021.100639
7. Csutora M, Vetőné Mózner Z (2014) Proposing a beneficiary-based shared responsibility approach for calculating national carbon accounts during the post-Kyoto era. Clim Policy 14(5):599–616. https://doi.org/10.1080/14693062.2014.905442
8. Dalkey N, Helmer O (1963) An experimental application of the DELPHI method to the use of experts. Manage Sci 9(3):458–467

9. Davis SJ, Peters GP, Caldeira K (2011) The supply chain of CO_2 emissions. *Proceedings of the National Academy of Sciences*, 108(45), 18554–18559. https://doi.org/10.1073/pnas.1107409108
10. Duan H, Mo J, Fan Y, Wang S (2018) Achieving China's energy and climate policy targets in 2030 under multiple uncertainties. Energy Econ 70:45–60. https://doi.org/10.1016/j.eneco.2017.12.022
11. Färe R, Grosskopf S, Lovell CAK, Yaisawarng S (1993) Derivation of shadow prices for undesirable outputs: A distance function approach. Rev Econ Stat 75:374–380
12. Färe R, Grosskopf S, Noh D, Weber WL (2005) Characteristics of a polluting technology: Theory and practice. J Econ 126:469–492. https://doi.org/10.1016/j.jeconom.2004.05.010
13. Ferng JJ (2003) Allocating the responsibility of CO_2 over-emissions from the perspectives of benefit principle and ecological deficit. Ecol Econ 46(1):121–141. https://doi.org/10.1016/S0921-8009(03)00104-6
14. Grasso M, Roberts J (2014) A compromise to break the climate impasse. Nat Clim Change 4:543–549. https://doi.org/10.1038/nclimate2259
15. Guan Y, Shan Y, Huang Q, Chen H, Wang D, Hubacek K (2021) Assessment to China's recent emission pattern shifts. *Earth's Future*, 9, e2021EF002241. https://doi.org/10.1029/2021EF002241
16. Guo LY, Feng C (2021) Are there spillovers among China's pilots for carbon emission allowances trading? Energy Econ 103:105574. https://doi.org/10.1016/j.eneco.2021.105574
17. Guo Y, Chen B, Li J, Yang Q, Wu Z, Tang X (2020) The evolution of China’s provincial shared producer and consumer responsibilities for energy-related mercury emissions. J Clean Prod 245:118678. https://doi.org/10.1016/j.jclepro.2019.118678
18. Hahn T et al (2024) Estimating countries’ additional carbon accountability for closing the mitigation gap based on past and future emissions. Nat Commun 15(1):9707. https://doi.org/10.1038/s41467-024-54039-x
19. Hailu A, Veeman TS (2000) Environmentally sensitive productivity analysis of the Canadian pulp and paper industry, 1959–1994: An input distance function approach. J Environ Econ Manag 40:251–274. https://doi.org/10.1006/jeem.2000.1124
20. Han X, Gao X, Ahmad F, Chandio AA, Khan S (2024) Carbon compensation and carbon neutrality: Regional variations based on net carbon transfer of trade in China. Geosci Front 15:101809. https://doi.org/10.1016/j.gsf.2024.101809
21. Hu S, Wang A, Lin B (2024) Marginal abatement cost of CO_2: A convex quantile non-radial directional distance function regression method considering noise and inefficiency. Energy 297:131323. https://doi.org/10.1016/j.energy.2024.131323
22. Jakob M, Ward H, Steckel JC (2021) Sharing responsibility for trade-related emissions based on economic benefits. Glob Environ Change 66:102207. https://doi.org/10.1016/j.gloenvcha.2020.102207
23. Kanbur R, Venables AJ (2007) Spatial disparities and economic development. In: Held D, Kaya A (eds) Global Inequality. Polity, Cambridge, pp 204–215

