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Living in more sustainable cities with lower climate impact: a metabolic perspective

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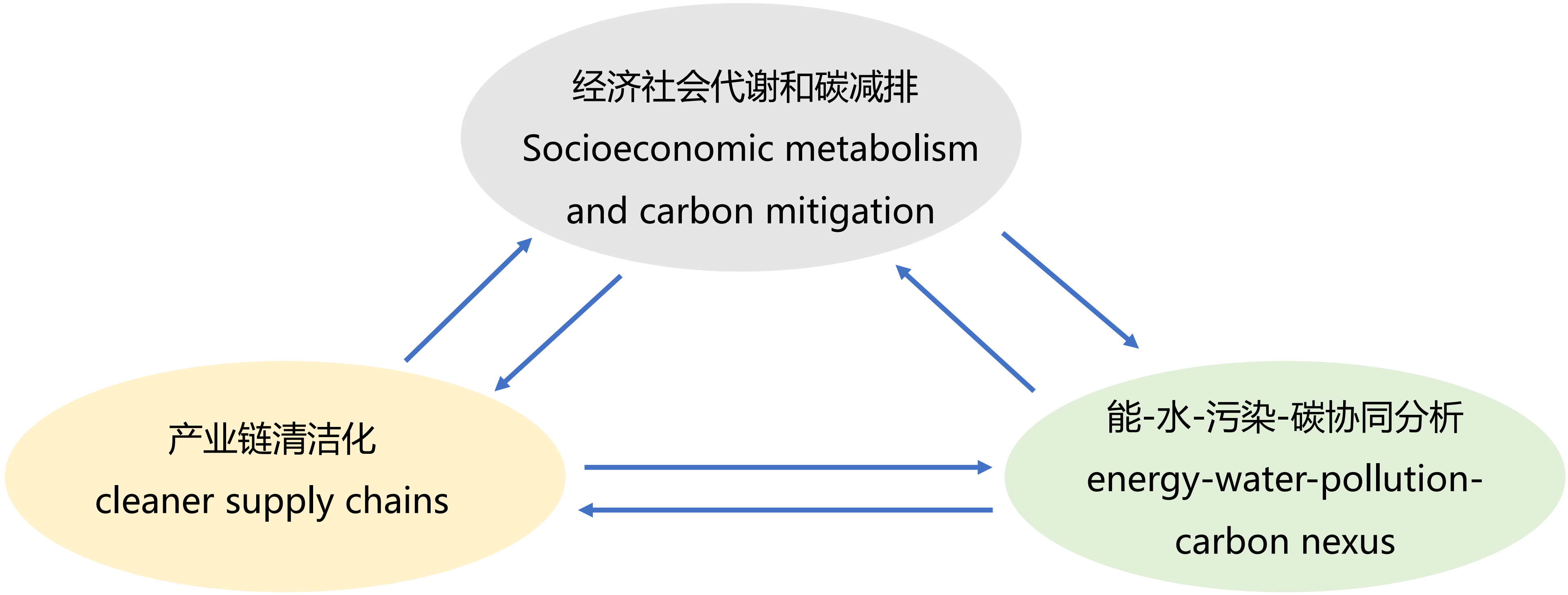
Main research interests

- **Applying systems ecology and ecological economics to realize sustainable development both at city and regional level.**



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Outline

01 Background & Questions

02 Urban carbon footprint

03 Physical and virtual carbon metabolism

04 Energy-water-carbon nexus

05 Prospects

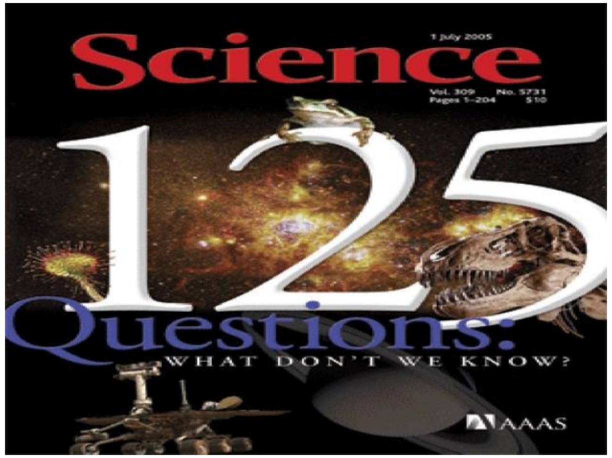
01

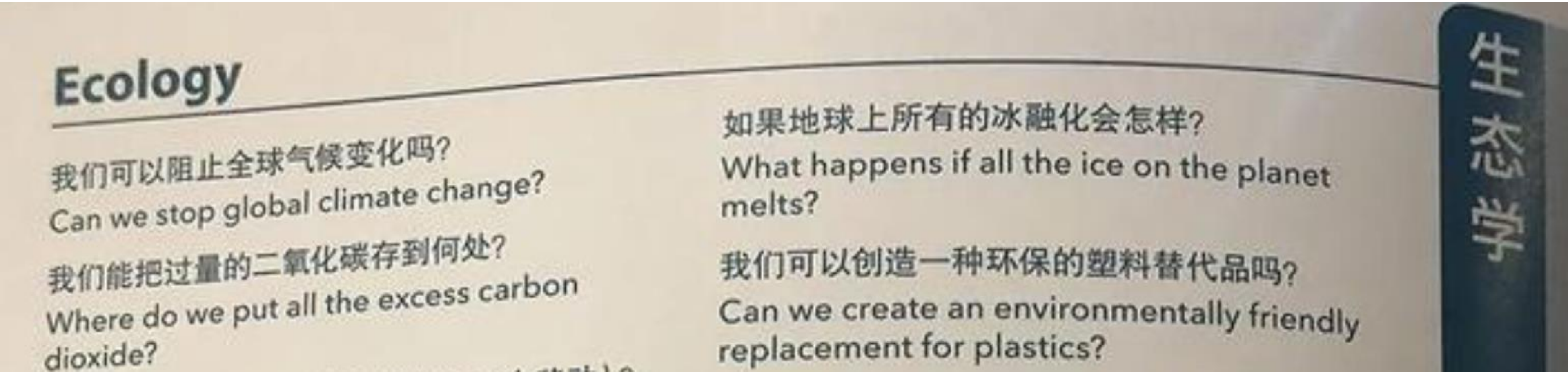
Background & Questions

1. Background & Questions

The crises of global climate change are the problems of the century

2015 Paris Agreement become effective which aims to hold global warming to levels well below 2°C and even 1.5°C.




Ecology

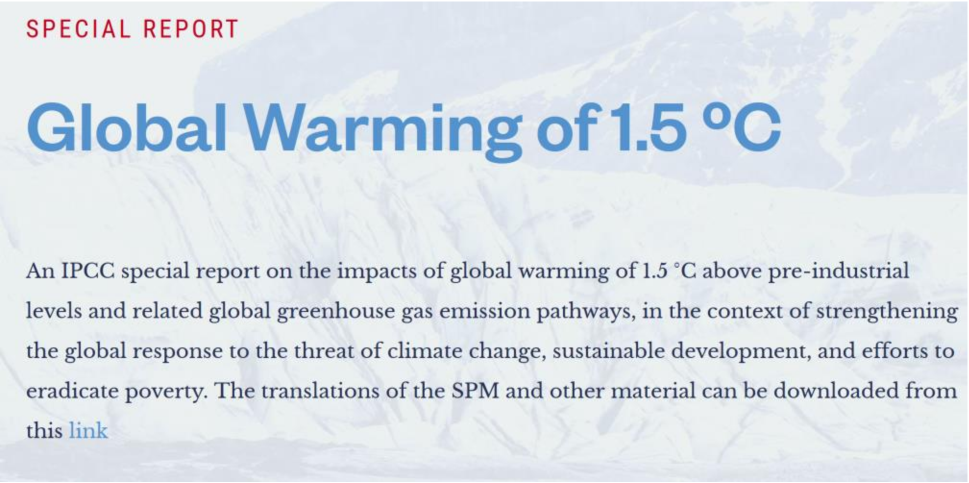
生态学

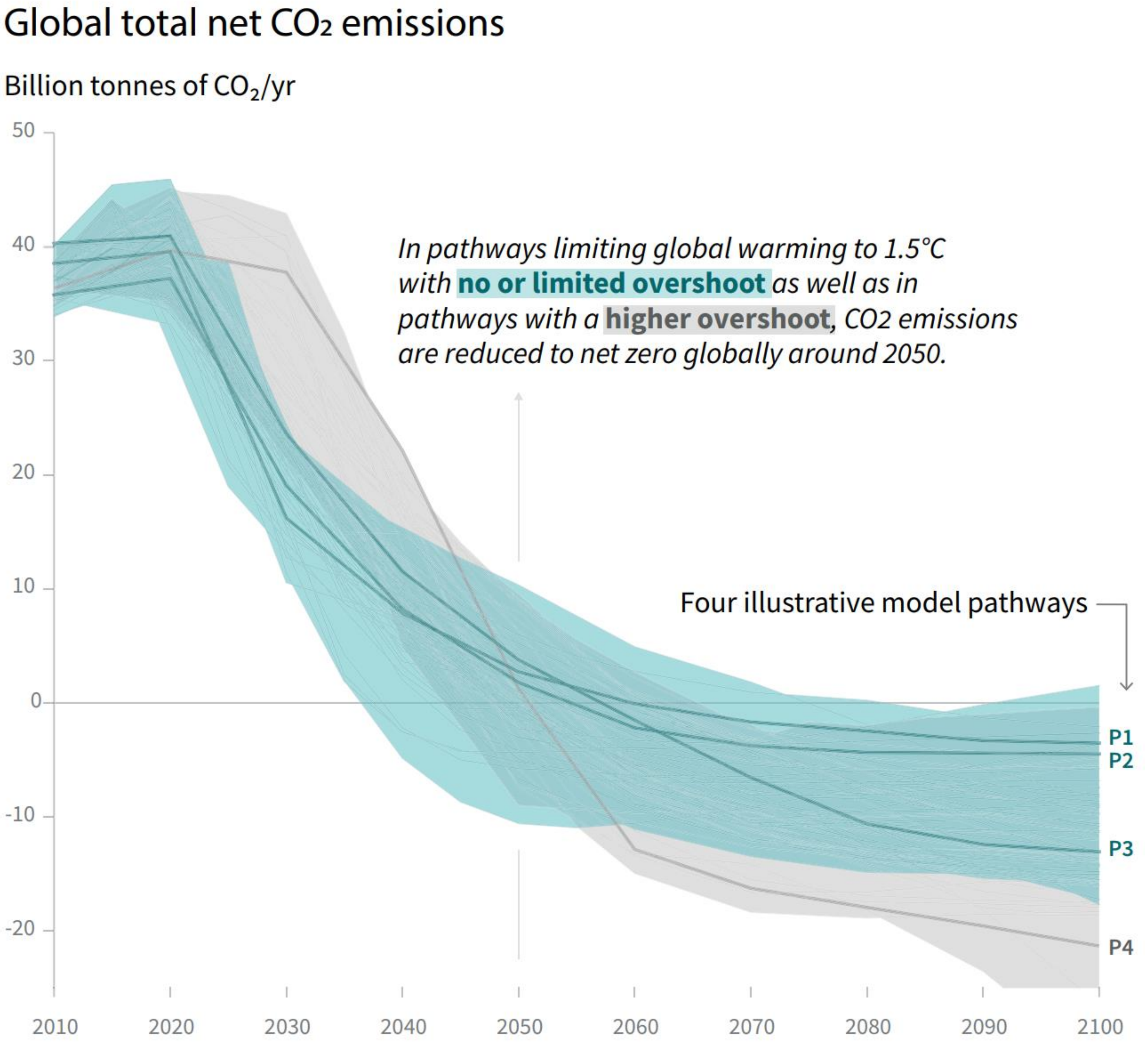
我们可以阻止全球气候变化吗?
Can we stop global climate change?

我们能把过量的二氧化碳存到何处?
Where do we put all the excess carbon dioxide?

如果地球上所有的冰融化会怎样?
What happens if all the ice on the planet melts?

我们可以创造一种环保的塑料替代品吗?
Can we create an environmentally friendly replacement for plastics?





In a 2018 special report, the Intergovernmental Panel on Climate Change said that countries must bring carbon dioxide emissions to **"net zero" by 2050** to keep global warming to within 1.5 °C of pre-industrial levels.

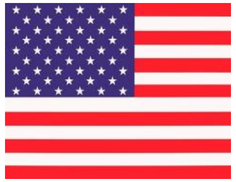
1. Background & Questions

~50 nations realized peak of CO_2 emissions

European Union achieved it in the late 1990s.

Brazil achieved

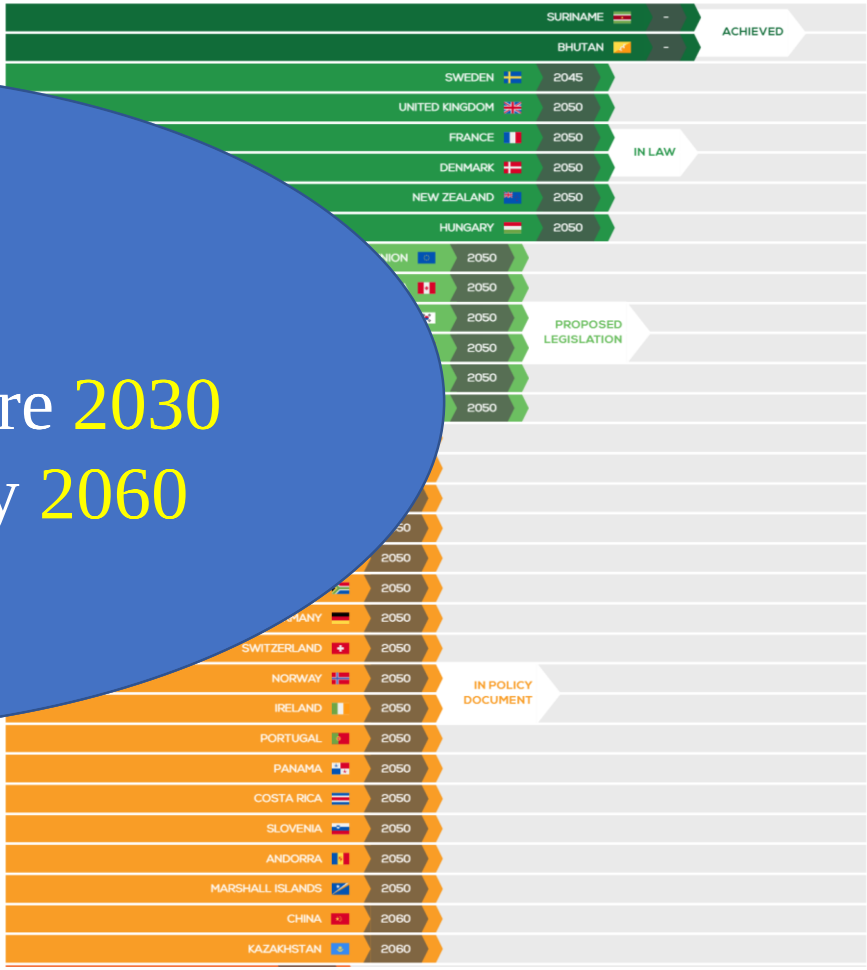
Australia a



America achieved it

Canada achieved it in 2007.

