Decarbonizing Households in China: Structural Drivers and Provincial Disparities in Carbon Footprints (2002–2022)

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Outlines

- Background & Motivation
- Research Objectives
- Methodology
- Results
- Conclusions & Policy Implications
- Limitations and future research

Background & Motivation

Why Chinese Household Emissions Matter?

- China has been the world's largest CO_2 emitter since 2007 (~30% of global emissions) (Guan et al., 2018; UNEP, 2023)
- Dual carbon targets: Peak by 2030, Carbon neutrality by 2060
- Household consumption accounts for over 70% of GHG emissions globally (including supply chain impacts) (Bjelle et al., 2021)
- household emissions more than doubled between 2002 and 2012 (Wu et al., 2019), its share in China increased from 27.0% (2012) to 33.6% (2017)

Dramatic Socioeconomic Transformation

- Urbanization rate: 39.1% (2002) → 65.2% (2022) & Per capita income growth: Urban +188%, Rural +378%
- Rising demand for cars, larger homes, energy-consuming appliances

Research Objectives

Current Research

- Income levels and consumption patterns (Cao et al., 2019; Peng et al., 2023; Bruckner et al., 2022; Wiedenhofer et al., 2017).
- Urban-rural differences (Connolly et al., 2022; Mi et al., 2020)
- Region disparities (Mi et al., 2020; Gao et al., 2024)

Regional disparities

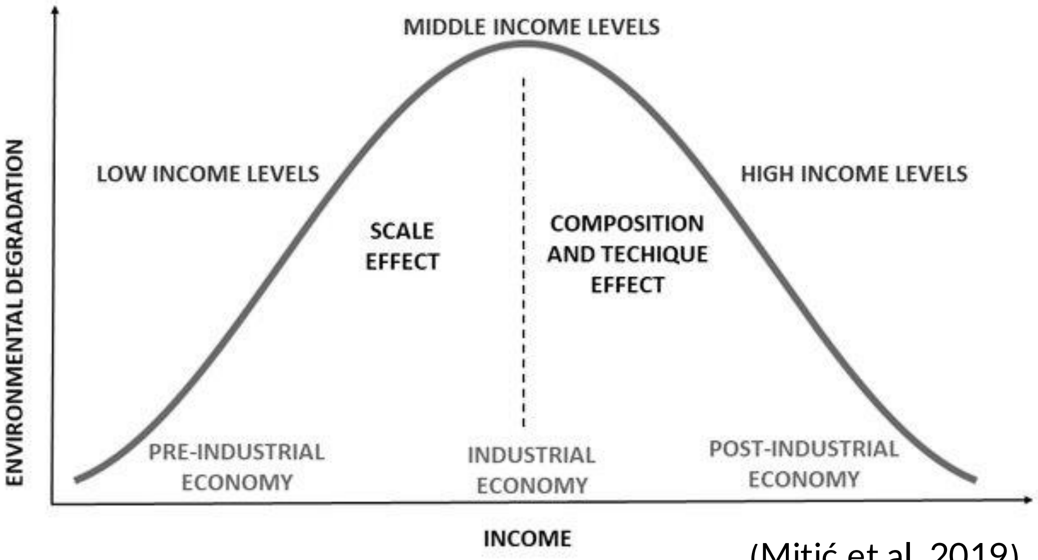
Research Gaps

- Most studies focus on national trends, overlooking regional differences
- Existing provincial analyses use short-term/cross-sectional data
- Structural determinants (production patterns, interprovincial spillovers) remain underexplored
- Few studies differentiate between energy efficiency and fuel switching

Research Objectives

Our Objectives

- Provincial-level analysis of household carbon emissions (2002-2022)
- Quantify direct and indirect emissions
- Disentangle structural drivers using SDA
- Provide region-specific policy recommendations



(Mitić et al, 2019)

Methodology

Data & Scope

China's interprovincial MRIO tables for the years 2002, 2007, 2012, and 2017, compiled by the *Development Research Center of the State Council* (Li et al., 2023).

30 mainland provinces; Tibet, Taiwan, Hong Kong and Macao excluded due to data availability

Region	Provinces
Northeast China (NE)	Liaoning (LN), Jilin (JL), Heilongjiang (HL)
Northern Municipalities (NM)	Beijing (BJ), Tianjin (TJ)
North Coast (NC)	Hebei (HE), Shandong (SD)
East Coast (EC)	Shanghai (SH), Jiangsu (JS), Zhejiang (ZJ)
South Coast (SC)	Fujian (FJ), Guangdong (GD), Hainan (HI)
Central China (CC)	Shanxi (SX), Anhui (AH), Jiangxi (JX), Henan (HA), Hubei (HB), Hunan (HN)
Northwest China (NW)	Inner Mongolia (IM), Shaanxi (SN), Gansu (GS), Qinghai (QH), Ningxia (NX), Xinjiang (XJ)
Southwest China (SW)	Guangxi (GX), Chongqing (CQ), Sichuan (SC), Guizhou (GZ), Yunnan (YN)

Eight meta-regions used for interpreting provincial patterns.