24. Kanbur R, Zhang X (2005) Fifty years of regional inequality in China: a journey through central planning, reform, and openness. Rev Dev Econ 9:87–106. https://doi.org/10.1111/j.1467-9361.2005.00265.x
25. Lenzen M, Murray J, Sack F, Wiedmann T (2007) Shared producer and consumer responsibility — theory and practice. Ecol Econ 61:27–42. https://doi.org/10.1016/j.ecolecon.2006.05.018
26. Leontief W (1974) Environmental Repercussions and the Economic Structure: An Input-Output Approach: A Reply. Rev Econ Stat 56(1):109–110. https://doi.org/10.2307/1926294
27. Li J, Zhang Z, Liang D et al (2026) China's Provincial Multi-Regional Input-Output Database for 2018 and 2020. Sci Data. https://doi.org/10.1038/s41597-025-06543-y
28. Li X, Wang R, Zhou Y, Yan Y, Xue J, Zhao Z (2026) An optimized shared responsibility accounting framework: unveiling the big black shadows behind small emitters in global value chains. Ecol Econ 240:108802. https://doi.org/10.1016/j.ecolecon.2025.108802
29. Liu L (2015) A critical examination of the consumption-based accounting approach: has the blaming of consumers gone too far? Wiley Interdisciplinary Reviews: Clim Change 6:1–8. https://doi.org/10.1002/wcc.325
30. Malaquias RF, Borges Junior DM, Malaquias FFO, Albertin AL (2019) Climate protection or corporate promotion? Energy companies, development, and sustainability reports in Latin America. Energy Res Social Sci 54:150–156. https://doi.org/10.1016/j.erss.2019.04.001
31. Marques A, Rodrigues J, Lenzen M, Domingos T (2012) Income-based environmental responsibility. Ecol Econ 84:57–65. https://doi.org/10.1016/j.ecolecon.2012.09.010
32. Mi Z et al (2021) Decoupling without outsourcing? How China's consumption-based CO_2 emissions have plateaued. iScience 24(10):103130. https://doi.org/10.1016/j.isci.2021.103130
33. Munksgaard J, Pedersen KA (2001) CO_2 Accounts for Open Economies: Producer or Consumer Responsibility? Energy Policy 29:327–334. https://doi.org/10.1016/S0301-4215(00)00120-8
34. Nardo M, Saisana M, Saltelli A, Tarantola S, Hoffmann A, Giovanni E (2008) Handbook on Constructing Composite Indicators: Methodology and User Guide. OECD Publishing, Paris. https://doi.org/10.1787/533411815016
35. Pearson K (1901) LIII. On lines and planes of closest fit to systems of points in space. Lond Edinb Dublin Philosophical Magazine J Sci 2(11):559–572. https://doi.org/10.1080/14786440109462720
36. Qin Q, Liu Y, Huang JP (2020) A cooperative game analysis for the allocation of carbon emissions reduction responsibility in China's power industry. Energy Econ 92:104960. https://doi.org/10.1016/j.eneco.2020.104960
37. Rennert K, Errickson F, Prest BC et al (2022) Comprehensive evidence implies a higher social cost of CO_2. Nature 610:687–692. https://doi.org/10.1038/s41586-022-05224-9
38. Saaty TL (1977) A scaling method for priorities in hierarchical structures. J Math Psychol 15(3):234–281. https://doi.org/10.1016/0022-2496(77)90033-5
39. Sen A (1999) Development as Freedom. Alfred Knopf, New York

40. Shan Y, Liu J, Liu Z, Xu X, Shao S, Wang P, Guan D (2016) New provincial CO_2 emission inventories in China based on apparent energy consumption data and updated emission factors. Appl Energy 184:742–750. https://doi.org/10.1016/j.apenergy.2016.03.073
41. Shan Y, Guan D, Zheng H et al (2018) China CO_2 emission accounts 1997–2015. Sci Data 5:170201. https://doi.org/10.1038/sdata.2017.201
42. Shan Y, Huang Q, Guan D et al (2020) China CO_2 emission accounts 2016–2017. Sci Data 7:54. https://doi.org/10.1038/s41597-020-0393-y
43. Shanghai Environment and Energy Exchange (2021) Annual trading data for China's national carbon market, 16 July–31 December 2021
44. Tian K et al (2025) Leveraging multinational enterprises to reduce the escalating regional carbon inequality in China. Nat Commun 16:6603
45. Wei C, Ni JL, Du LM (2012) Regional allocation of carbon dioxide abatement in China. China Econ Rev 23:552–565. https://doi.org/10.1016/j.chieco.2011.06.002
46. Winkler H, Rajamani L (2014) CBDR&RC in a regime applicable to all. Clim Policy 14(1):102–121. https://doi.org/10.1080/14693062.2013.791184
47. Xu J, Guan Y, Oldfield J, Guan D, Shan Y (2024) China carbon emission accounts 2020–2021. Appl Energy 360:122837. https://doi.org/10.1016/j.apenergy.2024.122837
48. Xue ZQ, Li N, Mu HL, Jiang YQ (2019) Abatement potential and shadow price of carbon dioxide emissions from fuel combustion in China's secondary industry. Climate Res 79:9–22. https://doi.org/10.3354/cr01572
49. Yan J, Li Y, Su B, Ng TS (2022) Contributors and drivers of Chinese energy use and intensity from regional and demand perspectives, 2012-2015-2017. Energy Econ 115:106357. https://doi.org/10.1016/j.eneco.2022.106357
50. Yang Z, Zhang B, Yang Y, Qin B, Wang Z (2024) Interprovincial inequality between economic benefit and carbon footprint: Perspective from China's Construction industry. Environ Impact Assess Rev 104:107293. https://doi.org/10.1016/j.eiar.2023.107293
51. Younus MAF (2017) Adapting to climate change in the coastal regions of Bangladesh: Proposal for the formation of community-based adaptation committees. Environ Hazards 16:21–49. https://doi.org/10.1080/17477891.2016.1211984
52. Yu J, Xian Q, Cheng S, Chen J (2024) Horizontal ecological compensation policy and water pollution governance: Evidence from cross-border cooperation in China. Environ Impact Assess Rev 105:107367. https://doi.org/10.1016/j.eiar.2023.107367
53. Zhang J, Wu G, Zhang J (2004) The estimation of China's provincial capital stock: 1952–2000. Econ Res J 10:35–44 (in Chinese)
54. Zheng H, Bai Y, Wei W, Meng J, Zhang Z, Song M, Guan D (2021) Chinese provincial multi-regional input-output database for 2012, 2015, and 2017. Sci Data 8:244. https://doi.org/10.1038/s41597-021-01023-5
55. Appendix