>30 nations formally delivered target time of carbon neutral



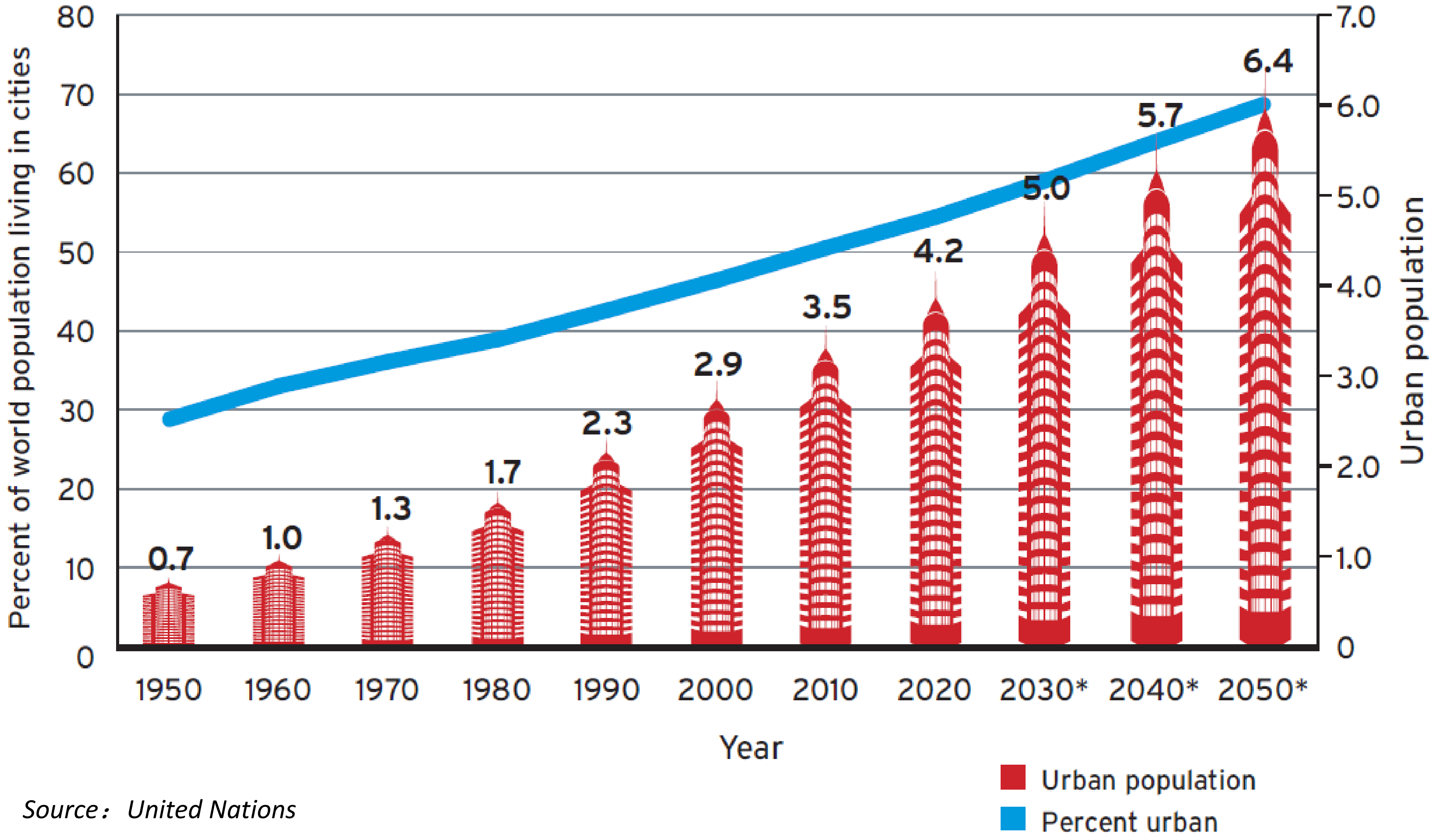
China

Carbon peaking before 2030

Carbon neutrality by 2060

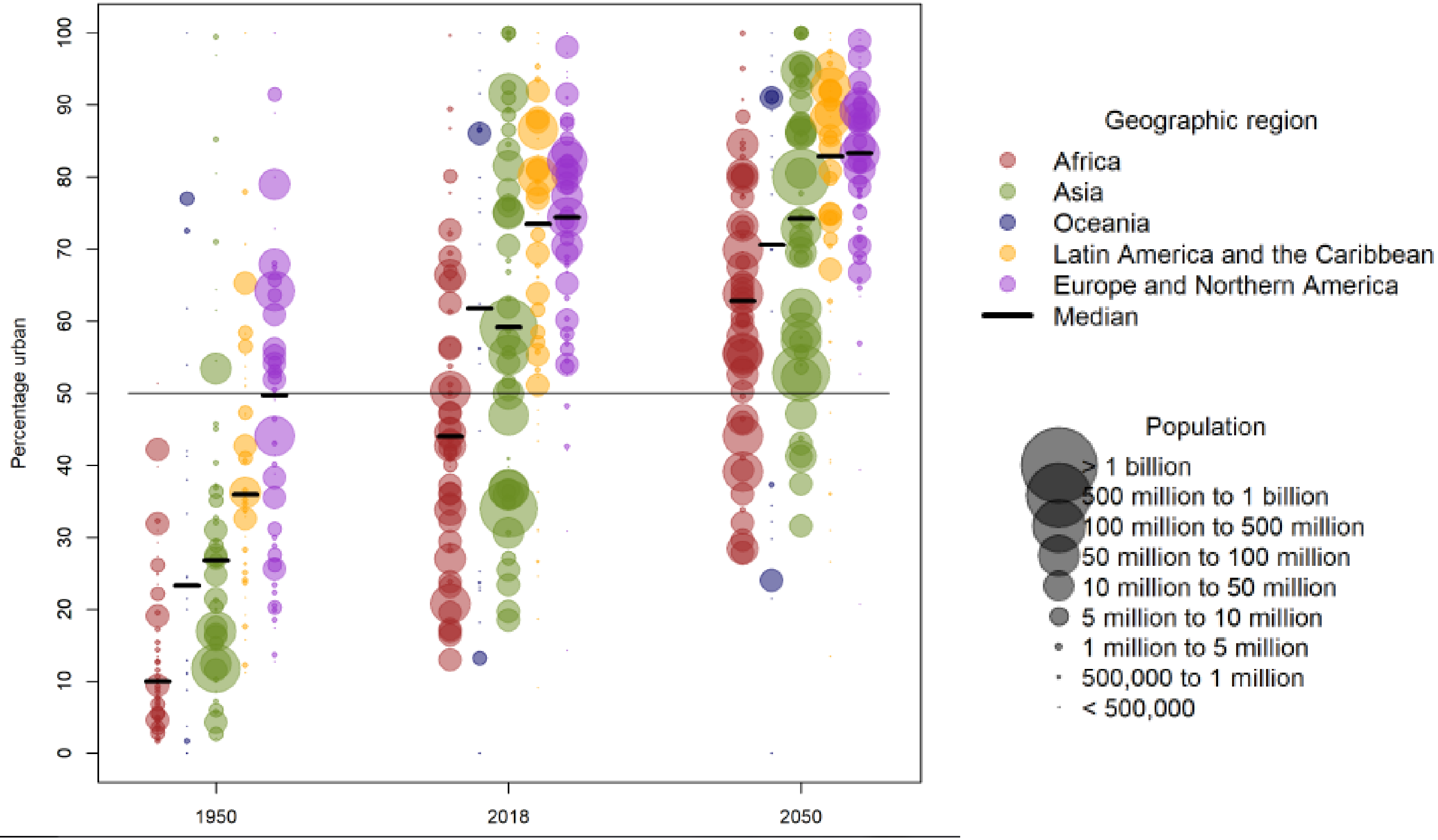
Realizing carbon neutral still has a long way to go.

Accelerating global urbanization



Source： United Nations

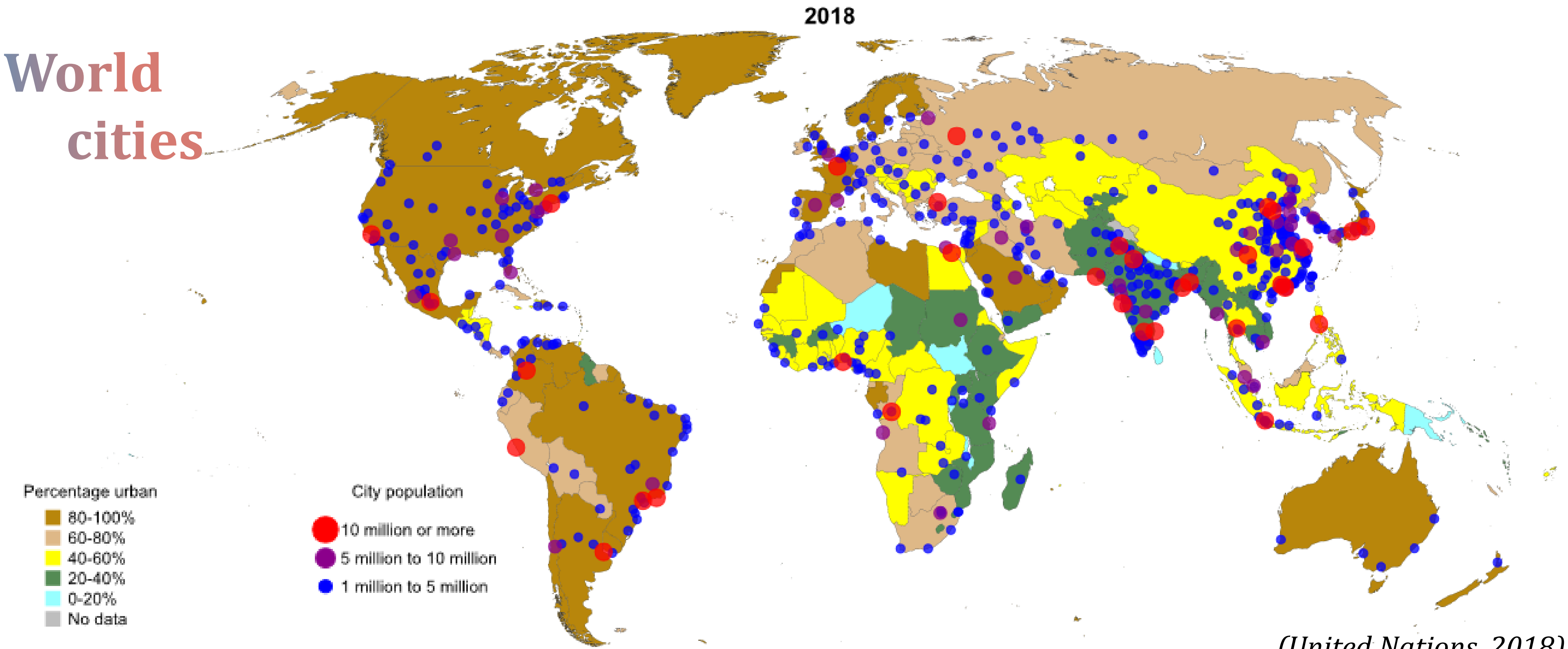
Proportion of urban population in the country



United Nations. 2019. World urbanization prospect 2018.

1. Background & Questions

World cities



(United Nations, 2018)

- **55%** of the world's population now resides in cities and projected to be **68%** by 2050 (United Nations, 2018).
- Over **70%** of carbon emissions are from or related to cities (IEA, 2008).
- **1.5 ℃** target requires a major cut of carbon emissions associated with urban activities.

1. Background & Questions

The Duality of Urban development（双重性）

问题 Problem

快速城市化带来的全球性环境排放影响

机会 Opportunities

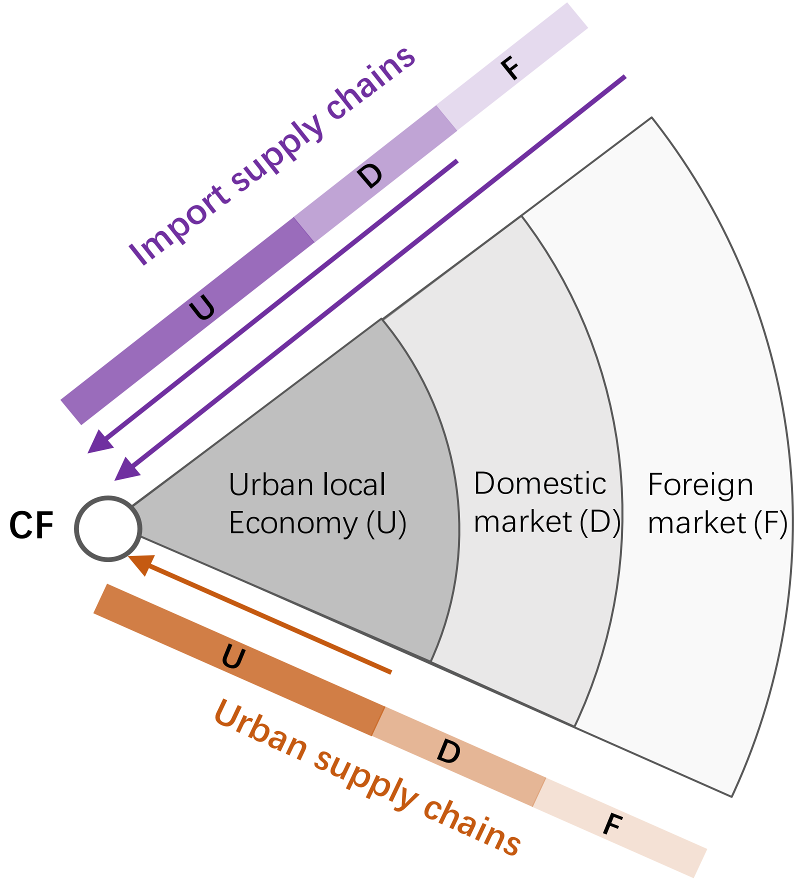
城市的技术引擎可带动全球低碳零碳经济发展

02

Urban carbon footprint

Current CF approaches portray different ranges of urban activities

from territorial to whole supply chain accounting…



"Global Protocol for Community-Scale GHG Emissions"

Local Governments for Sustainability (ICLEI)
World Resources Institute (WRI)
C40 Cities Climate Leadership Group

scope	definition
Scope 1	GHG from sources located within the city boundary
Scope 2	GHG occurring as a consequence of the use of grid-supplied electricity, heat, steam and/or cooling within the city boundary
Scope 3	All other GHG that occur outside the city boundary as a result of activities taking place within the city boundary

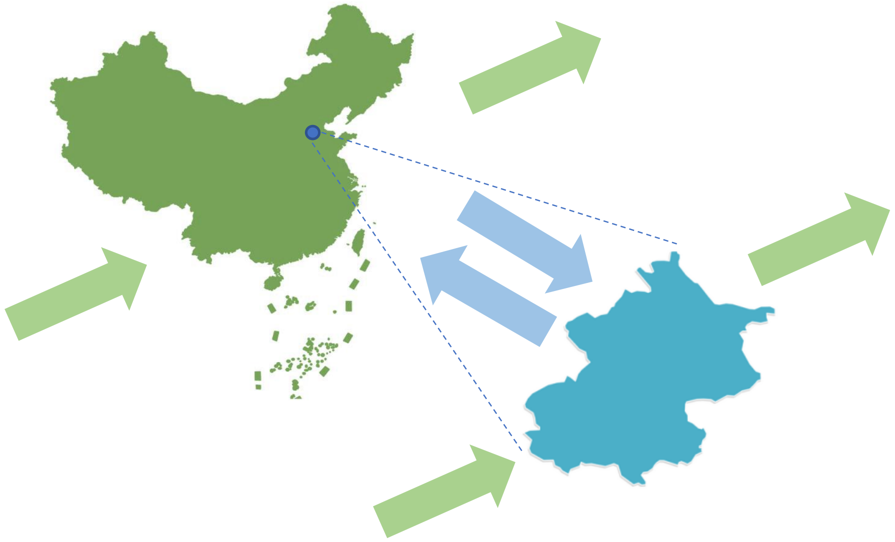
2.2 Significance and objective

National-level accounting

- ❖ Widely discussed
- ❖ International trade
- ❖ Ready-to-use (MR)IO table
- ❖ Well-developed satellite data

City-level accounting

- ❖ Less studied
- ❖ Nested trade network
- ❖ Scarce urban IO tables
- ❖ Limited satellite data
- ❖ Ambiguous system boundaries ?