- **Household CO_2 Emissions**

$$F = F^d + F^i$$

- **Input-Output Analysis**

$$F^i = \mathbf{f}'(\mathbf{I}-\mathbf{A})^{-1}\mathbf{h} = \mathbf{f}'\mathbf{L}\mathbf{h}$$

- **Structural Decomposition Analysis**

$$\frac{F_1^i}{F_0^i} = \frac{\mathbf{f}_1'\mathbf{L}_1\mathbf{h}_1}{\mathbf{f}_0'\mathbf{L}_0\mathbf{h}_0} = \frac{(\boldsymbol{c}_1' \circ \boldsymbol{e}_1')\mathbf{L}_1\mathbf{h}_1}{(\boldsymbol{c}_0' \circ \boldsymbol{e}_1')\mathbf{L}_1\mathbf{h}_1}$$

CO_2 emissions per unit of energy consumption

$$\times \frac{(\boldsymbol{c}_0' \circ \boldsymbol{e}_1')\mathbf{L}_1\mathbf{h}_1}{(\boldsymbol{c}_0' \circ \boldsymbol{e}_0')\mathbf{L}_1\mathbf{h}_1}$$

energy efficiency

$$\times \frac{\mathbf{f}_0'\mathbf{L}_1\mathbf{h}_1}{\mathbf{f}_0'\mathbf{L}_0\mathbf{h}_1}$$

sub-industrial structure

$$\times \frac{\mathbf{f}_0'\mathbf{L}_0(\mathbf{H}_{s1}\hat{\mathbf{y}}_1)(p_1\mathbf{u}_1)}{\mathbf{f}_0'\mathbf{L}_0(\mathbf{H}_{s0}\hat{\mathbf{y}}_1)(p_1\mathbf{u}_1)}$$

household consumption preferences

$$\times \frac{\mathbf{f}_0'\mathbf{L}_0(\mathbf{H}_{s0}\hat{\mathbf{y}}_1)(p_1\mathbf{u}_1)}{\mathbf{f}_0'\mathbf{L}_0(\mathbf{H}_{s0}\hat{\mathbf{y}}_0)(p_1\mathbf{u}_1)}$$

household consumption level

$$\times \frac{\mathbf{f}_0'\mathbf{L}_0(\mathbf{H}_{s0}\hat{\mathbf{y}}_0)(p_1\mathbf{u}_1)}{\mathbf{f}_0'\mathbf{L}_0(\mathbf{H}_{s0}\hat{\mathbf{y}}_0)(p_0\mathbf{u}_1)}$$

total population

$$\times \frac{\mathbf{f}_0'\mathbf{L}_0(\mathbf{H}_{s0}\hat{\mathbf{y}}_0)(p_0\mathbf{u}_1)}{\mathbf{f}_0'\mathbf{L}_0(\mathbf{H}_{s0}\hat{\mathbf{y}}_0)(p_0\mathbf{u}_0)}$$

urbanization level

Methodology

- **Household CO_2 Emissions**

$$F = F^d + F^i$$

Direct Emissions

$$F^d = \sum_s Ef_s \times fuel_s$$ (CEADs, 2025)

Inirect Emissions

$$F^{in} = \mathbf{f}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{h} = \mathbf{f}'\mathbf{L}\mathbf{h}$$

- China's interprovincial MRIO tables for the years 2002, 2007, 2012, and 2017, compiled by the *Development Research Center of the State Council* (Li et al., 2023).

- For 2022 F^i, assumed:
  - $\mathbf{L}$ unchanged from 2017;
  - $\mathbf{f}'$ follow national sectoral CO_2/GDP trends 2017-2022;
  - $\mathbf{H_p}$ grows in proportion to urban/rural per capita expenditure data;
  - sectoral structures within each expenditure category remain constance