56. Appendix Table 1 Consolidated Industrial Classification

Figures

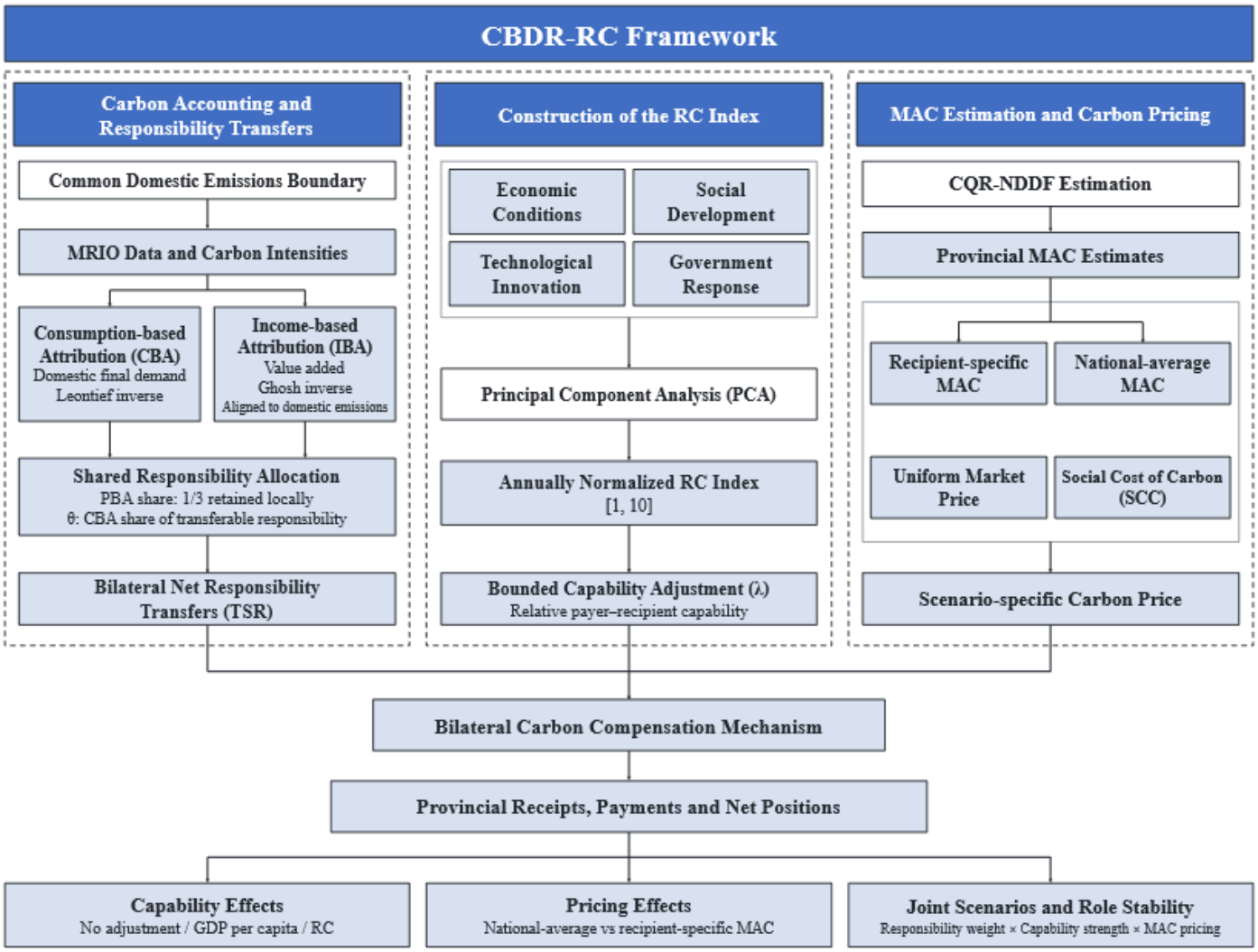
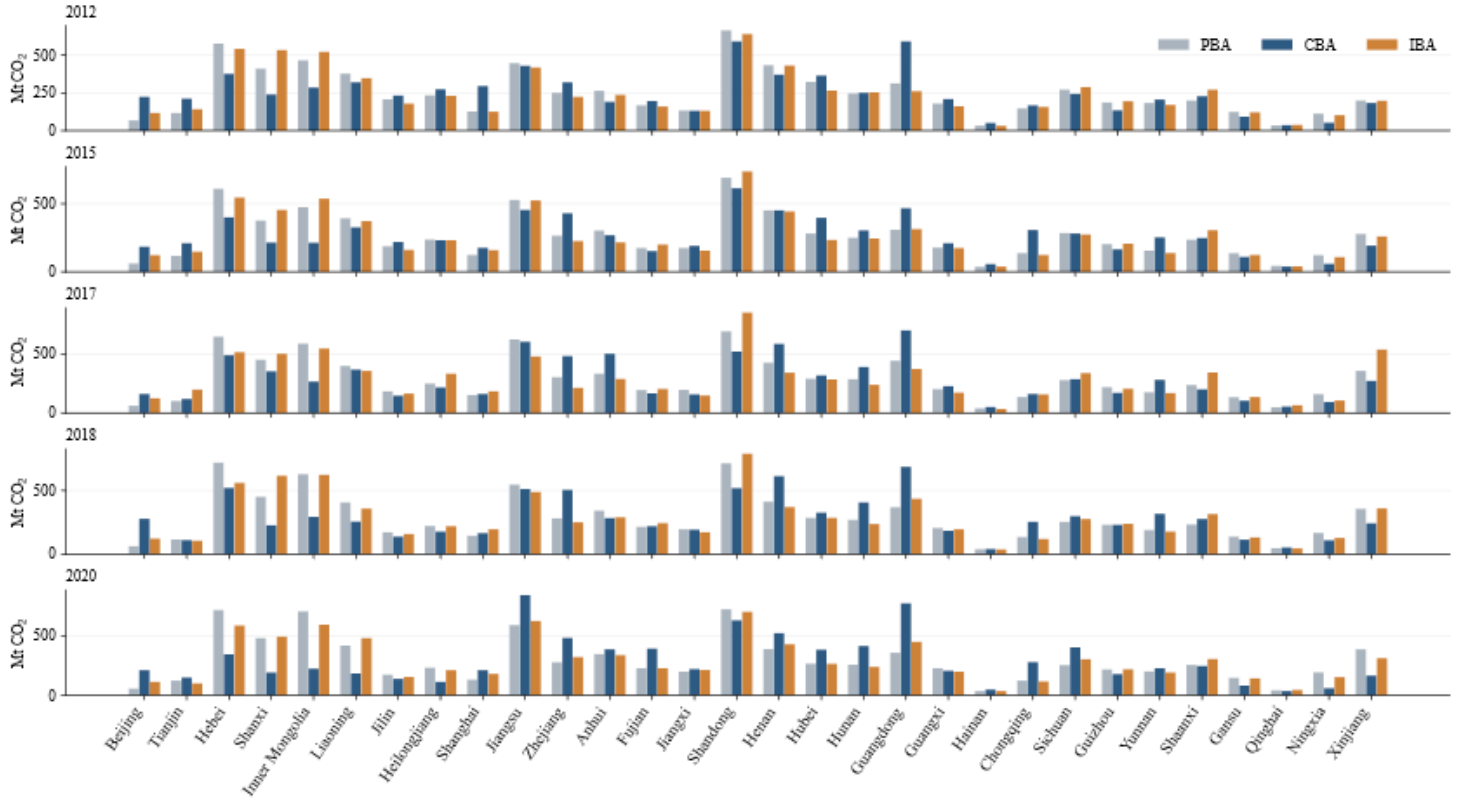