Objective

- Searching for proper city-scale carbon footprint indicators for climate mitigation
- Delivering the impacts and responsibilities of urban economy and its trade partners

Questions focused

What are the **system boundaries** of various carbon footprints and whether is there a double counting issue that follows?

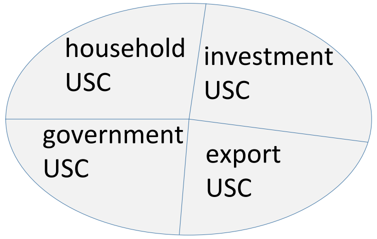
What is role of decoupling urban **infrastructure and consumption growth** from carbon emissions given their contribution to total carbon flow paths?

How **sensitive** are various accounts of carbon in response to regulatory policies?

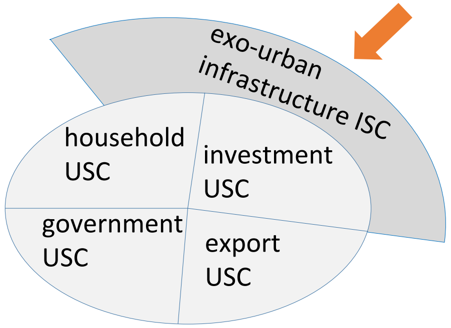
2.3 Methodology

Accounting system boundaries of five types of carbon footprints

Territorial carbon emission (TCE)

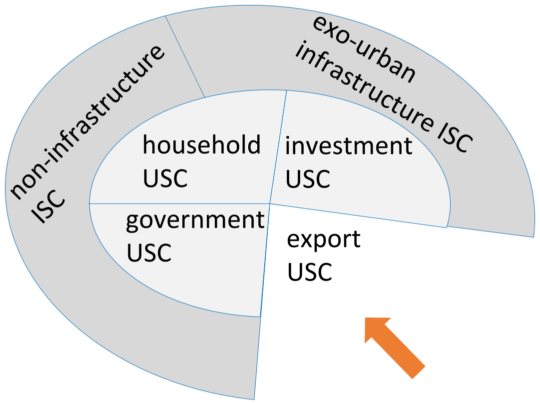


Community-wide infrastructure carbon footprint (CIF)

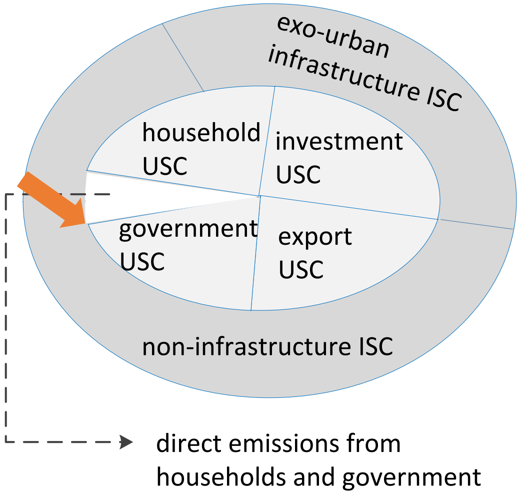


- ISC: carbon emission from import supply chains
- USC: carbon from urban supply chains

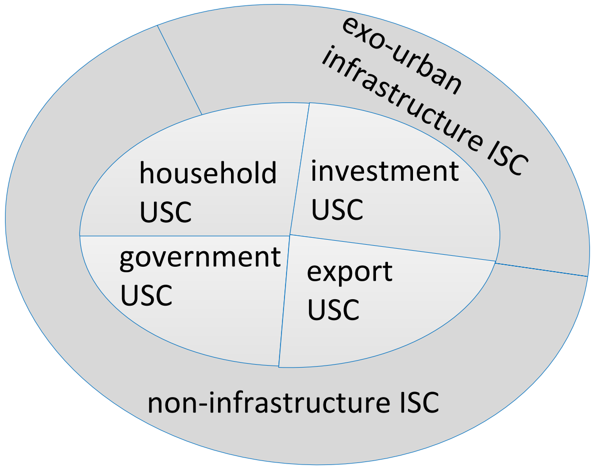
Consumption-based carbon footprint (CBF)



Wide production carbon footprint (WPCF)



Full-scope carbon footprint (FSCF)



2.3 Methodology

Footprint type	Coverage of scopes	Main implication	*Possible double counting?*
Territorial carbon emission (TCE)	Scope 1 emissions	Impact of local urban energy use and industrial processes on global climate change	No double counting
Community-wide infrastructure carbon footprint (CIF)	Scope 1 + Scope 2 + infrastructure-related Scope 3 emissions	Impact of key urban infrastructure on global climate change	Footprints of cities cannot be simply added up
Consumption-based carbon footprint (CBF)	Scope 1 + Scope 2 + Scope 3 emissions driven by final consumption (export excluded)	Impact of urban consumption on global climate change	No double counting
Wide production carbon footprint (WPCF)	Scope 1 (direct emissions from households excluded) + Scope 2 + Scope 3 emissions	Impact of production of urban products on global climate change	Footprints of cities cannot be simply added up
Full-scope carbon footprint (FSCF)	Scope 1 + Scope 2 + Scope 3 emissions	Impact of urban production and consumption on global climate change	Footprints of cities cannot be simply added up

2.3 Methodology

Urban carbon footprints accounting

$$TCF=\sum_{i=1}\sum_{j=1}\text{activity}(i,j)\times\text{emission coefficient}(i,j)$$

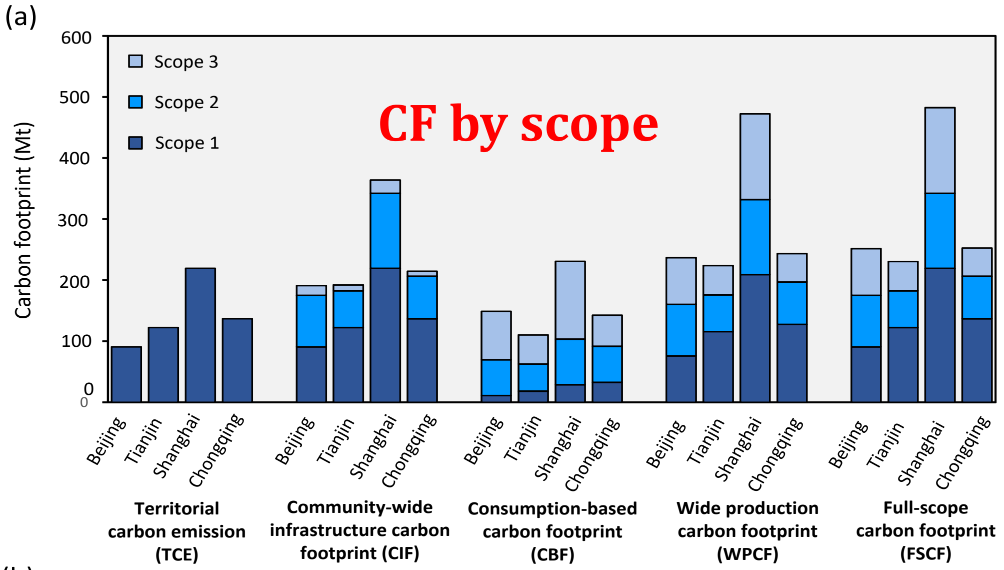
$$CIF=k(I-A)^{-1}y^{infra\text{-}im}+TCF$$

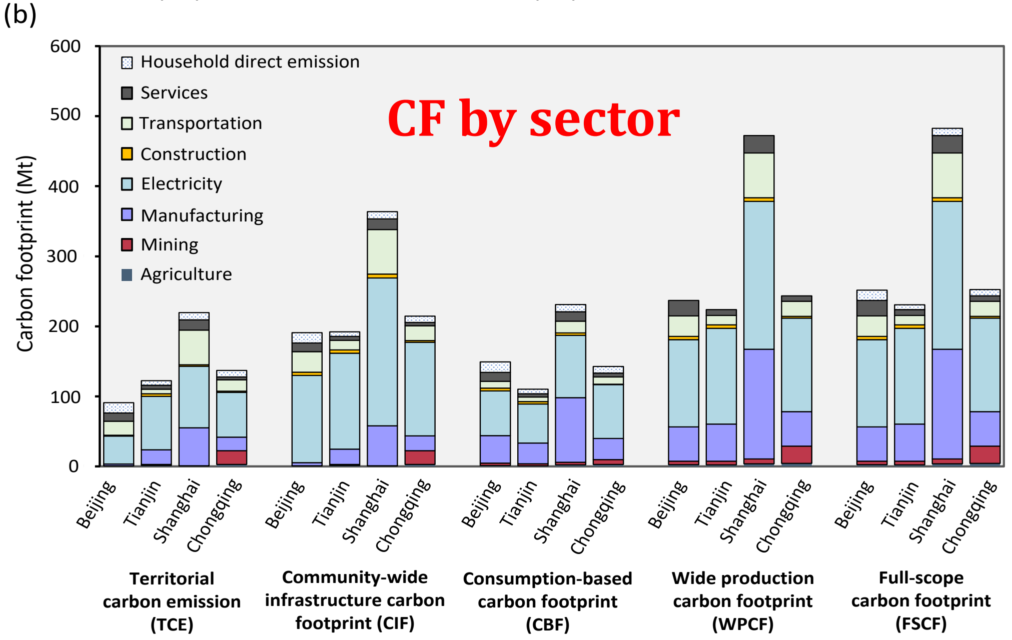
$$CBF=k(I-A)^{-1}y^{fc}$$

$$WPCF=k(I-A)^{-1}(y^{fc}+y^{ex})$$

$$FSCF=k(I-A)^{-1}(y^{fc}+y^{ex})+C^{hg}$$

2.4.1 Results: carbon footprints comparison





The CIFs surpassed TCEs: 70-144 Mt
Infrastructure imports: 57-110%
Non-infrastructure imports: 25-51%

CIF: scope 2 major
CBF:
- Half is scope 3
- BJ, TJ, SH > CQ

WPCF:
- 50% scope 1
- 50% (scope 2 + scope 3)
- 32% from scope 3 in BJ

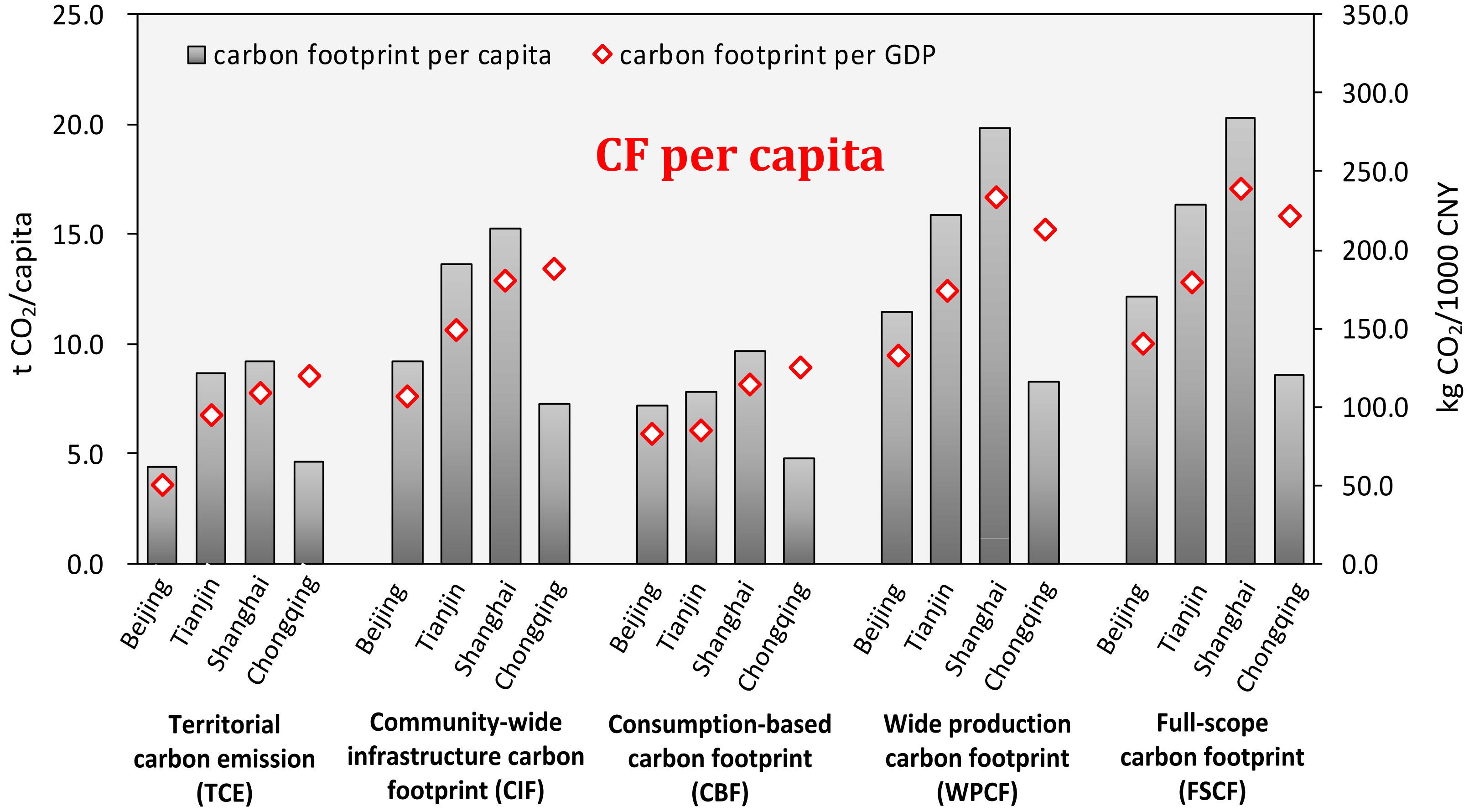
Electricity:
- 40-60% of total TCE
- 58-71% of total CIF
- 44-59% of FSCF in all four cities