Methodology

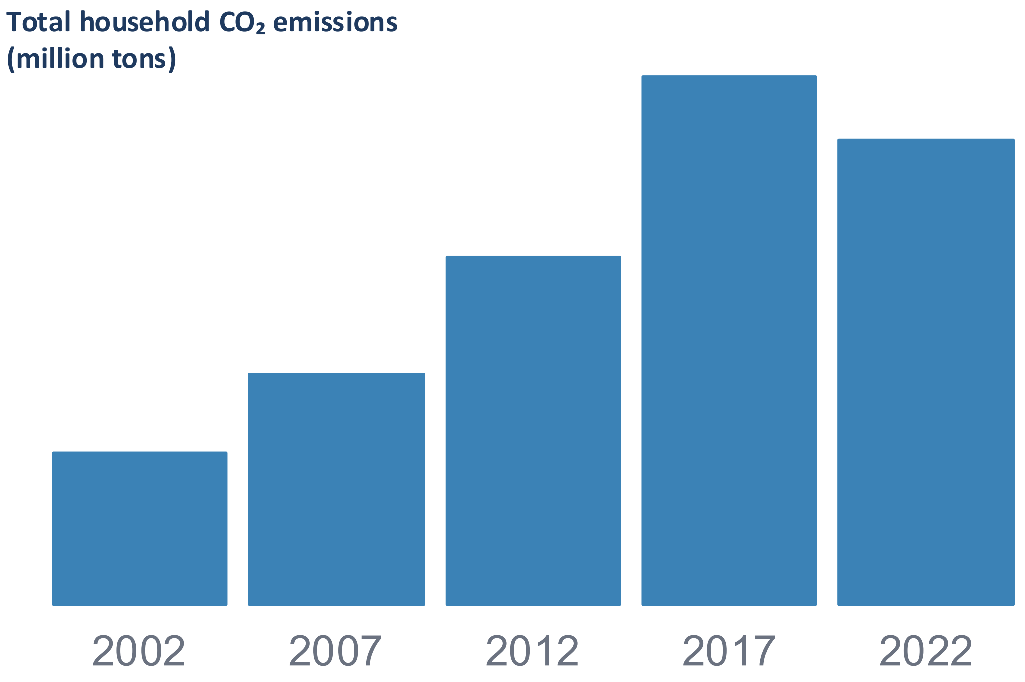
Structural Decomposition Analysis

$$
\begin{aligned}
\frac{F_1^{in}}{F_0^{in}} &= \frac{\mathbf{f}_1'\mathbf{L}_1\mathbf{h}_1}{\mathbf{f}_0'\mathbf{L}_0\mathbf{h}_0} \\
&= \frac{(\boldsymbol{CI}_1' \circ \boldsymbol{EI}_1')\mathbf{L}_1\mathbf{h}_1}{(\boldsymbol{CI}_0' \circ \boldsymbol{EI}_1')\mathbf{L}_1\mathbf{h}_1} \\
&\times \frac{(\boldsymbol{CI}_0' \circ \boldsymbol{EI}_1')\mathbf{L}_1\mathbf{h}_1}{(\boldsymbol{CI}_0' \circ \boldsymbol{EI}_0')\mathbf{L}_1\mathbf{h}_1} \\
&\times \frac{\mathbf{f}_0'\mathbf{L}_1\mathbf{h}_1}{\mathbf{f}_0'\mathbf{L}_0\mathbf{h}_1} \\
&\times \frac{\mathbf{f}_0'\mathbf{L}_0\left[\left((\boldsymbol{FS}_1 \circ \boldsymbol{TF}_1) \cdot \boldsymbol{HV}_1\right) \cdot \mathbf{P}_1\right]}{\mathbf{f}_0'\mathbf{L}_0\left[\left((\boldsymbol{FS}_0 \circ \boldsymbol{TF}_1) \cdot \boldsymbol{HV}_1\right) \cdot \mathbf{P}_1\right]} \\
&\times \frac{\mathbf{f}_0'\mathbf{L}_0\left[\left((\boldsymbol{FS}_0 \circ \boldsymbol{TF}_1) \cdot \boldsymbol{HV}_1\right) \cdot \mathbf{P}_1\right]}{\mathbf{f}_0'\mathbf{L}_0\left[\left((\boldsymbol{FS}_0 \circ \boldsymbol{TF}_0) \cdot \boldsymbol{HV}_1\right) \cdot \mathbf{P}_1\right]} \\
&\times \frac{\mathbf{f}_0'\mathbf{L}_0\left[\left((\boldsymbol{FS}_0 \circ \boldsymbol{TF}_0) \cdot \boldsymbol{HV}_1\right) \cdot \mathbf{P}_1\right]}{\mathbf{f}_0'\mathbf{L}_0\left[\left((\boldsymbol{FS}_0 \circ \boldsymbol{TF}_0) \cdot \boldsymbol{HV}_0\right) \cdot \mathbf{P}_1\right]} \\
&\times \frac{\mathbf{f}_0'\mathbf{L}_0\left[\mathbf{H}_{\mathbf{p0}} \cdot (\boldsymbol{TP}_1 \circ \boldsymbol{PS}_1)\right]}{\mathbf{f}_0'\mathbf{L}_0\left[\mathbf{H}_{\mathbf{p0}} \cdot (\boldsymbol{TP}_0 \circ \boldsymbol{PS}_1)\right]} \\
&\times \frac{\mathbf{f}_0'\mathbf{L}_0\left[\mathbf{H}_{\mathbf{p0}} \cdot (\boldsymbol{TP}_0 \circ \boldsymbol{PS}_1)\right]}{\mathbf{f}_0'\mathbf{L}_0\left[\mathbf{H}_{\mathbf{p0}} \cdot (\boldsymbol{TP}_0 \circ \boldsymbol{PS}_0)\right]}
\end{aligned}
$$

1. Carbon Intensity (CI): CO_2 per unit of energy
2. Energy Intensity (EI)
3. Production Structure (L):Technological shifts
4. Consumption Structure (FS):
5. Interregional Trade (TF)
6. Consumption Level (HV)
7. Population (TP)
8. Urban-Rural Structure (PS)

Results

Finding 1: household emissions peaked after 2017



- Overall household emissions reached a turning point between 2017 and 2022.
- Indirect emissions drove most of the growth before 2017 and most of the decline after 2017.
- Direct emissions grew more slowly and reached 453 MT in 2022.