Figure 1

Design framework for the bilateral carbon compensation mechanism



CBA of 190.92 Mt. Shandong ranked first under IBA in all five years, and the five largest IBA responsibilities accounted for 34.37–36.08% of the domestic total.

Figure 2

The comparison of carbon responsibility under PBA/CBA/IBA in 2012, 2015, 2017, 2018, and 2020. Unit: Mt

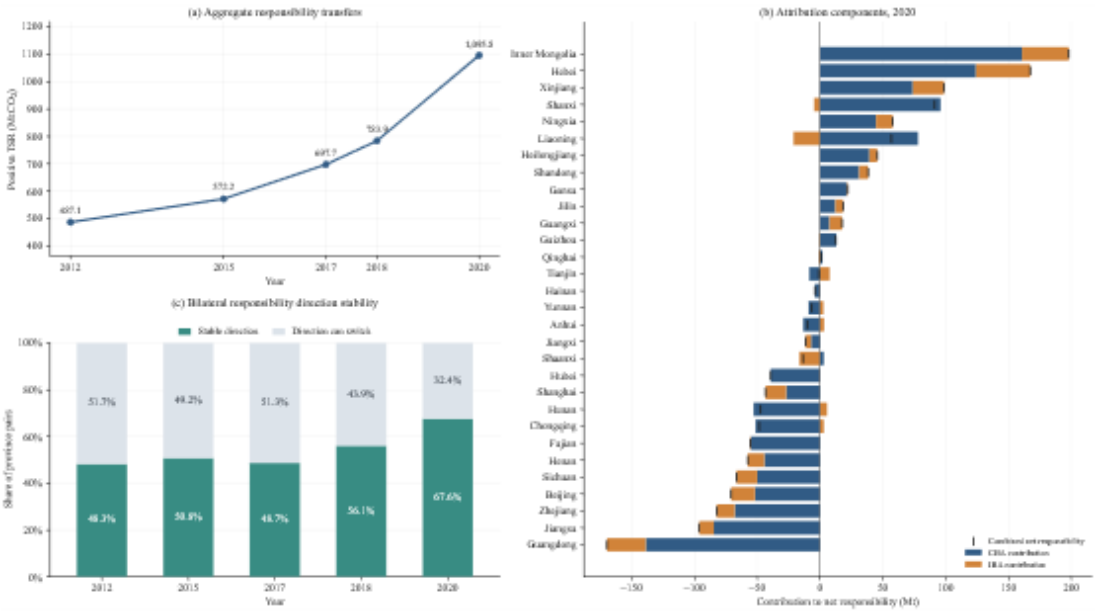


Figure 3

Responsibility transfers, attribution components, and bilateral direction stability.