Manufacture:
- major sector of CBF, WPCF, FSCF

Transportation:
- 18-23% of TCE & CIF for BJ & SH

Household:
- 16% of TCE for BJ
- 6-10% of CBF

2.4.1 Results: carbon footprints comparison



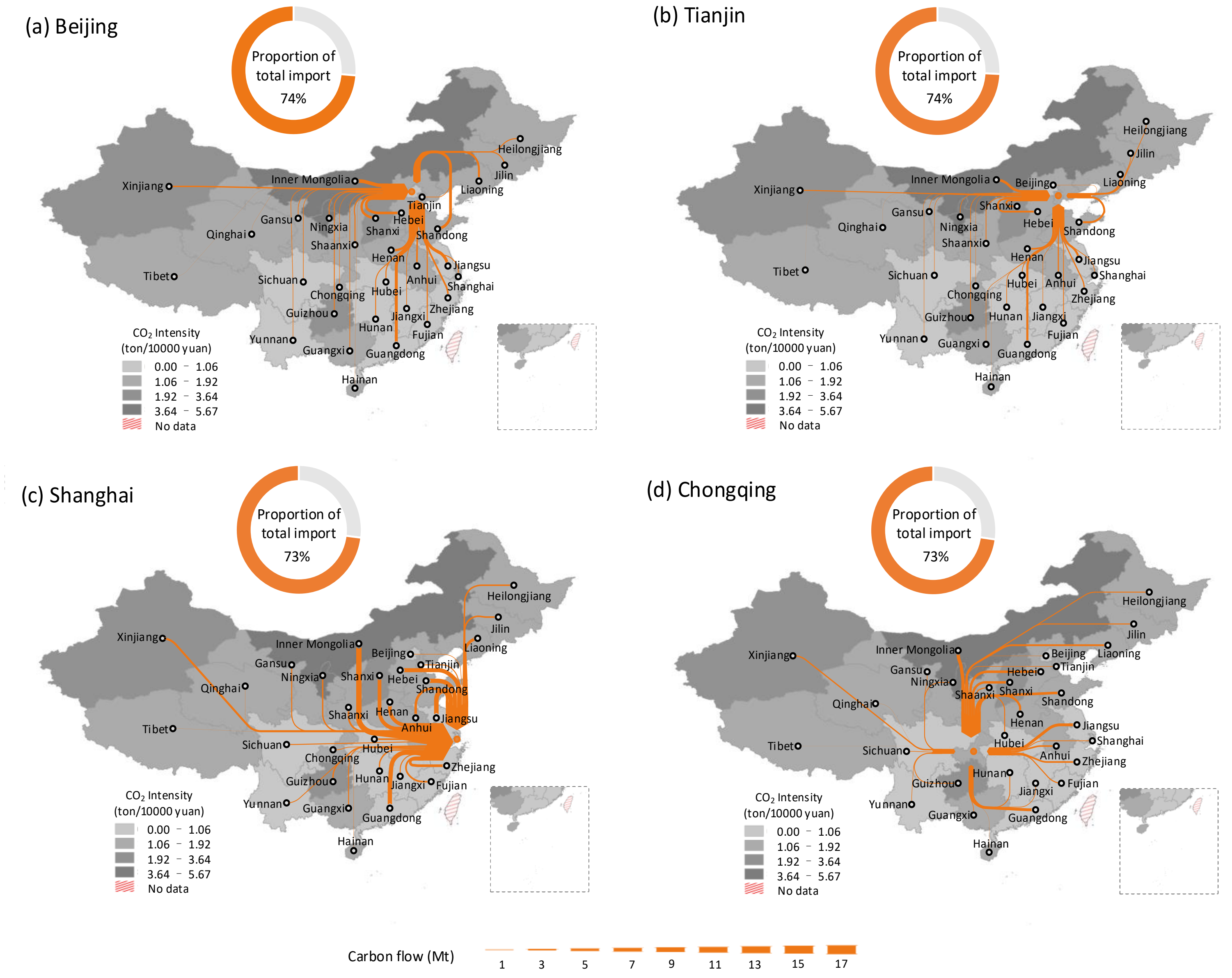
Per capita footprint:

- SH > TJ > BJ/ CQ in every measurement.
- 11.7 t/capita for FSCF, 8.0 t/capita for CIF.
- The CBF of Chongqing (4.8 t/capita) is only half of that of Shanghai

Carbon intensity:

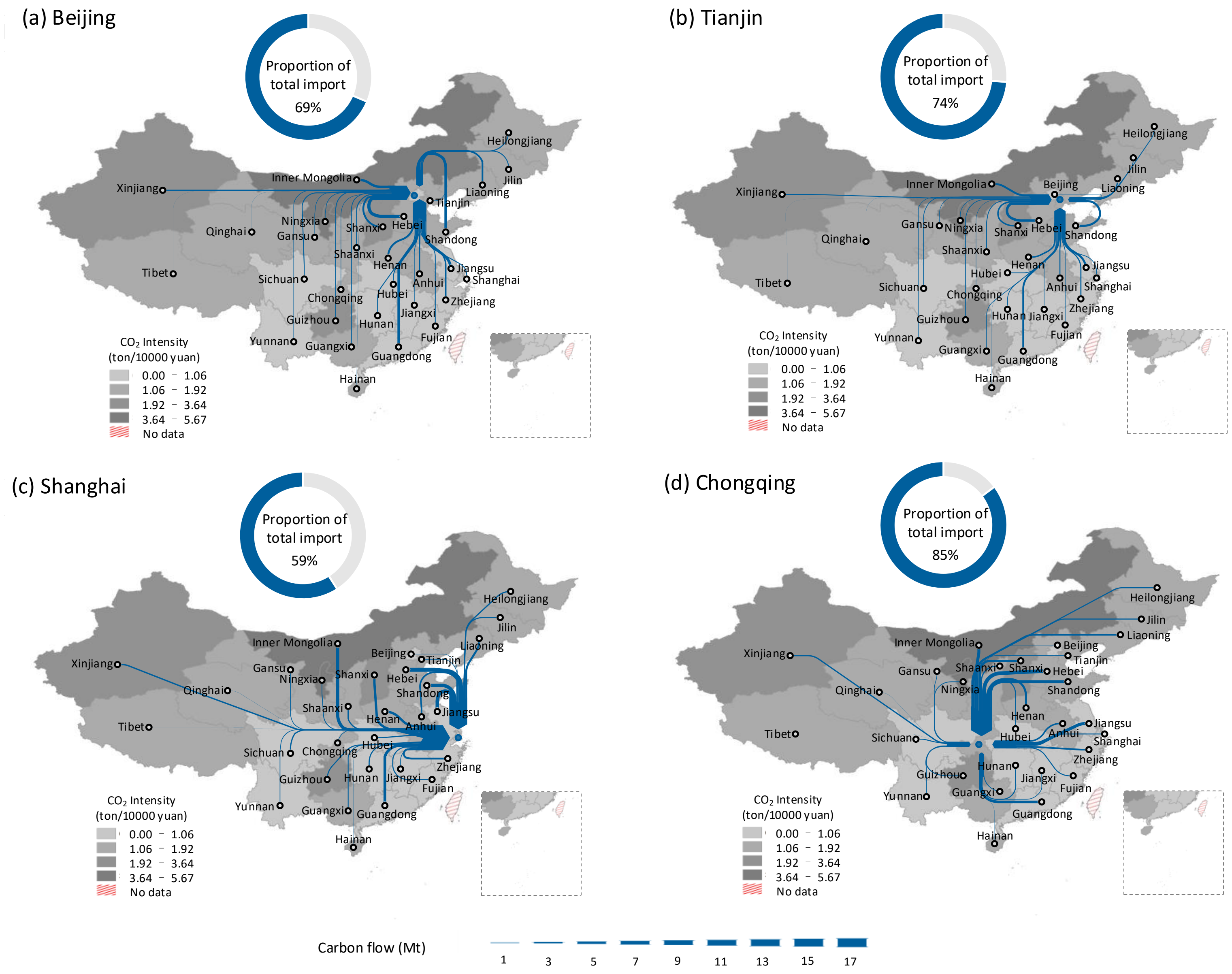
- CQ > SH > TJ > BJ in TCE, CIF and CBF
- CQ is 1.8 times higher than BJ in CIF intensity
- SH > CQ in WPCF

2.4.3 Transfer of carbon emission driven by infrastructure-related import



- over 70% of the total import
- Inner Mongolia 10%
- BJ & TJ import from north and northeast China
- SH from Jiangsu

2.4.3 Transfer of carbon emission driven by consumption-related import



● CBF-related import: CQ (85%), SH (58%)

Carbon

● externalized:

Hebei (9%), Jiangsu (8%),

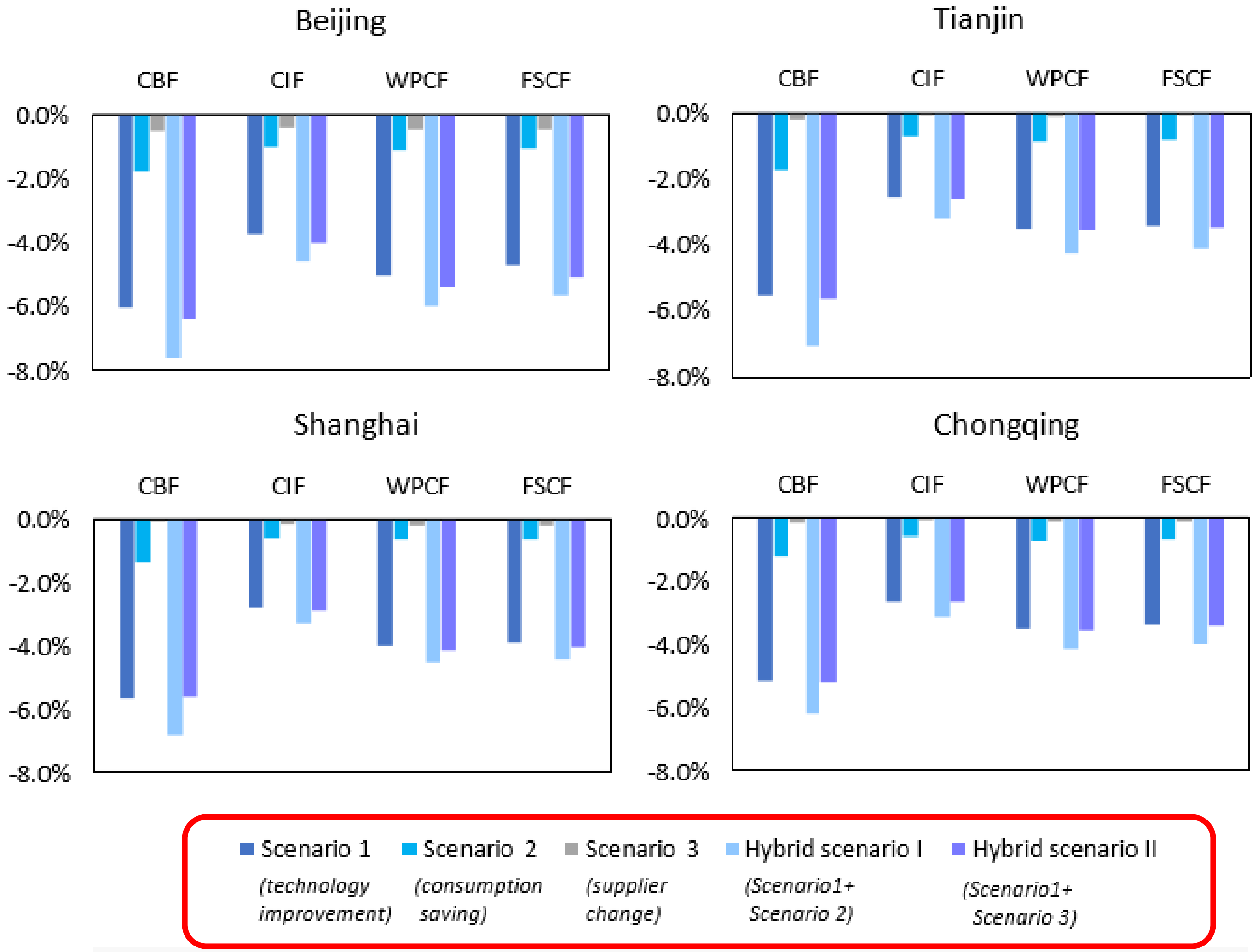
Guangdong and Inner Mongolia (7%)

2.4.4 Results: scenario analysis

Scenarios	Change in carbon intensities (k)	Change in urban demand (y)
Scenario 1 (technology improvement)	Carbon intensities of five regions with the largest contribution to the cities' carbon imports are reduced by **20%**	Business as usual
Scenario 2 (reduced consumption)	Business as usual	Final demand of the megacities in the five largest contributing regions (suppliers) is reduced by **20%**
Scenario 3 (supplier change)	Business as usual	**20%** of final demand of the megacities in the five largest contributing regions (suppliers) is replaced by five other regions having the lowest carbon intensities
Hybrid scenario I (Scenario 1+ Scenario 2)	Carbon intensities of five regions having the largest carbon import are reduced by **20%**	Final demand of the megacities in the five largest contributing regions (suppliers) is reduced by **20%**
Hybrid scenario II (Scenario 1+ Scenario 3)	Carbon intensities of five regions having the largest carbon import are reduced by **20%**	**20%** of final demand of the megacities in the five largest contributing regions (suppliers) is replaced by five other regions having the lowest carbon intensities

2.4.4 Results: scenario analysis

Changes in carbon footprints of four megacities under policy scenarios compared with 2012



CIF: Community-wide infrastructure carbon footprint
CBF: Consumption-based carbon footprint
WPCF: Wide production carbon footprint
FSCF: Full-scope carbon footprint

- Hybrid scenario I was superior to all
- other scenarios
- Scenario 1 > 2 > 3

- FSCFs were most reduced:
- (1.5 times of CBF reduced in SH)
- CBF were most sensitive:

  CBF: 5.1%-6.0%

  CIF: 2.6%-3.7%

Simply switching supplier is not a solution!

2.5 Conclusions

- Infrastructure-related import adds 57%–110% to the territorial carbon emission for the four cities (dominated by Scope 2 emissions, i.e. electricity import)
- The per capita "footprint gap" among cities varies notably with different accounting boundaries. The biggest inter-city gap was found to be 11.7 t/capita in full-scope carbon footprint (i.e. Scope 1+2+3).
- Tracking consumption-based or tracking infrastructure-based carbon flow are different but both important strategy when designing mitigation policies aligned with city typologies and developmental stages.
- Integrating the supply and demand policies would be a better option to push the limit of deep urban decarbonization.

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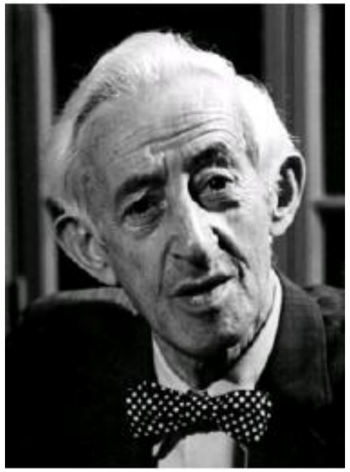
03 Physical and virtual carbon metabolism

Carbon metabolism of urban system—Methodology

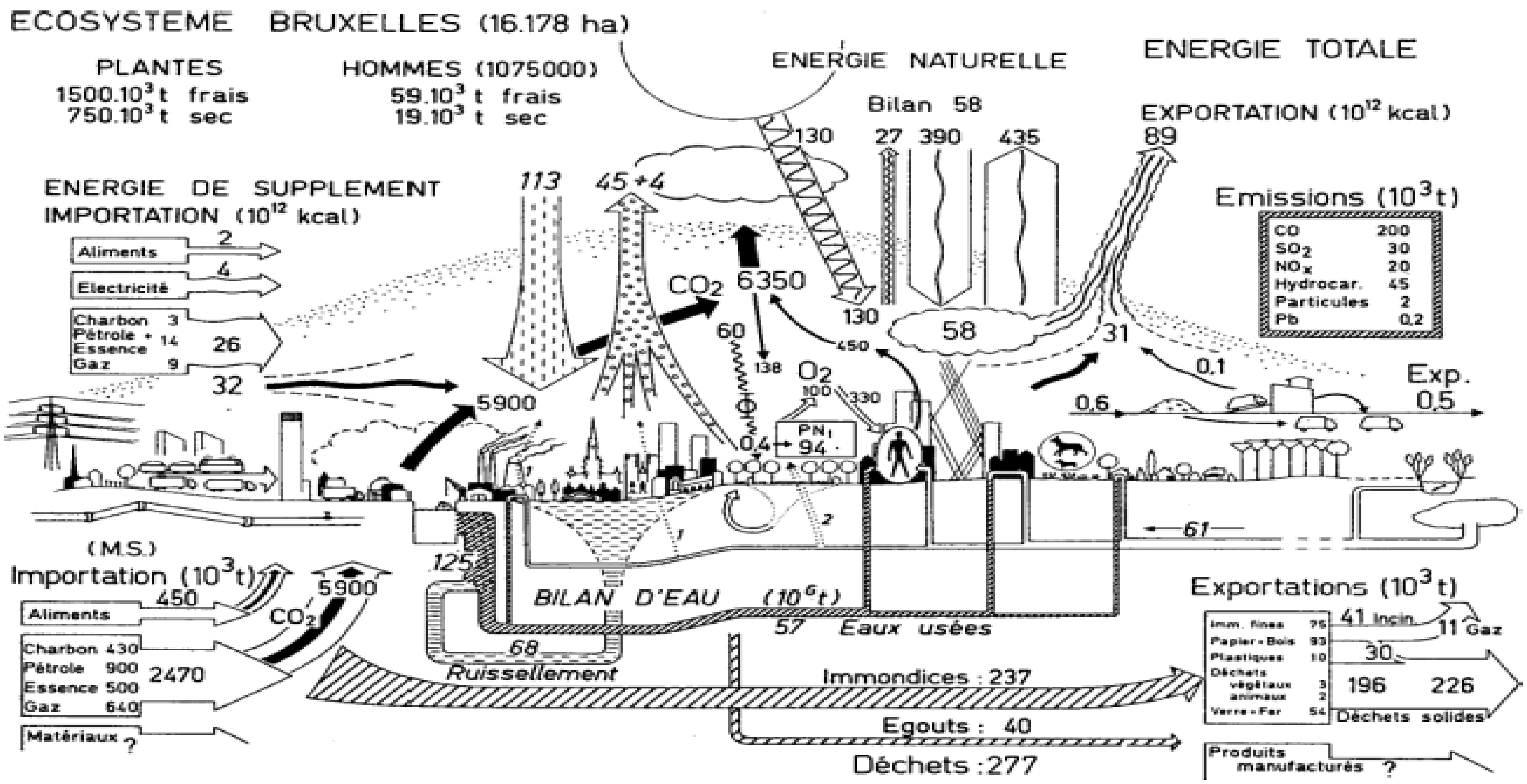
The bio-inspired concept "***metabolism***" in urban ecosystem: Abel Wolman (Scientific American, 1995.)