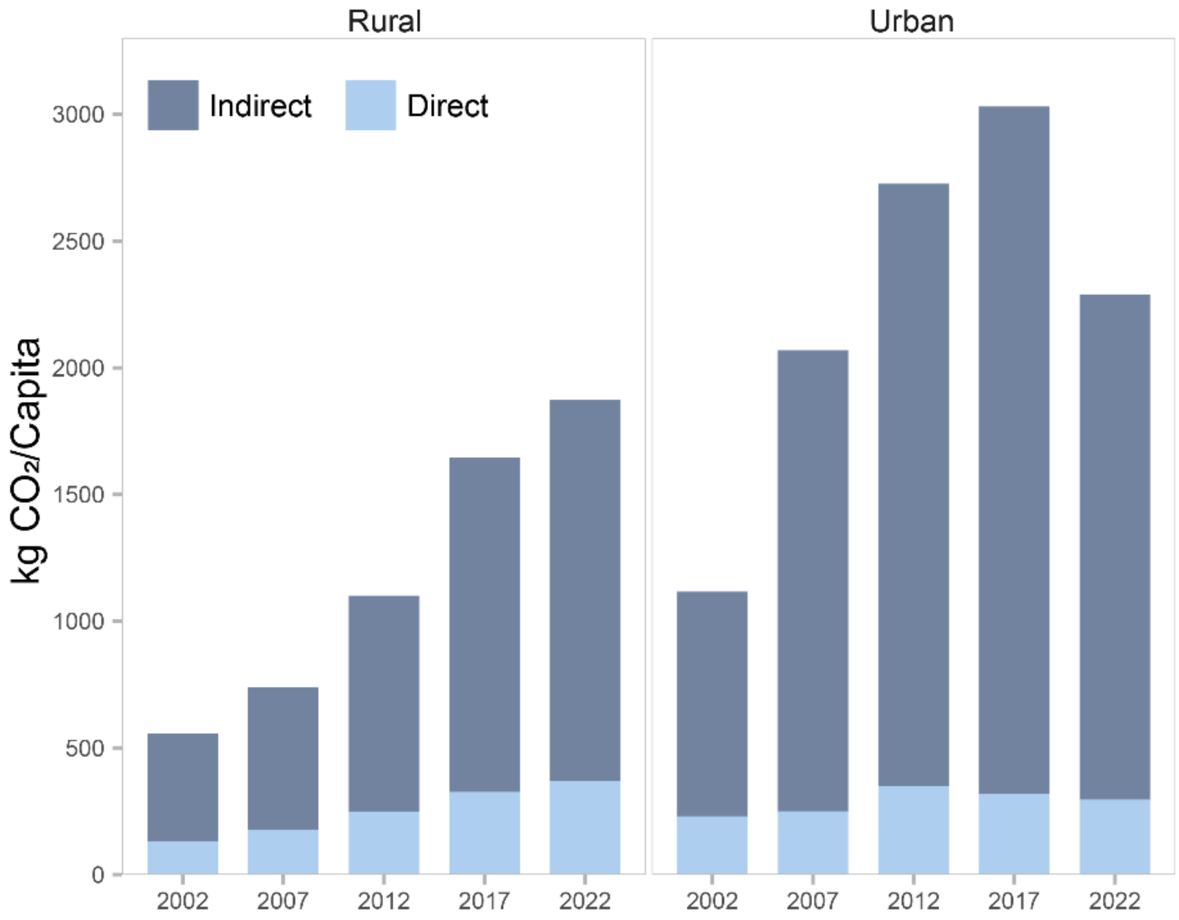
3.5×
Increase in total emissions, 2002–2017