(a) Aggregate positive bilateral TSR in the five benchmark years, counted once. (b) CBA and IBA contributions to provincial net responsibility in 2020 under equal weighting. Black markers indicate their sum; positive values denote net responsibility claims. (c) Percentage shares of the 435 unique province pairs with stable or switching responsibility directions as θ varies from 0 to 1 within each benchmark year. Stable directions remain unchanged throughout this range, whereas switching directions reverse at an interior threshold. The PBA share is fixed at one third, and θ represents the CBA share of the remaining two thirds.

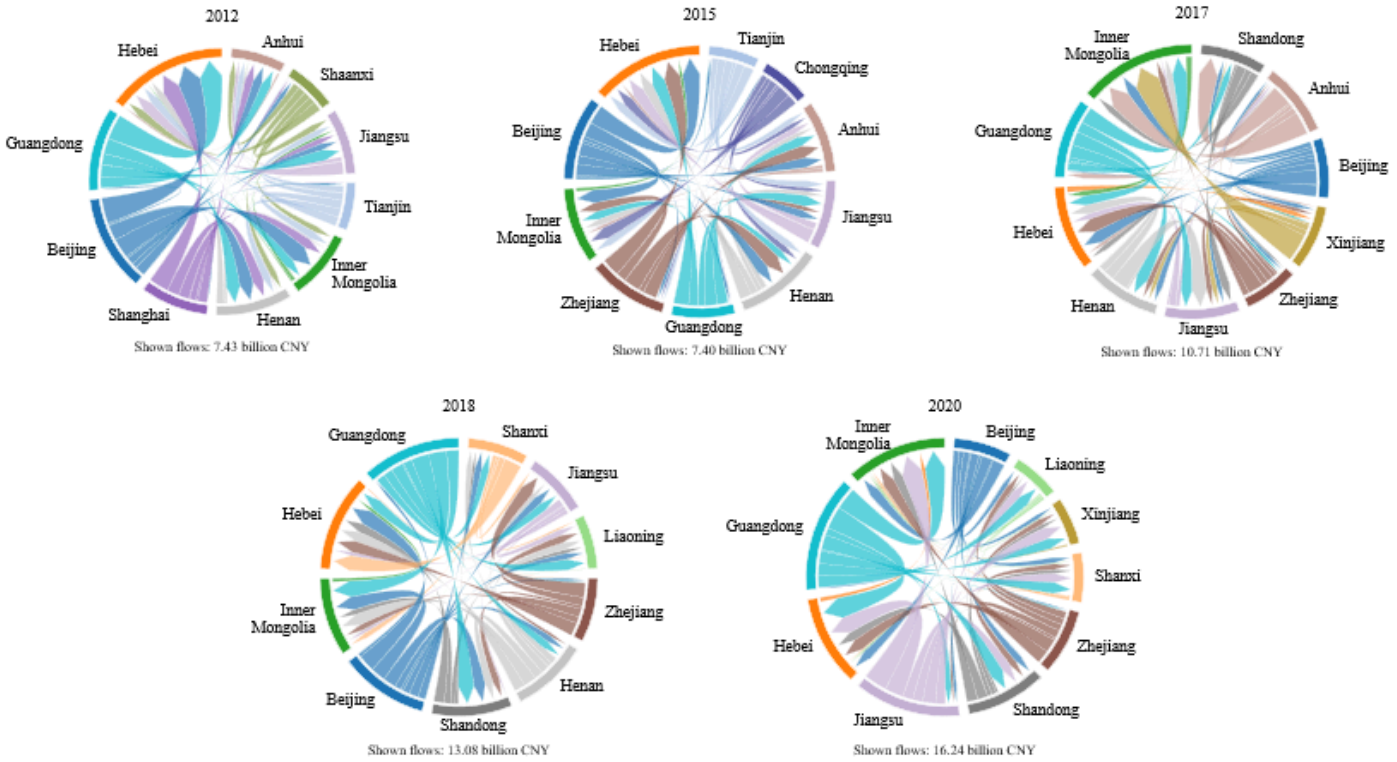


Figure 4

Directed bilateral carbon compensation flows among the ten provinces with the largest total compensation involvement in each benchmark year under the market-price baseline.

Note: Arc and ribbon widths are scaled separately within each year. “Shown flows” reports payments among the selected provinces; links involving other provinces are omitted.



Figure 5

PCA composite capability scores across provinces, 2012–2020.