Ecologists and urbanists have been seeking revelations and pragmatic methods of treating cities as metabolic organisms for appraising their ***structure and function embedded in the metabolism processes*** in various regions around the globe.



"In the U.S. today attention is focused on shortages of water and the pollution of water and air. There is plenty of water, but supplying it requires foresight……"

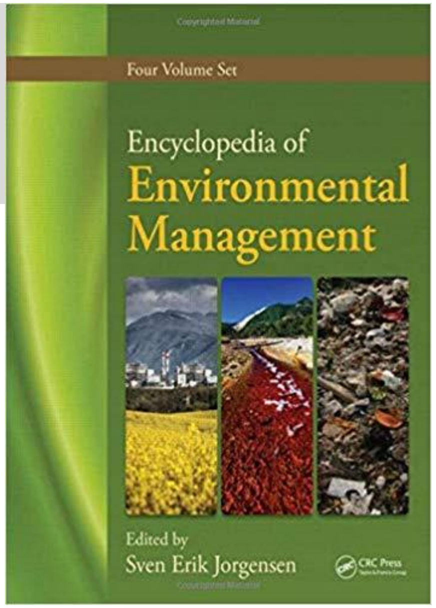
Urban metabolism: material and energy flux



Brussels, Belgium early 1970s. Source:Duvigneaud and Denayeyer-De Smet, 1977

3.1 Background & Basic scientific question

Encyclopedia of Environmental Management DOI: 10.1081/E-EEM-120053897



Sustainable Urban Metabolism

Shaoqing Chen and Bin Chen
School of Environment, Beijing Normal University, Beijing, China

Abstract

Cities' performance is key to a more sustainable society. The complexity of urban sustainability seeks for strong methodologies in assessing production and consumption activities of cities. In view of a bioinspired metaphor "metabolism", a city can be seen as an organism that intakes, digests, and releases materials and simultaneously exchanges energy with the external environment. Urban metabolism (UM) has become a methodological framework in which the analyses of all the energy and material flows associated with the production and consumption activities in cities are encapsulated. A range of approaches of measuring the intensity and structure of UM are evaluated for their applications and insights for urban sustainability. Urban metabolic data and case studies are also overviewed. Last, but not the least, future prospects regarding research development of UM are discussed for their potential application in urban energy and infrastructure planning.

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Material Flow Analysis、Urban Metabolism and Carbon Reduction

nature COMMUNICATIONS

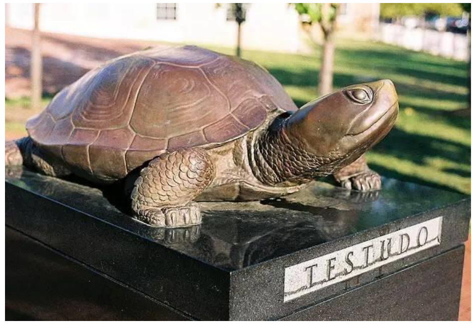
ARTICLE

https://doi.org/10.1038/s41467-019-13757-3 OPEN

Physical and virtual carbon metabolism of global cities

Shaoqing Chen[1,2,3], Bin Chen[1*], Kuishuang Feng[4], Zhu Liu[5*], Neil Fromer[6], Xianchun Tan[7], Ahmed Alsaedi[8], Tasawar Hayat[8,9], Helga Weisz[10,11], Hans Joachim Schellnhuber[10] & Klaus Hubacek[12,13,14*]

Urban activities have profound and lasting effects on the global carbon balance. Here we develop a consistent metabolic approach that combines two complementary carbon accounts, the physical carbon balance and the fossil fuel-derived gaseous carbon footprint, to track carbon coming into, being added to urban stocks, and eventually leaving the city. We find that over 88% of the physical carbon in 16 global cities is imported from outside their urban boundaries, and this outsourcing of carbon is notably amplified by virtual emissions from upstream activities that contribute 33–68% to their total carbon inflows. While 13–33% of the carbon appropriated by cities is immediately combusted and released as CO_2, between 8 and 24% is stored in durable household goods or becomes part of other urban stocks. Inventorying carbon consumed and stored for urban metabolism should be given more credit for the role it can play in stabilizing future global climate.

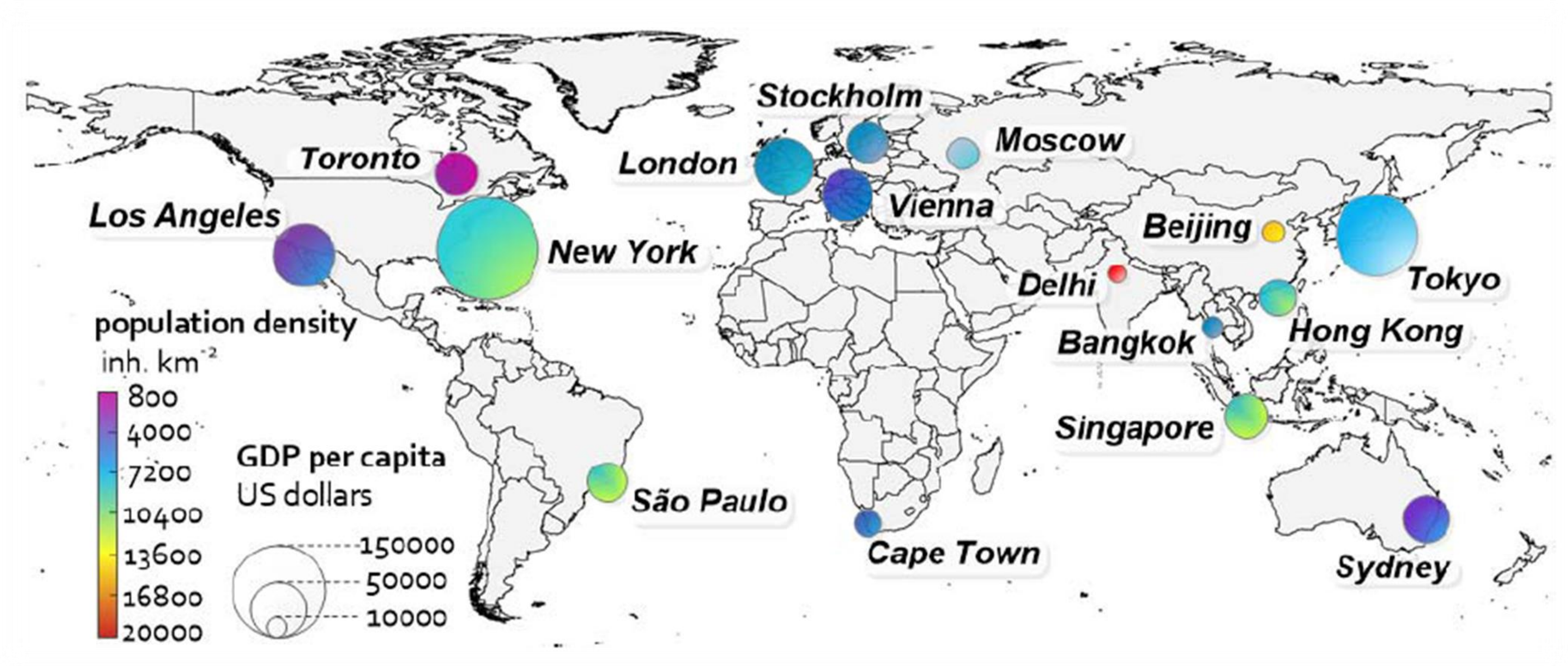


What is the past and present life of carbon in urban society?

Source

Activity

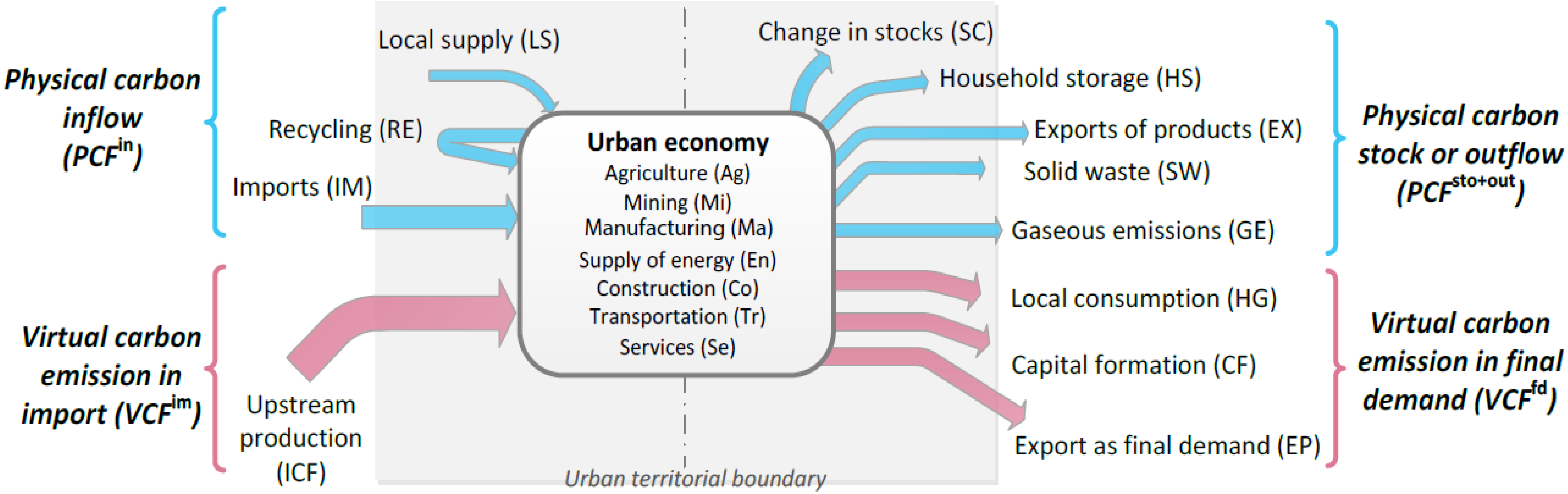
Fate



Chen, S.Q., Chen, B., Feng, K., Liu, Z., ……Klaus Hubacek (2020). Physical and virtual carbon metabolism of global cities. ***Nature Communications***.

Research Framework

Physical carbon footprint + virtual carbon footprint = More complete analysis of urban carbon metabolism

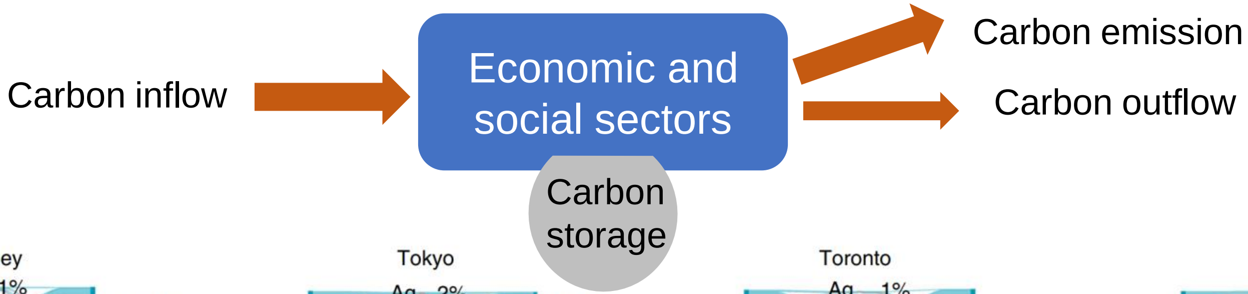


Questions:

- 碳排放到底在完整碳平衡里占什么位置？除此以外，还有哪些碳流可能影响气候变化？
- What is the role carbon emission play in complete carbon balance? Which carbon flows could influence climate change?

- 全球城市脱碳的路径是否都一致？低收入强脱碳的可能么？
- Is it that the pathways of decarbonization in global cities are consistent? It is possible to realize low income and strong decarbonization?

3.2 Main research results



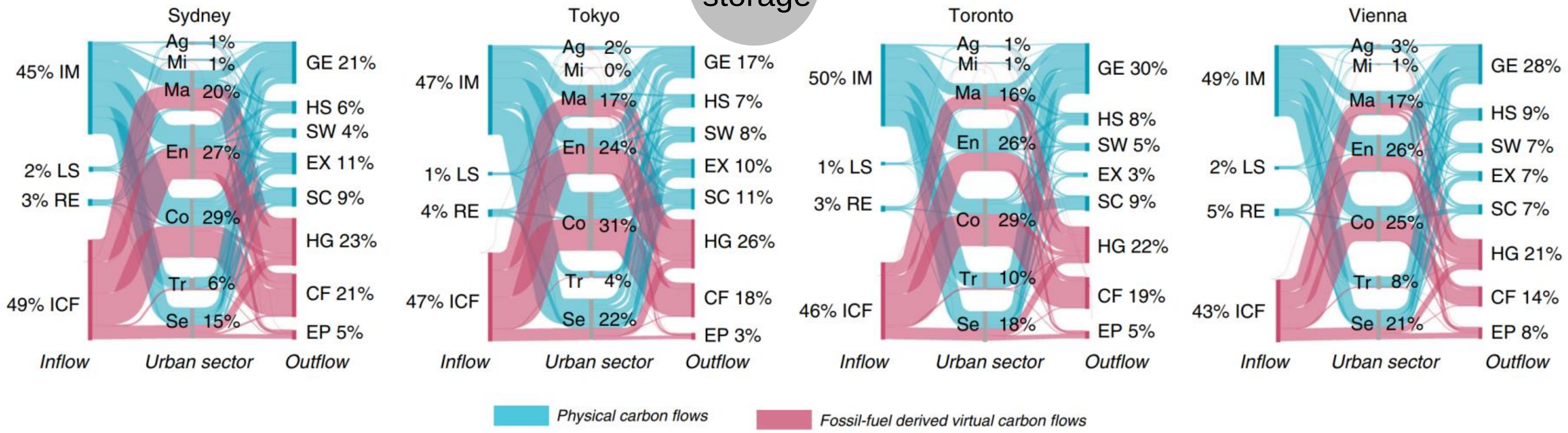


Fig. 3 Physical carbon and fossil fuel-derived gaseous virtual carbon flows (excluding CH_4) modeled for 16 global cities. These Sankey diagrams show the in- and outflows of physical carbon (in blue) and fossil fuel-derived virtual carbon (in red) associated with urban economic sectors. The numbers represent the proportions of flows to the total carbon balance of the respective city. The physical carbon inflows include: imports from other regions (IM), local supply by urban ecosystems (LS), and recycling of materials (RE), and physical carbon stocks and outflows, including household storage (HS), changes in carbon stock in urban sectors (SC), gaseous emissions (GE), solid waste (SW), and physcial export of carbon in goods (EX). Fossil fuel-derived virtual carbon embodied in import (ICF) to cities is accounted for, and is then allocated to flows driven by household and government expenditure (HG), fixed capital formation (CF), and exports as final demands (EP). Fossil-fuel derived virtual carbon flows are modeled using input-output analysis. The sectors are agriculture (Ag), mining (Mi), manufacturing (Ma), supply of energy (En), construction (Co), transportation (Tr), and services (Se).