−2.9%/yr
Average annual decline in indirect emissions, 2017–2022

453 MT
Direct household emissions in 2022

Results

Finding 2: Urban emissions stabilized; rural emissions continued to rise

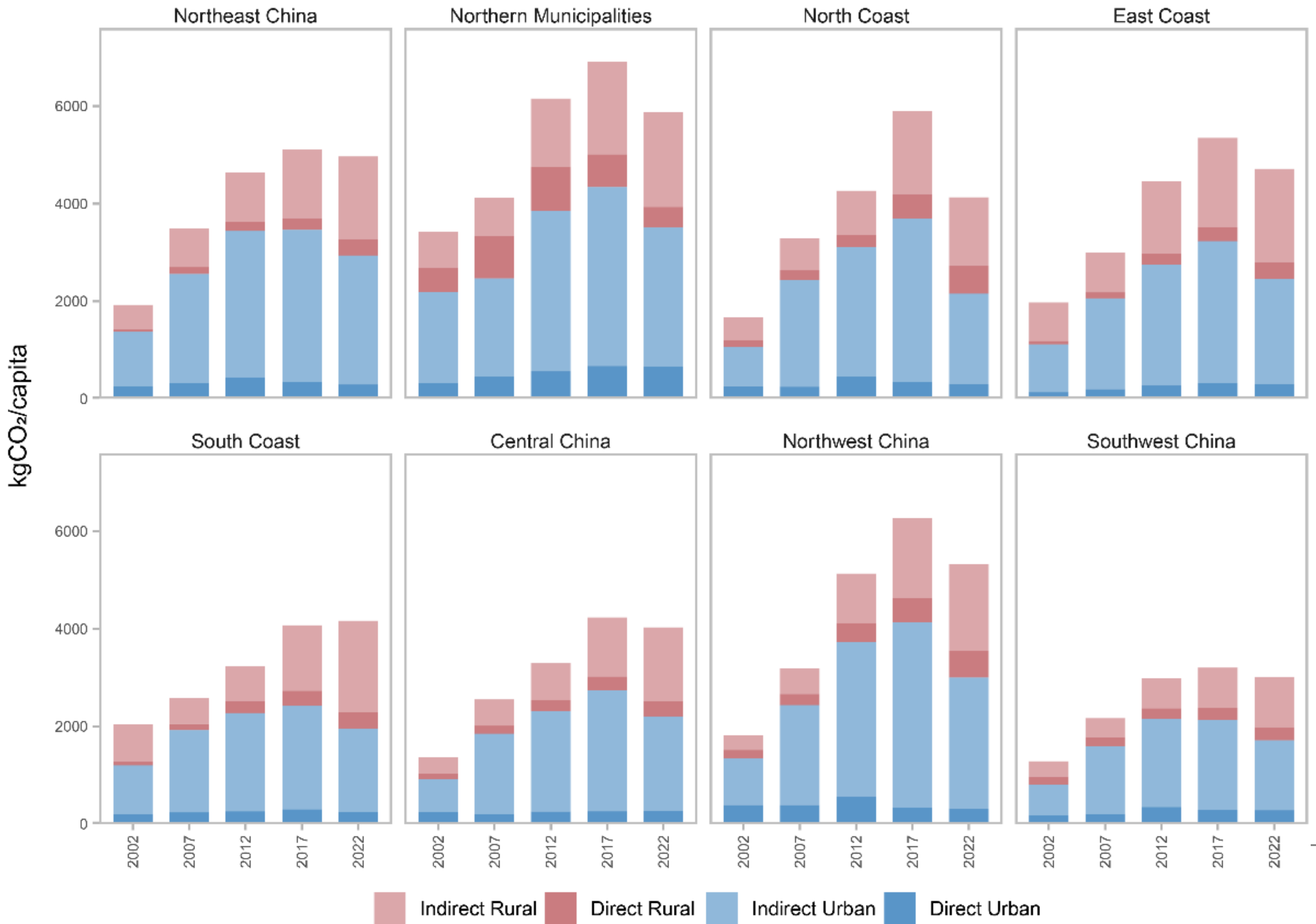


- Urban per capita footprints peaked around 2017 and fell to about 2.3 tCO_2 in 2022.
- Rural per capita footprints rose from 0.56 tCO_2 in 2002 to about 1.9 tCO_2 in 2022.
- The urban-rural per capita gap narrowed to around 0.4 tCO_2 by 2022.
- Since 2017, rural households have surpassed urban households in per capita direct emissions.

Rural decarbonization is no longer a marginal issue. It is central to China's next phase of demand-side mitigation.

Results

Finding 3: regional pathways differ sharply: Climate, income, infrastructure, and fuel access shape provincial footprints



- Cold northern regions and affluent coastal provinces show higher per capita emissions.
- Northern Municipalities had the highest urban and rural emissions in 2022.
- Southwest China maintained the lowest per capita emissions.
- By 2022, some regions such as the South Coast saw rural per capita emissions exceed urban levels.

Results

Finding 4: the fuel transition is fast but uneven: Coal declined dramatically in cities, but remains important in rural northern China

54% → 4.7%

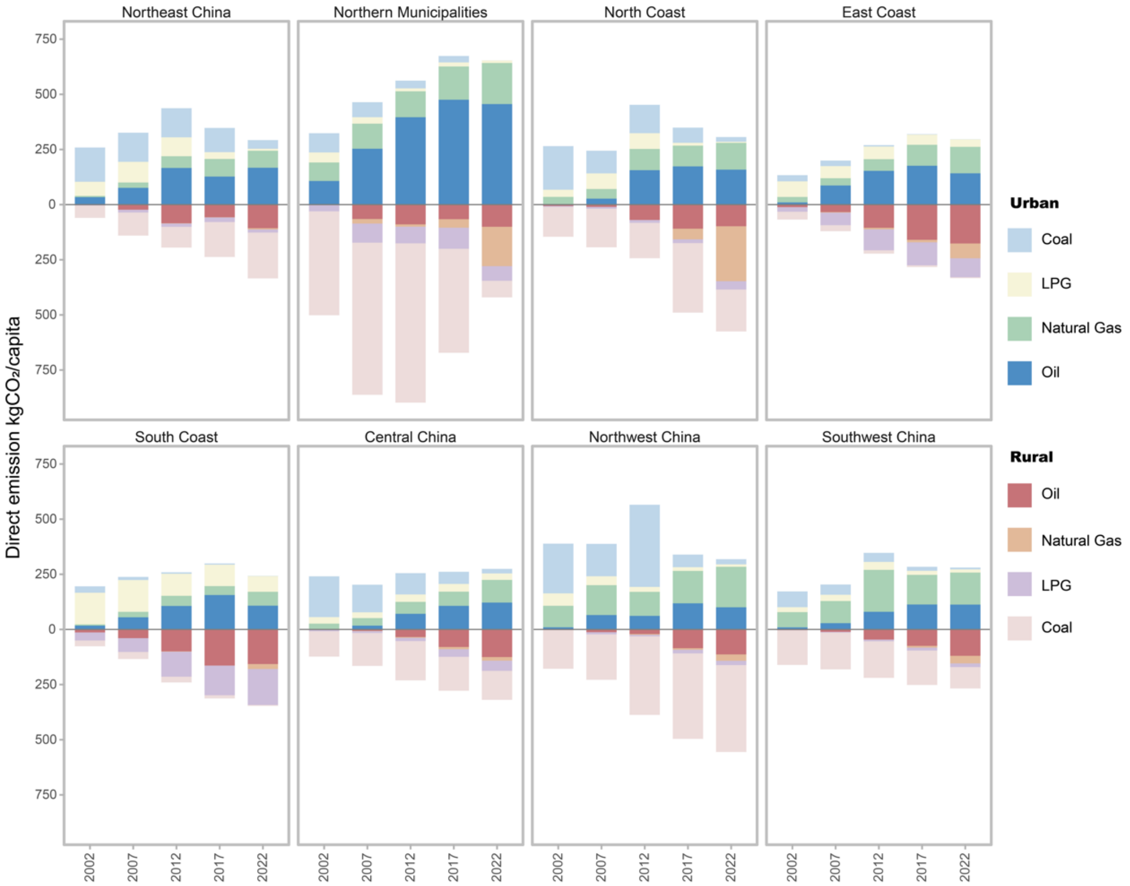
Urban coal share in direct emissions, 2002–2022