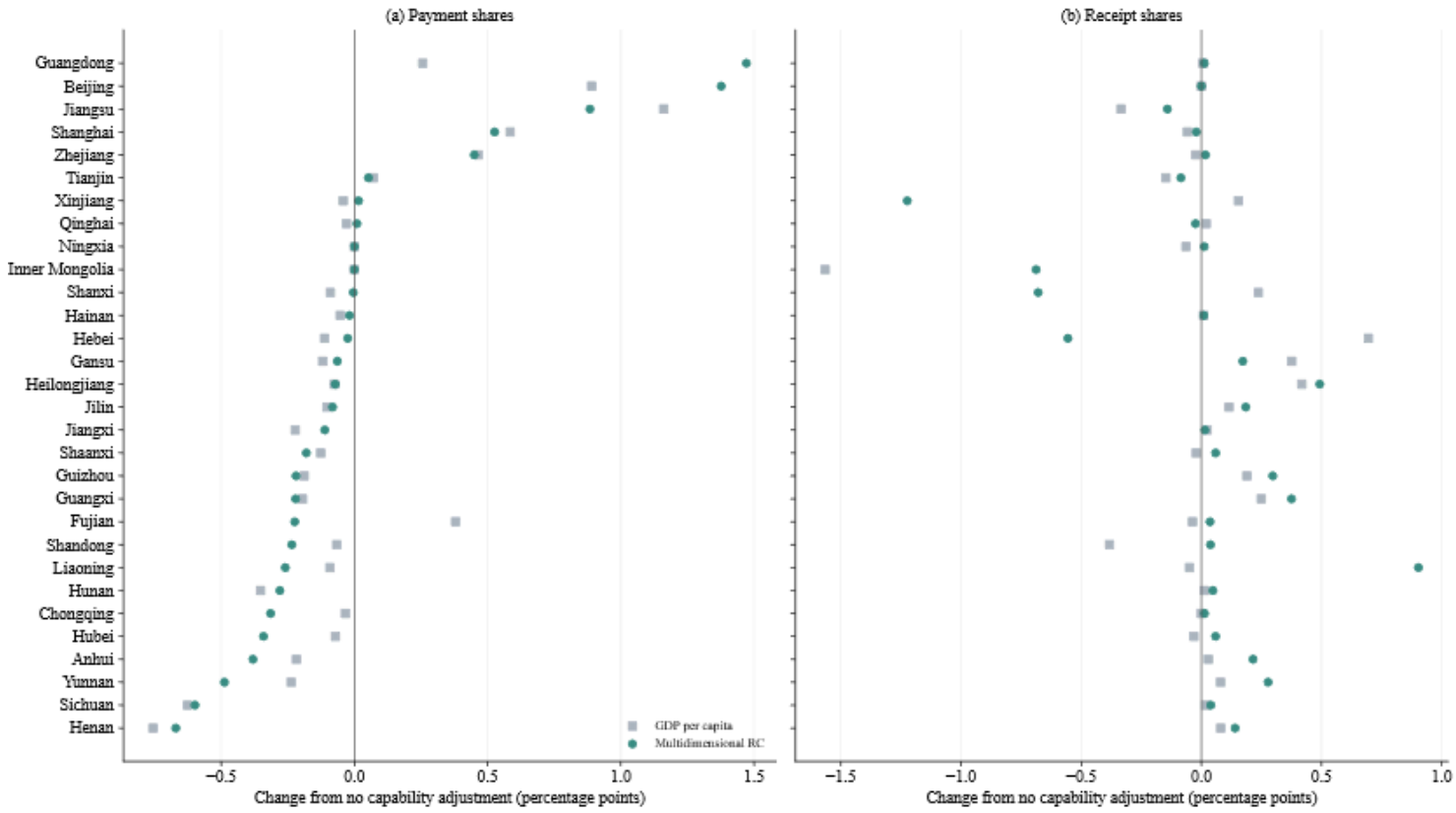


Figure 6

Effects of capability adjustment on provincial payment and receipt shares in 2020. (a) Changes in payment shares. (b) Changes in receipt shares.