Blue: **Inflow and outflow of material carbon**
Red: **Inflow and outflow of virtual carbon**

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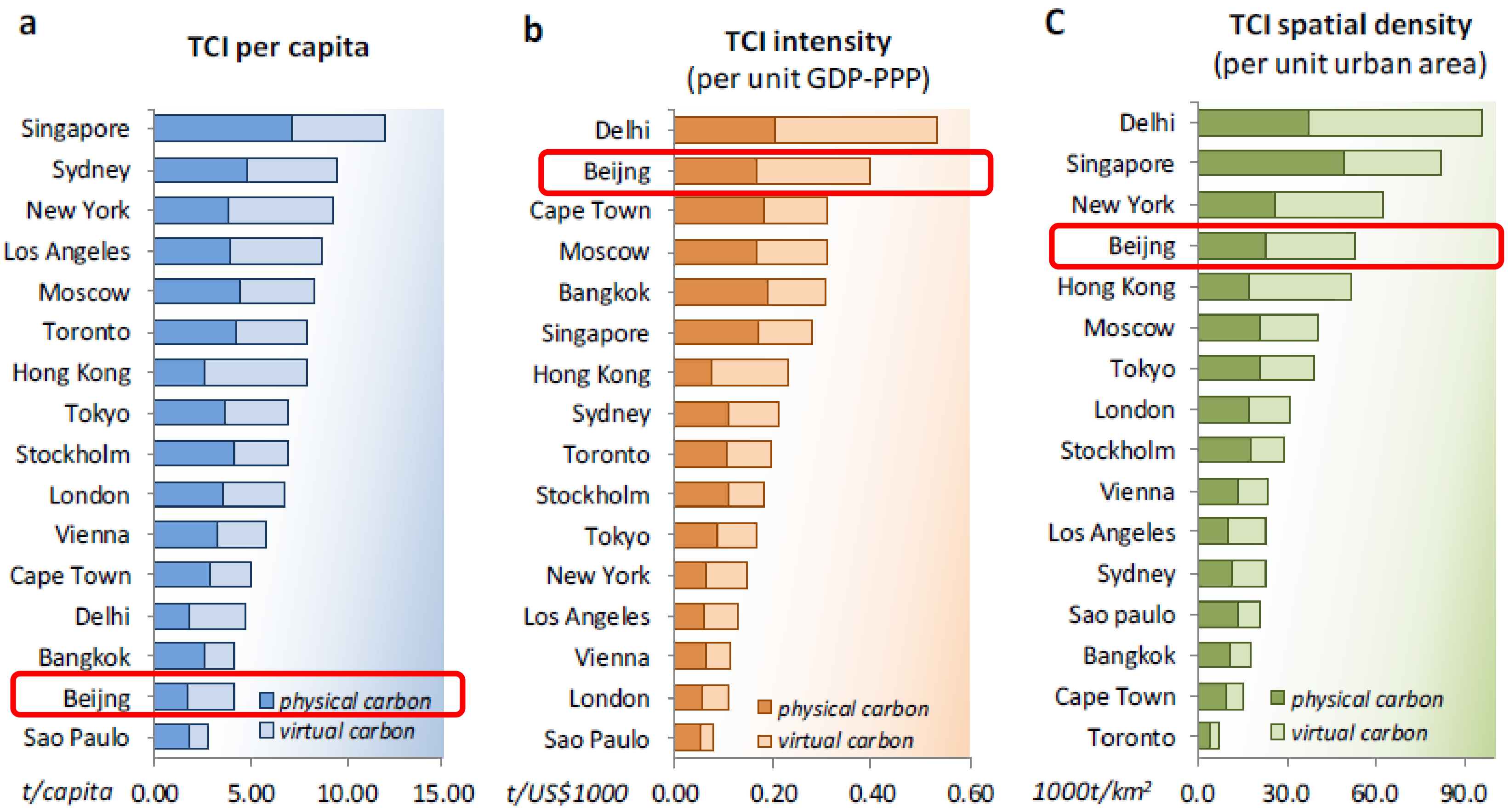
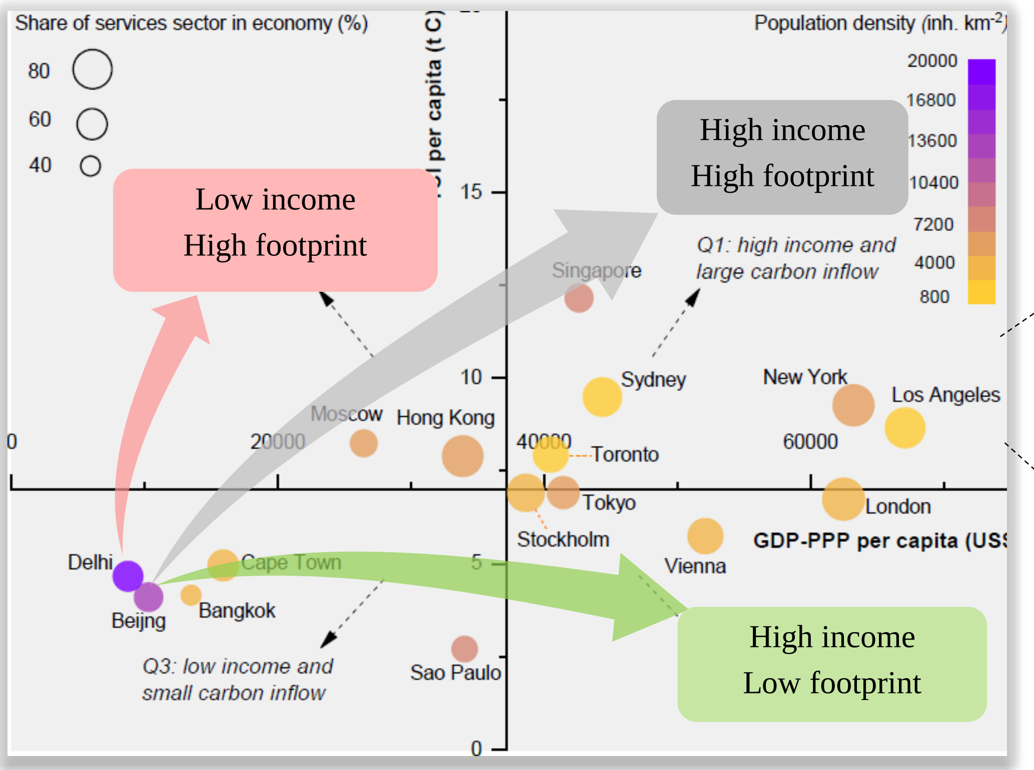
物质碳和虚拟碳在城市气候影响中扮演的角色

Role of physical and virtual carbon

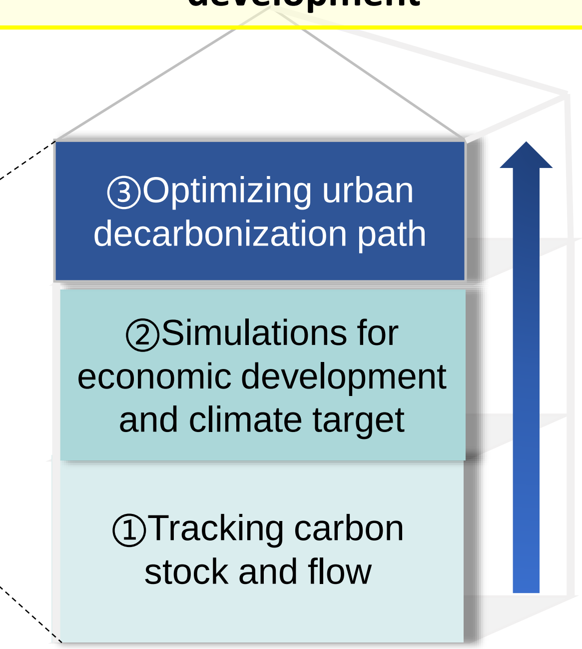


3.2 Main research results

Revealing the differences of urban carbon metabolic pathways



Sustainable and low-carbon urban development



- Urban low carbon sustainable development along Belt and Road.
- At city level, implementing
  《National Climate Change Program》
  《China's National Plan on Implementation of the 2030 Agenda for Sustainable Development》

3.3 Main conclusions

- Over 88% of the physical carbon in 16 global cities is imported from outside their urban boundaries, and this externalization of carbon is notably amplified by virtual emission from upstream activities that contribute 33%-68% to their total carbon inflows（严重外向型）

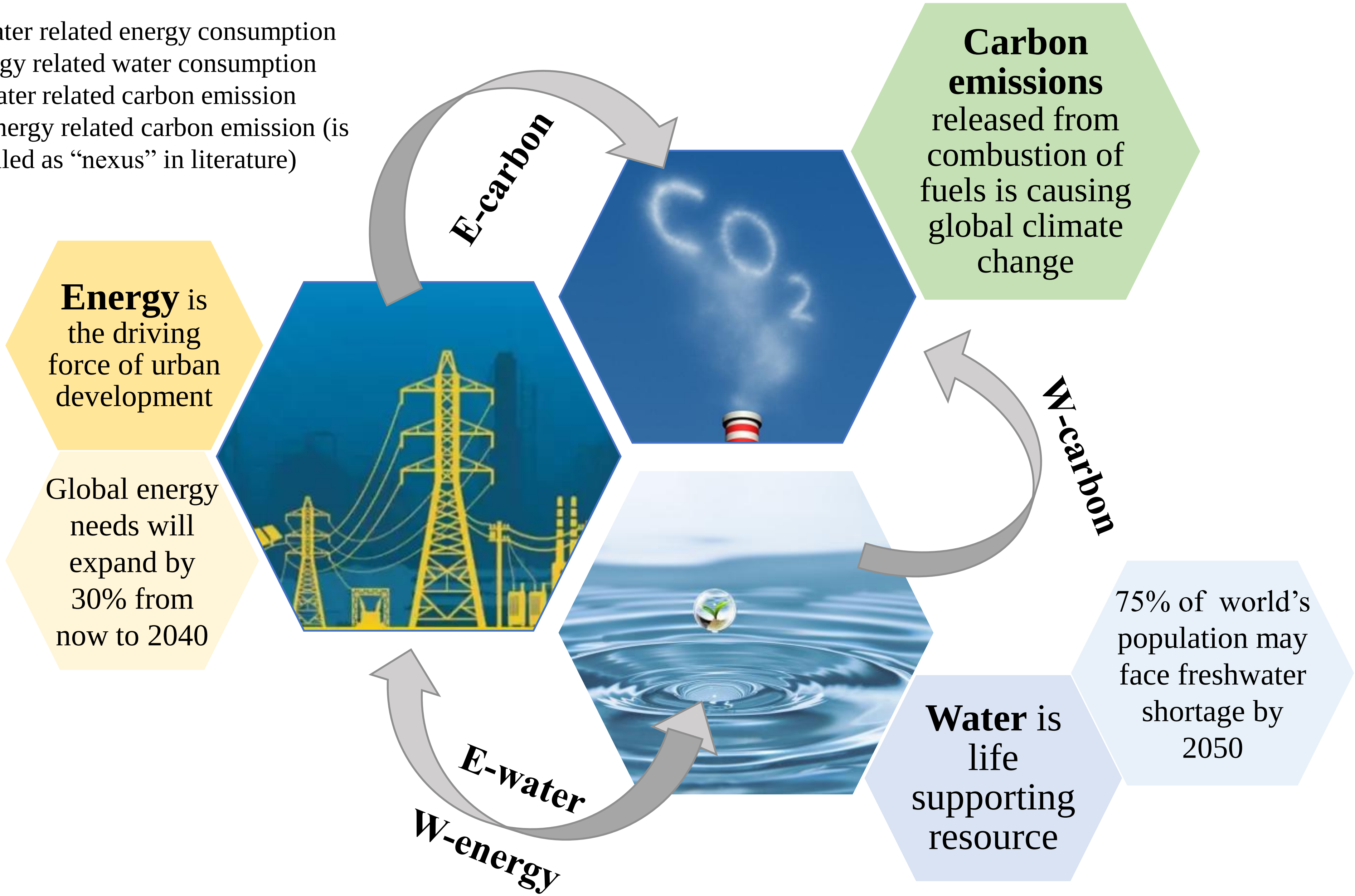
- While 13%-33% of the carbon appropriated by cities is immediately combusted and released as CO_2, **between 8% and 24% is stored in durable household goods or becomes part of other urban stocks (carbon storage is considerable)** **(**存量相当可观！）

- **Inventorying carbon consumed and stored for urban metabolism** should be given more credit for the role it can play in stabilizing future global climate (predicting future climate change) （未来废弃物管理挑战）

04 Energy-water-carbon nexus

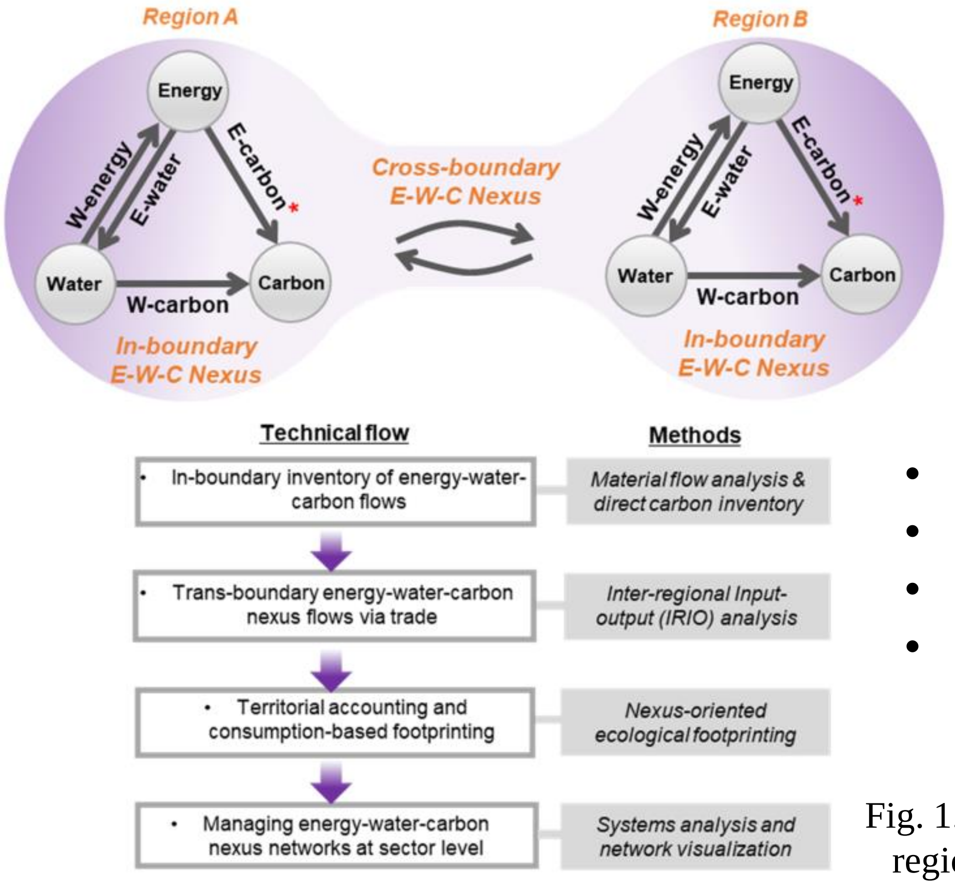
4.1 Background

W-energy: water related energy consumption
E-water: energy related water consumption
W-carbon: water related carbon emission
E-carbon*: energy related carbon emission (is usually not called as “nexus” in literature)



4.2 Significance and objective

- Tracking trade-related nexus is especially significant for regions that are increasingly engaged in globalization
- How inter-regional trade impact regional nexus footprints remains largely unknown.