37.3%

Rural coal share remained in 2022

16

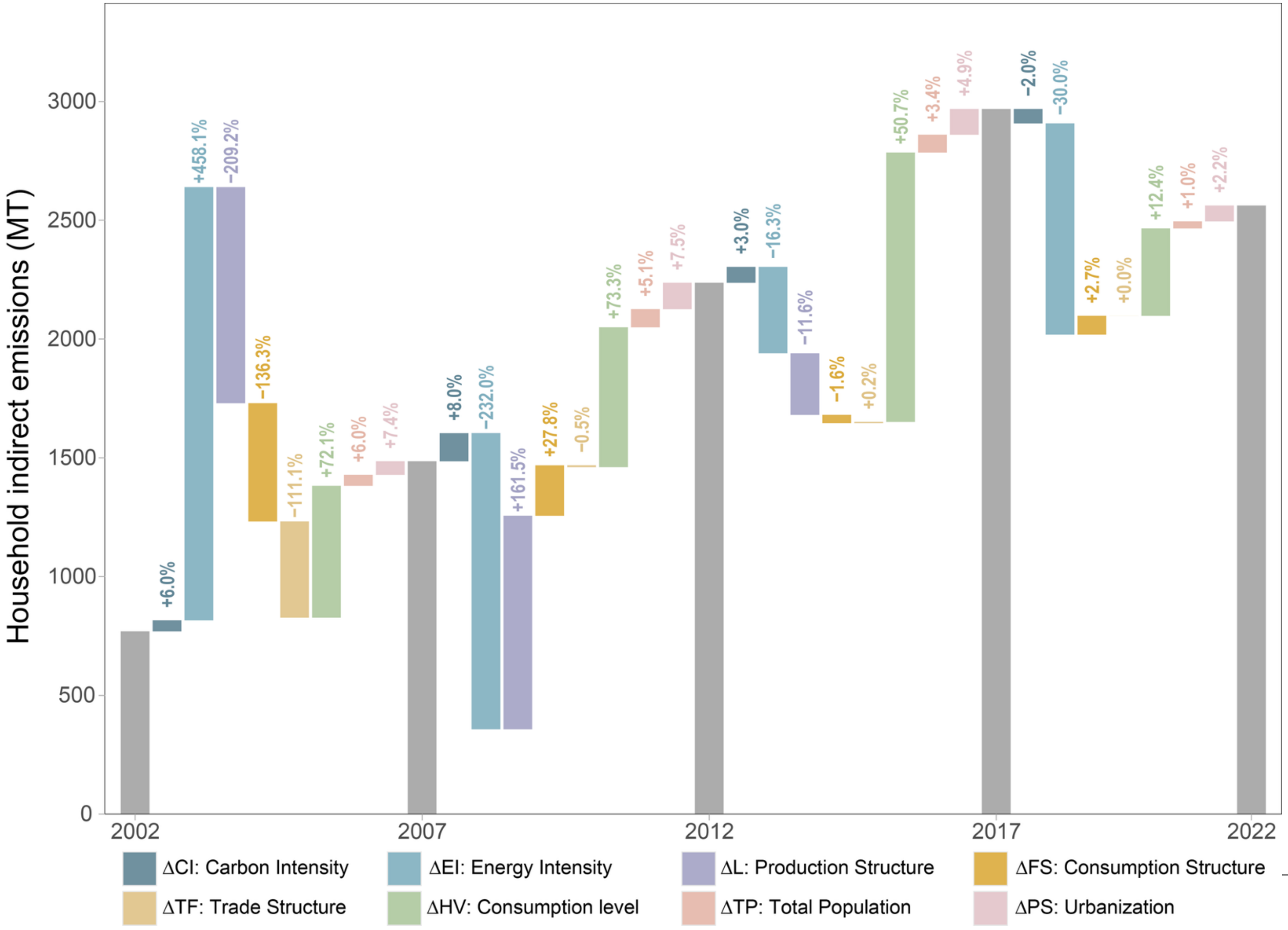
Provinces where rural oil emissions surpassed urban per capita oil emissions by 2022



- Natural gas replaced coal and LPG, especially in urban areas and gas-rich regions.
- Rural coal phase-out progressed in coastal and northern municipality regions, but lagged in the Northwest and Northeast.
- Rising oil use reflects increasing private motorization in both urban and rural households.