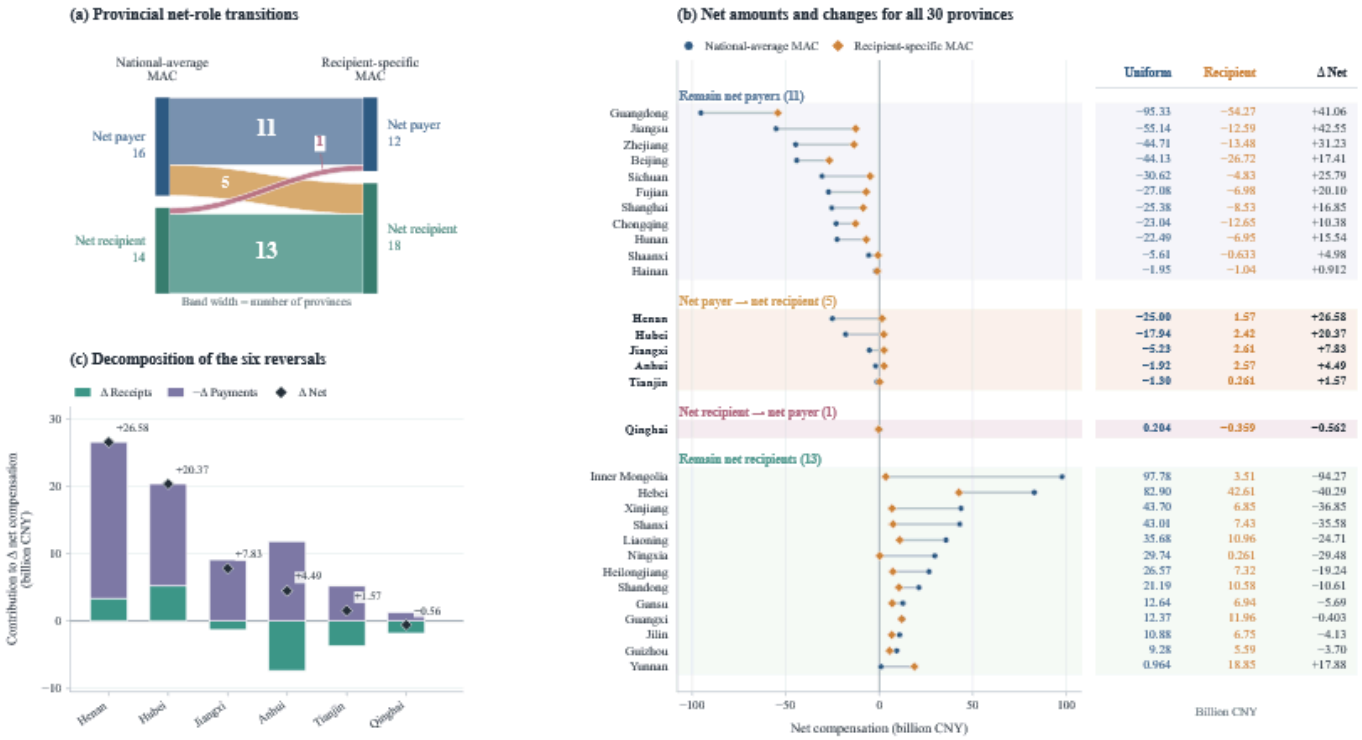


Figure 7

Provincial net compensation and role transitions under alternative MAC pricing in 2020.

(a) Net payer–recipient transitions from national-average to recipient-specific MAC pricing. (b) Net compensation under both pricing rules and the corresponding changes for all 30 provinces. (c) Decomposition of net compensation changes for the six provinces with role reversals. Band widths in (a) represent province counts. All monetary amounts are expressed in billion CNY at 2000 prices.

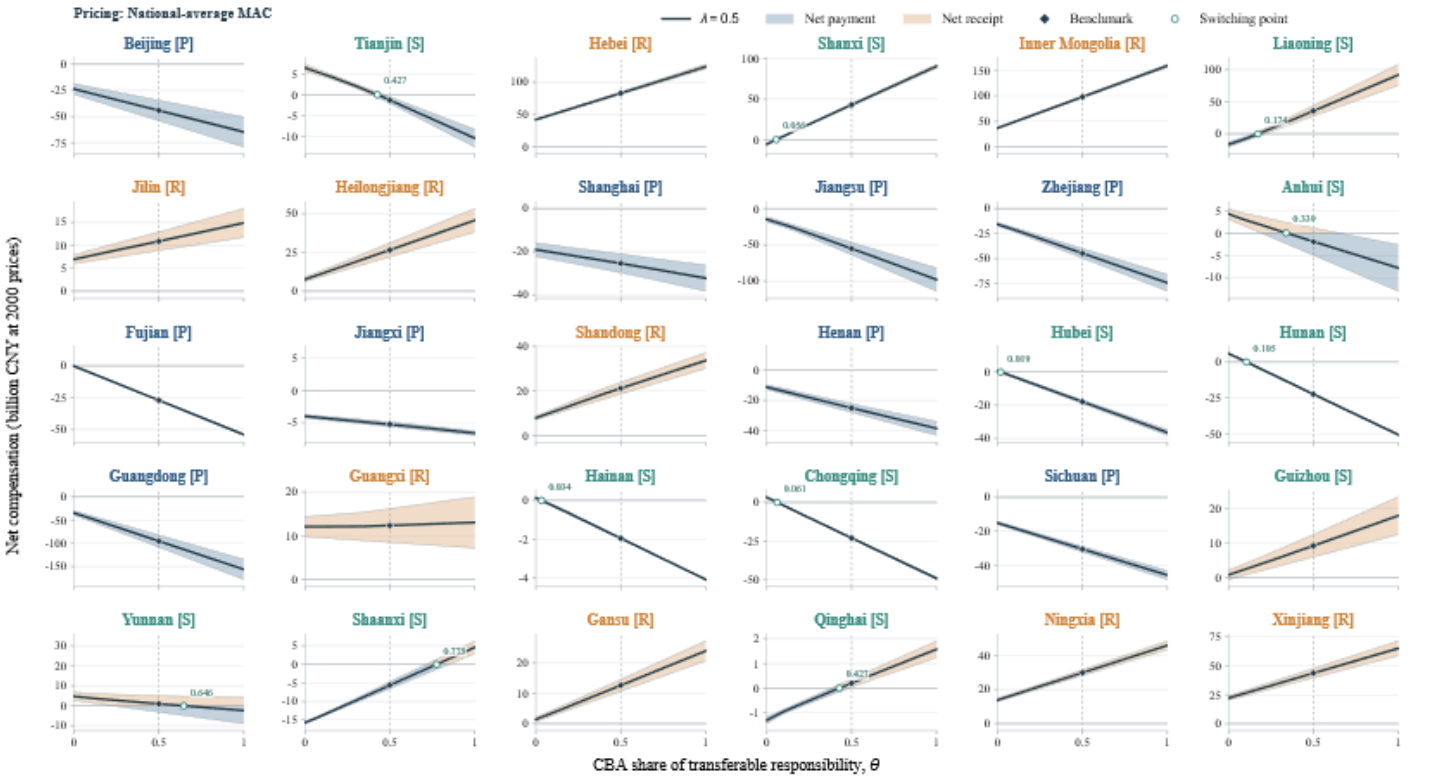


Figure 8

Provincial net compensation under national-average MAC pricing, 2020.