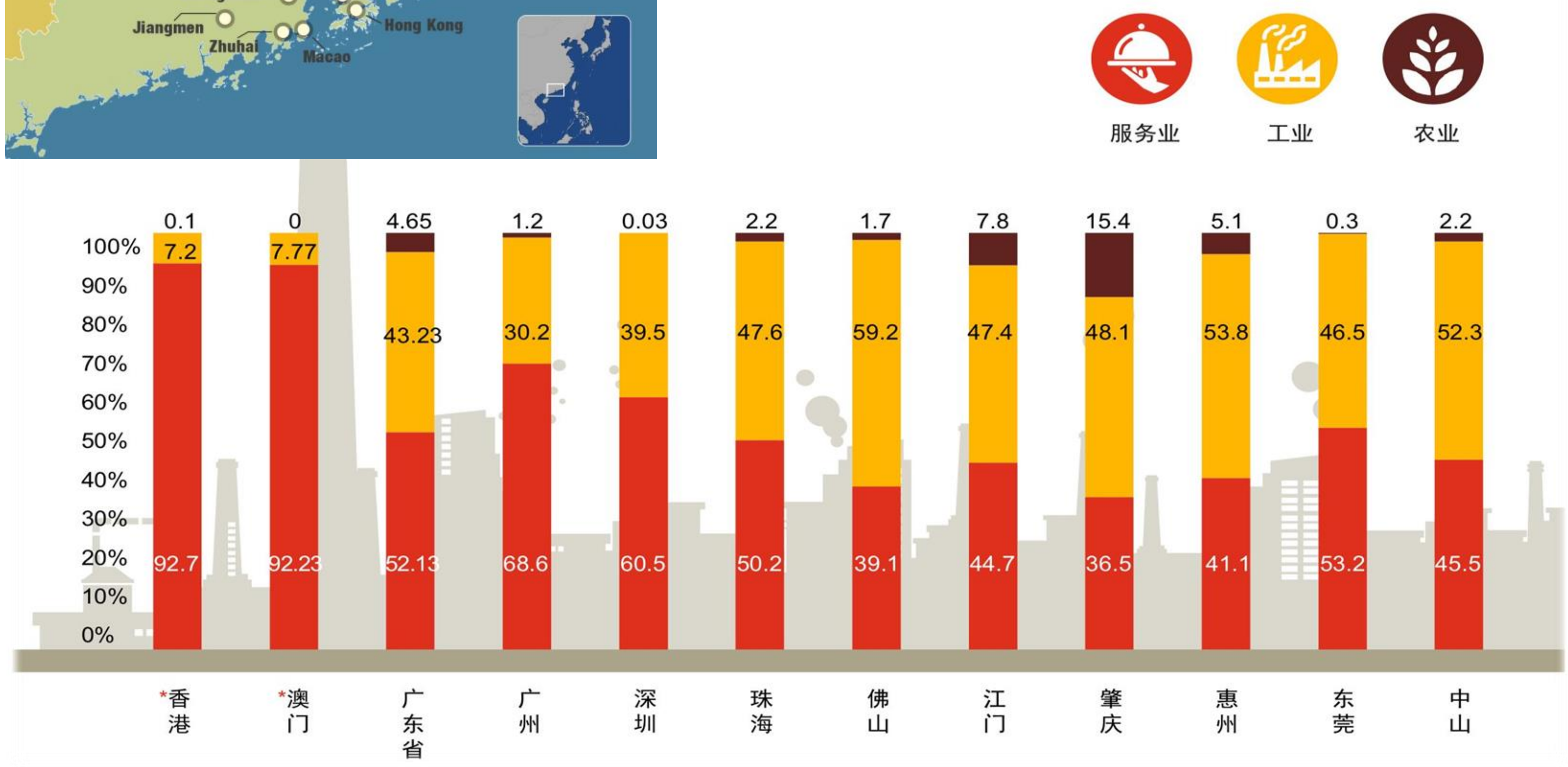


- **W-energy:** water related energy consumption
- **E-water:** energy related water consumption
- **W-carbon:** water related carbon emission
- **E-carbon*:** energy related carbon emission (is usually not called as “nexus” in literature)

Fig. 1. Interactive modelling framework for inter-regional energy-water-carbon (E-W-C) nexus.

4.3 Materials and method

Guangdong-Hong Kong-Macao Bay Area
(Guangdong & Hong Kong)



REGIONAL FEATURE

- ➢ Port economy, frequent inter-regional trade, industrial economy and service economy complement each other.
- ➢ Energy and water use between regions are particularly connected

Methodology: Input-output analysis (IOA)

Monetary Input		Monetary Output	Intermediate Monetary Output Sector 1	2	…	n	Final Demand Y	Total Output X
Intermediate Monetary Input	Sector	1	x_{11}	x_{12}	…	x_{1n}	Y_1	X_1
		2				x_{2n}	Y_2	X_2
		…	…		…	…	…	…
		n	x_{n1}	x_{n2}	…	x_{nn}	Y_n	X_n
Value-added		V	V_1	V_2	…	V_n		
Total Input		X	X_1	X_2	…	X_n		
Physical Input			Physical Input Distribution Sector					
Resource	Category	1	r_{11}	r_{12}	…	r_{1n}		
		2	r_{21}	r_{22}	…	r_{2n}		
		…	…	…	…	…		
		m	r_{m1}	r_{m2}	…	r_{mn}		
Waste	Category	m+1	$W_{(m+1)1}$	$W_{(m+1)2}$	…	$W_{(m+1)n}$		
		m+2	$W_{(m+2)1}$	$W_{(m+2)2}$	…	$W_{(m+2)n}$		
		…	…	…	…	…		
		m+k	$W_{(m+k)1}$	$W_{(m+k)2}$	…	$W_{(m+k)n}$		

Urban economy

$(I-A)^{-1}y$

Energy/water/carbon

k

$$\mathbf{EEF} = k(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y}$$

EEF: embodied energy/material flow
k: direct energy/material use intensity
A: direct production coefficient matrix
L=(I-A)$^{-1}$: completely consumable coefficient matrix
y: final demand of urban economy

An important tool for:
- ✓ Consumption-based eco-footprint
- ✓ Embodied energy/material flows among sectors
- ✓ Impact of trade on local metabolism

4.3 Materials and method

Defining energy-water-carbon nexus

Material flow-energy flow analysis

Energy
$$
\begin{cases}
E_i = \sum_{k=1} e_i^k h^k \\
W_i^e = p_i \alpha_i \\
C_i = \sum_{k=1} e_i^k h^k \delta^k r^k
\end{cases}
$$
E-water

Carbon

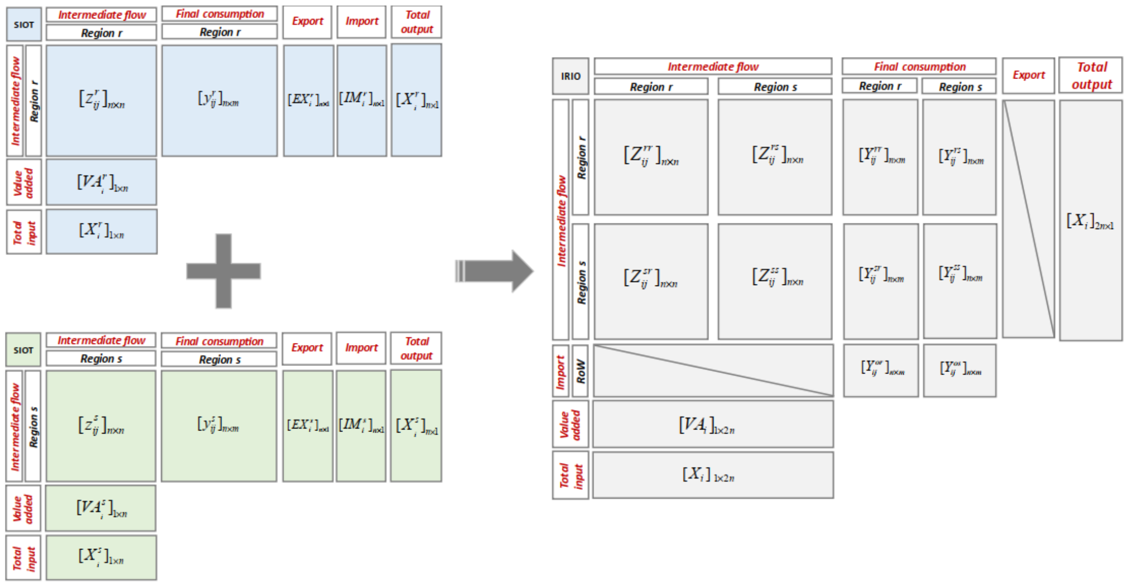
Water
$$
\begin{cases}
W_i = \sum_{n=1} w_i^n \\
E_i^w = W_i \beta_i \\
C_i^w = E_i^w \gamma_i
\end{cases}
$$
W-energy

W-carbon

- ***W-energy:*** *water-related energy consumption*
  水用能：与水相关的能耗
- ***E-water:*** *energy-related water consumption*
  能用水：与能源相关的水耗
- ***W-carbon:*** *water-related carbon emission*
  水排碳：与水相关的碳排放

Embodied flows accounting for energy-water-carbon nexus

Regional IO-connected MRIO



Embodied flows modelling for energy-water-carbon nexus

Input-output analysis

wide spread top down method for embodied flows analysis

$$\theta_i^t = \frac{d_i^t}{X_i}$$

$$L = (I - A)^{-1}, \quad A = [a_{ij}]$$

$$f^t = \begin{pmatrix} f_{rr}^t & f_{rs}^t \\ f_{sr}^t & f_{ss}^t \end{pmatrix} = \begin{pmatrix} \theta_r^t & 0 \\ 0 & \theta_s^t \end{pmatrix} \begin{pmatrix} L_{rr} & L_{rs} \\ L_{sr} & L_{ss} \end{pmatrix} \begin{pmatrix} y_{rr} & y_{rs} \\ y_{sr} & y_{ss} \end{pmatrix}$$

$$T_i^t = \sum_{j=1} f_{r(j) \to s(i)}^t + \sum_{j=1} f_{s(i) \to r(j)}^t$$

Footprint evaluation of energy-water-carbon nexus

Ecological footprinting

$$\begin{cases} TEA^t = \dfrac{d^t}{p} & \text{Territorial accounting} \\ CBF^t = \dfrac{F^t}{p} & \text{Consumption based footprint} \end{cases}$$