Results

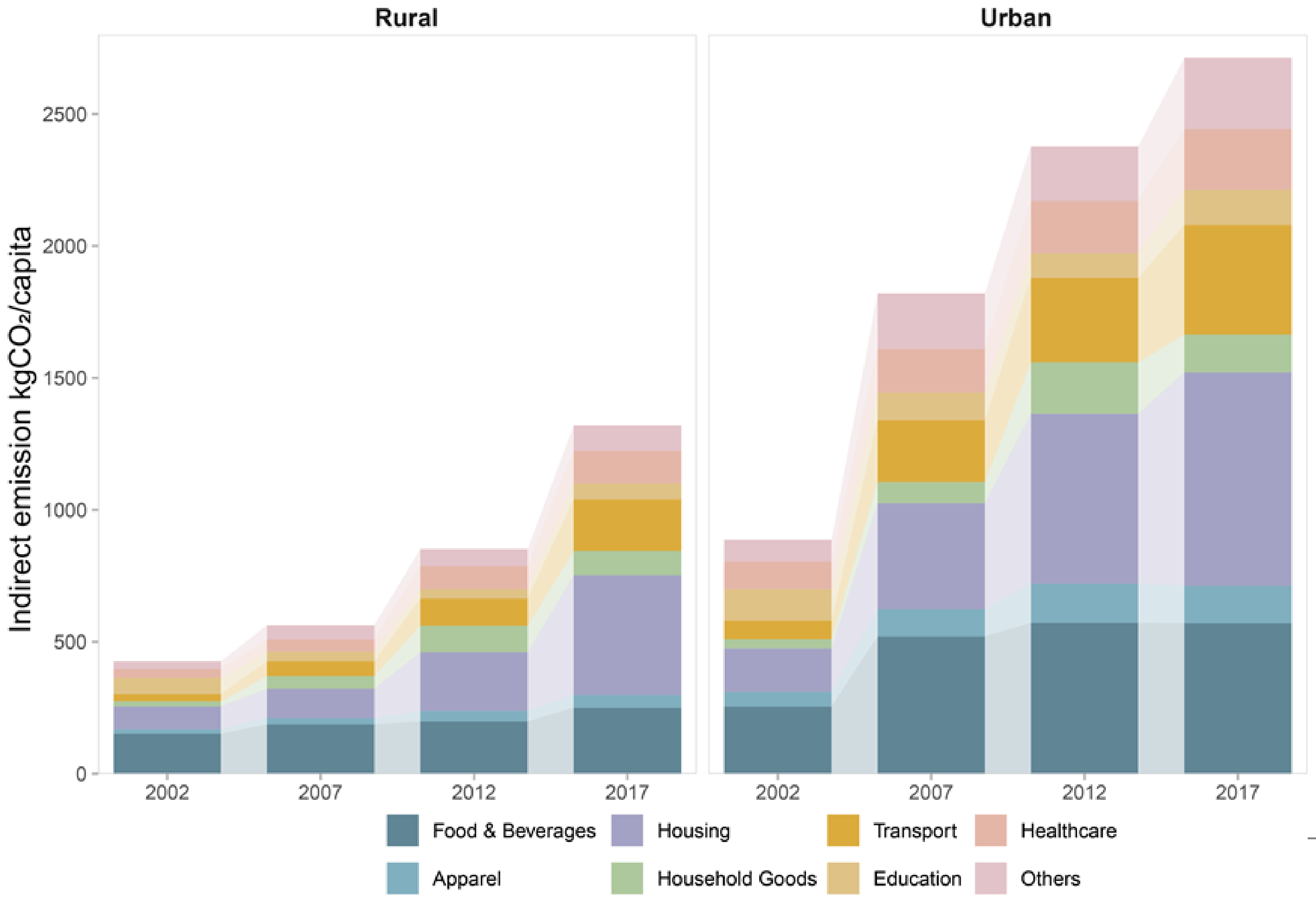
Finding 5: efficiency gains offset consumption growth



- 2002–2007: rapid increase driven by energy intensity and consumption growth after WTO accession.
- 2007–2012: energy efficiency became the leading mitigation factor under energy-intensity targets.
- 2012–2017: consumption level remained the main upward pressure; mitigation weakened.
- 2017–2022: indirect emissions declined, mainly due to improved carbon efficiency and slower consumption growth.

Results

Finding 6: the composition of household footprints has shifted toward energy-intensive services: from food to housing and transportation