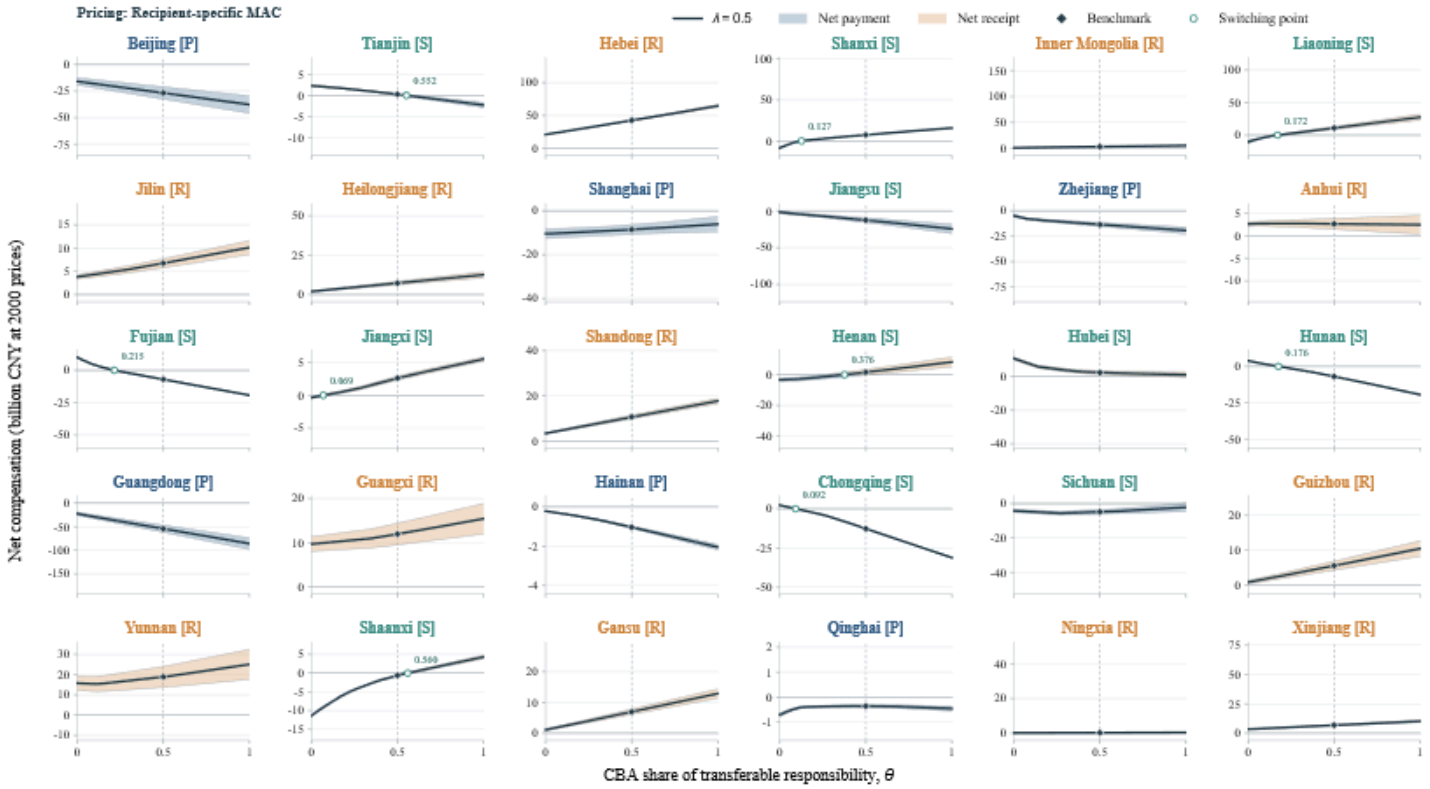


Figure 9

Provincial net compensation under recipient-specific MAC pricing, 2020.

Note: Solid lines show net compensation at =0.5, and shaded bands cover in [0,1] at each . Diamonds mark the benchmark = =0.5; open circles and labels indicate switching thresholds on the solid lines. P, S and R denote stable net payers, switchable roles and stable net recipients, respectively, over , in [0,1] under the indicated pricing rule. Vertical scales vary across provinces but match for each province between the two figures.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- FigureS1.svg
- SupplementaryMethod.docx
- SupplementaryDataS1.xlsx
- SupplementaryDataS2.xlsx
- Appendix.docx