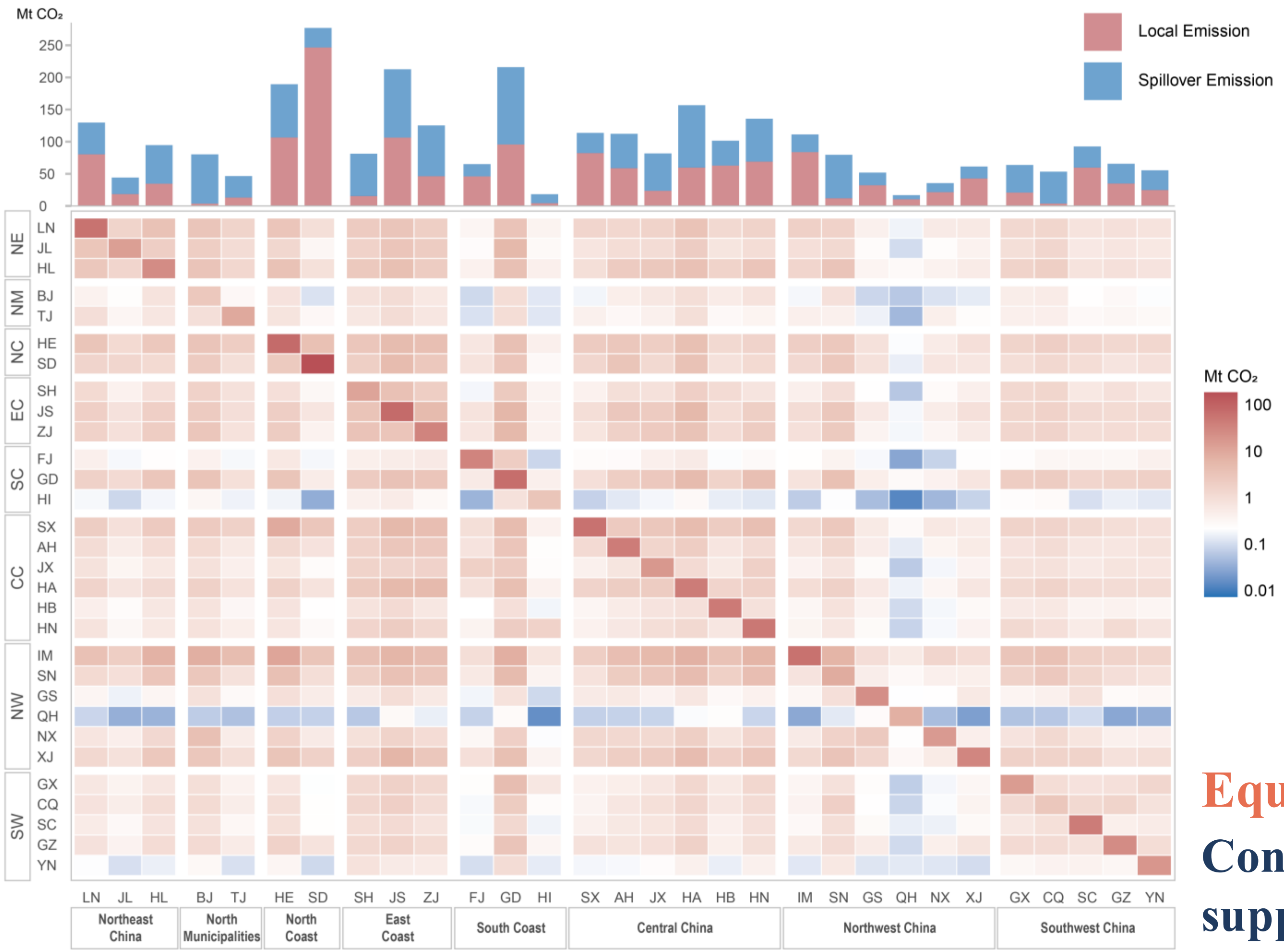


- Residence-related emissions surpassed food and became the largest indirect category.
- Electricity and heat supply account for around 80% of residence-related emissions since 2012.
- Transport emissions rose with private mobility and infrastructure expansion.
- Food's relative share nearly halved from 2002 to 2022.

The next frontier is not only diet or basic consumption, but buildings, electricity quality, heat systems, and transport demand.

Results

Finding 7: footprints are spatially decoupled: Affluent consumption regions increasingly outsource production-based emissions



- National outsourced share of indirect emissions rose from 41.6% in 2012 to 48.8% in 2017.
- Beijing, Chongqing, Shanghai, and Tianjin outsourced most of their indirect emissions in 2017.
- Shanxi, Inner Mongolia, and Shandong acted as major carbon-intensive production hubs.
- Production-consumption responsibility is therefore spatially uneven.

Equity issue

Consumption-based mitigation should be coordinated wit support for industrial decarbonization in supplying regio

Conclusions

- China's household carbon transition has entered a new phase — but the transition is uneven across households, sectors, and provinces.

Turning point

Total household emissions peaked between 2017 and 2022.

Uneven transition

Urban footprints stabilized; rural footprints continued to rise.

Structural shift

Housing and transport replaced food as the dominant indirect categories.

Spatial responsibility

Affluent regions outsource emissions to industrial inland provinces.

Policy implications

1. Accelerate rural clean energy transition

- Expand rural electrification, distributed renewables, clean heating, insulation, and EV charging infrastructure.

2. Strengthen urban demand-side strategies

- Use carbon labels, green building codes, low-carbon transport, incentives, and carbon pricing to shift behavior.

3. Coordinate interregional responsibility

- Develop fiscal transfers, embodied-carbon accounting, sectoral benchmarks, and supply-chain governance.

Policy principle: combine household behavior change with infrastructure, energy-system, and supply-chain transformation.

Limitations and future research

- **Current Limitations**
  - 2022 estimates rely on assumptions because a 2022 interprovincial MRIO table is not available.
  - Only fossil-fuel CO_2 from commercial energy is included.
  - Non-commercial biomass and non-CO_2 GHGs may be underestimated, especially for rural households.
  - Sectoral averages cannot reveal detailed product-level or household-level heterogeneity.
  - Imported embodied emissions are excluded due to insufficient provincial end-use data.
- **Next steps**
  - Integrate household microdata with MRIO-based footprints.
  - Extend the framework to broader GHG inventories.
  - Model imported embodied emissions explicitly.
  - Develop region-specific policy simulations for clean heating, EVs, building efficiency, and supply-chain responsibility.

Thank You

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