4.4.2 Results: Footprint evaluation

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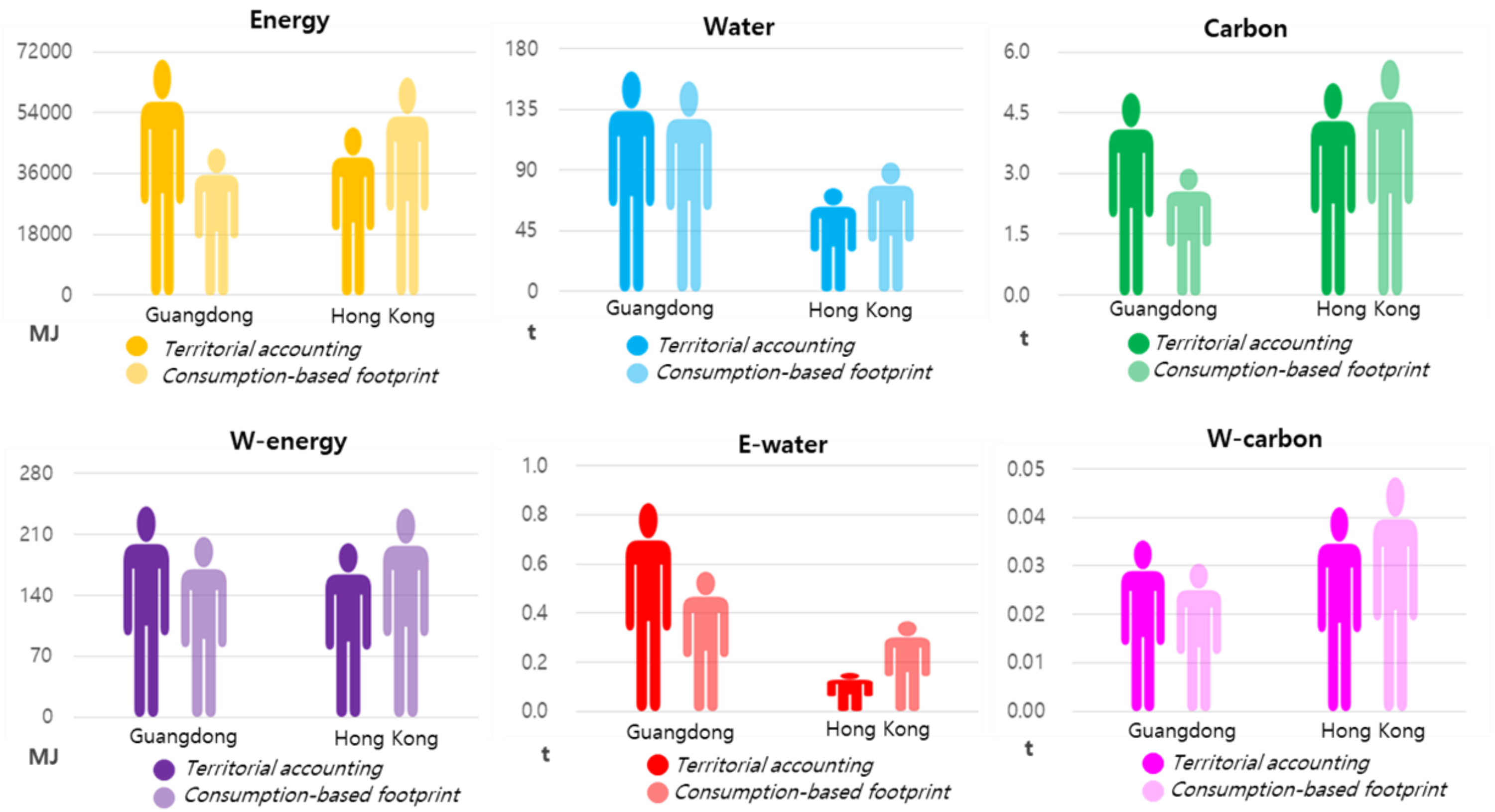
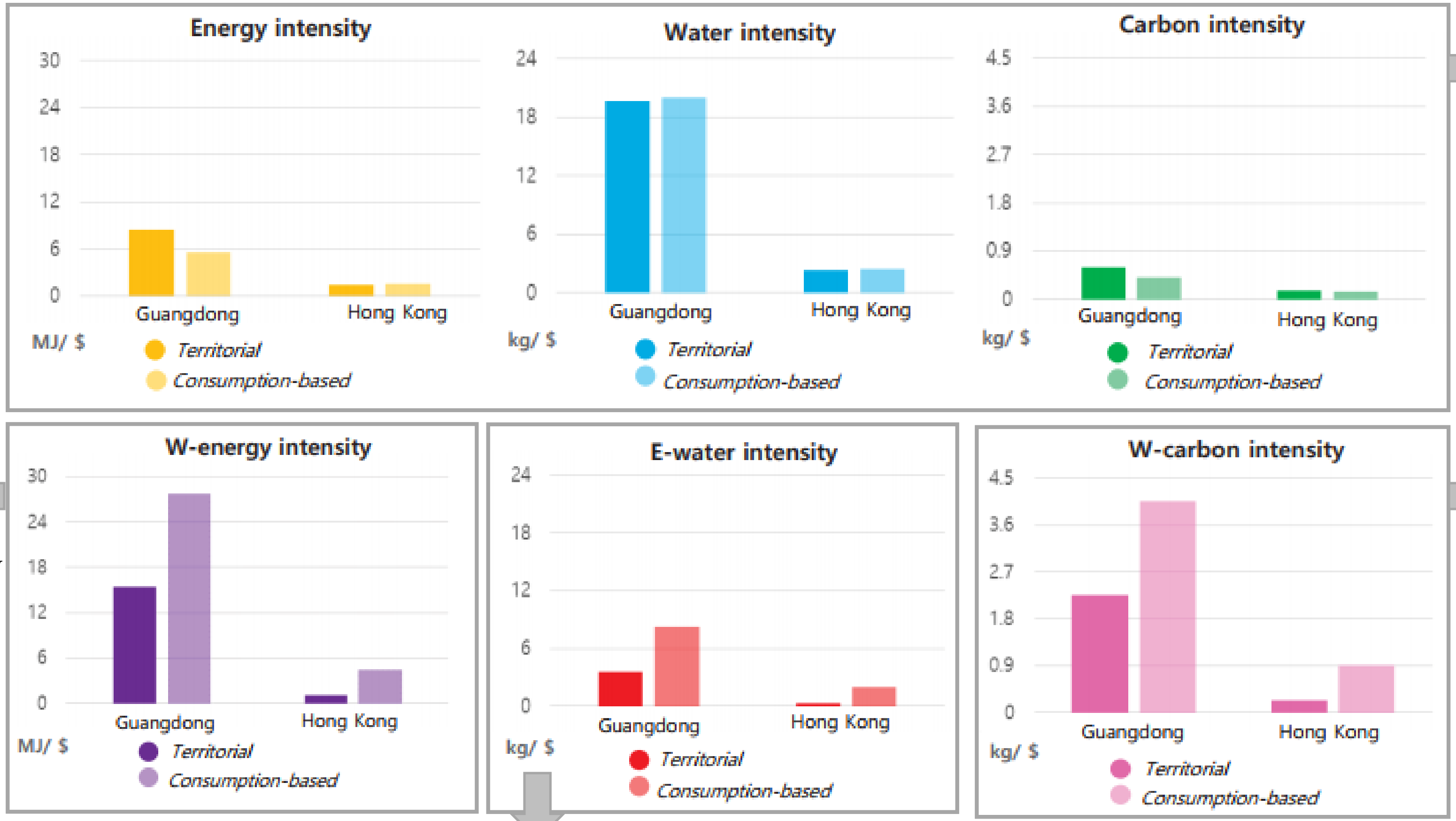


Fig. 3. Per capita energy-water-carbon territorial accounting and consumption-based footprint of Guangdong and Hong Kong

Comparison within one region
Guangdong TEA>CBF
Hong Kong CBF>TEA

Comparison between two regions
TEA Guangdong > Hong Kong
Except carbon
CBF Hong Kong > Guangdong
Except water and E-water

4.4.2 Results: Footprint evaluation



Reflect the average efficiency level of the whole economy

Reflect the efficiency level of water sector

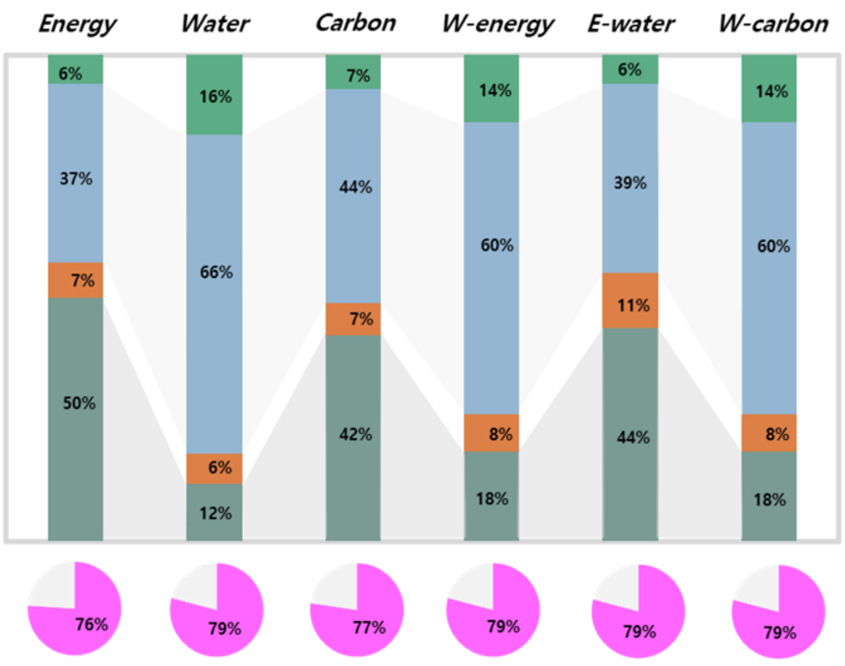
Reflect the efficiency level of water sector

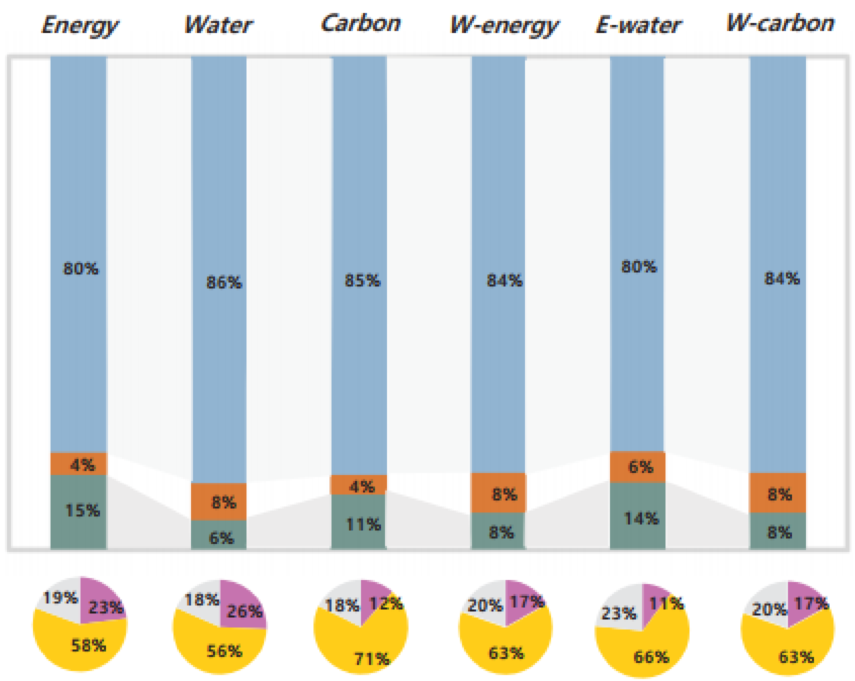
Reflect the efficiency level of energy sector

- Nexus footprints are a small proportion of the total environmental footprints
- Nexus footprint intensities are significantly higher for energy and carbon
- Such intensity gap is even more prominent from a consumption-based view
- An exception lies in water and E-water

4.4.3 Results: Footprint decomposition

Guangdong





Hong Kong

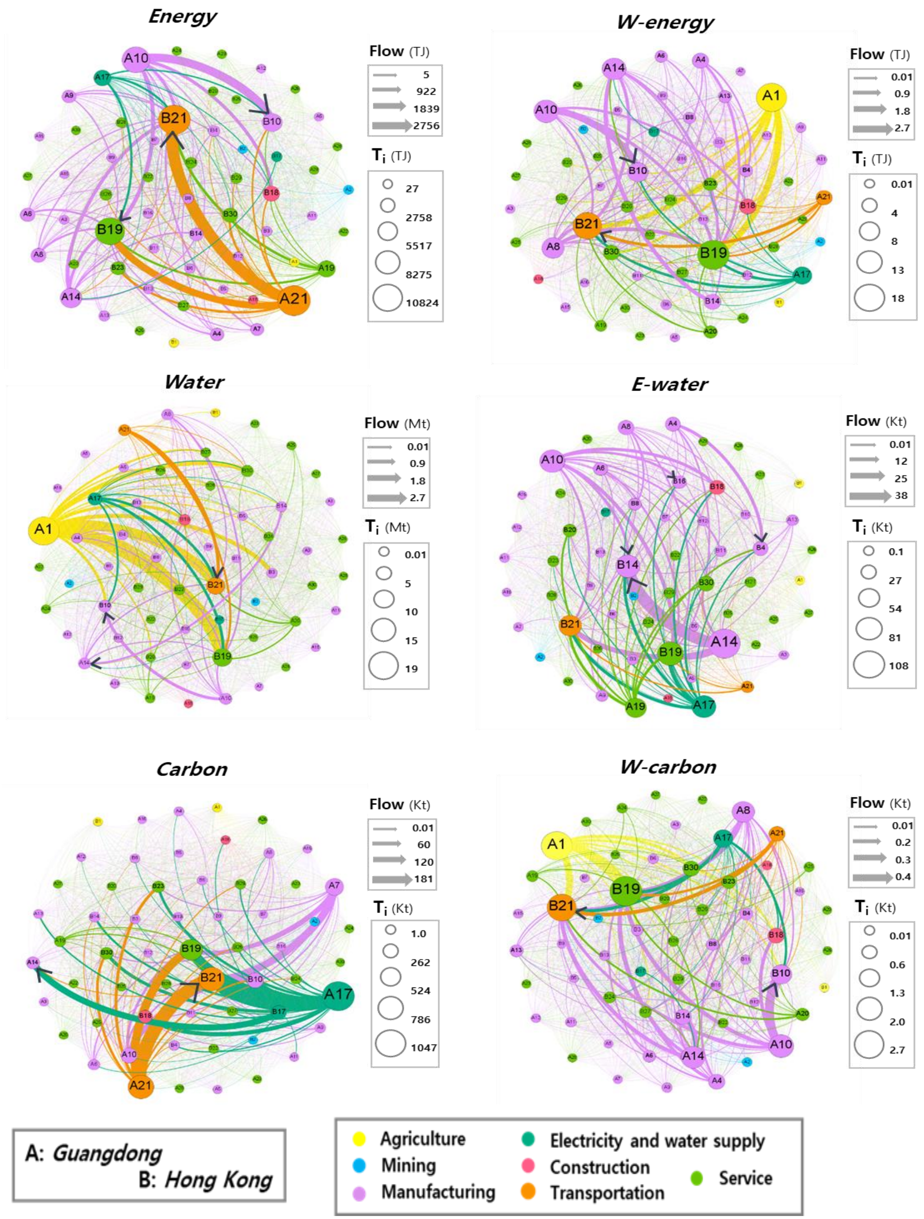
Guangdong

- 76–79% of embodied flows are supplied by local production within the region.
- Water-related footprints: urban, rural and government consumption
- Energy-related footprints: fixed capital formation

Hong Kong

- In comparison, globalization has a greater impact on the environmental footprints.
- All kinds of footprint: urban consumption

4.4.3 Results: Network visualization



- Embodied transfer from Guangdong to Hong Kong dominate in all types of flow networks

- Dominant exporting sectors vary in different types of flow network.
  - For energy-related embodied flow networks (Energy and E-water)

Transportation (flows in orange)

Manufacturing sectors (flows in purple)

  - For water-related embodied flow networks (Water, W-energy and W-carbon)

Agriculture (flows in yellow)

  - For carbon embodied flow network

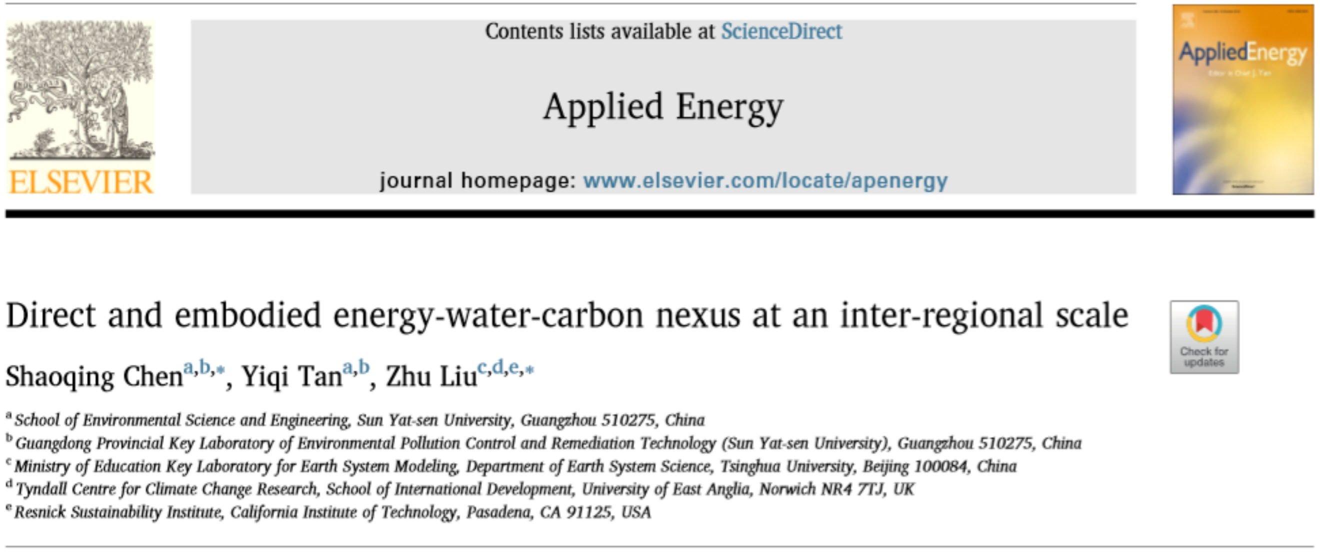
Electricity and water supply (flows in deep green)

- Dominant importing sector are wholesale and retails and Transportation in Hong Kong.

4.6 Main contributions

Take home message

- A novel framework is proposed for inter-regional energy-water-carbon nexus.
- Nexus footprint intensities are much higher than the total footprint intensities.
- Inter-regional trade plays a significant role in energy-water-carbon nexus.
- Managing energy-water-carbon nexus from perspective of industrial chains is more effective.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Direct and embodied energy-water-carbon nexus at an inter-regional scale

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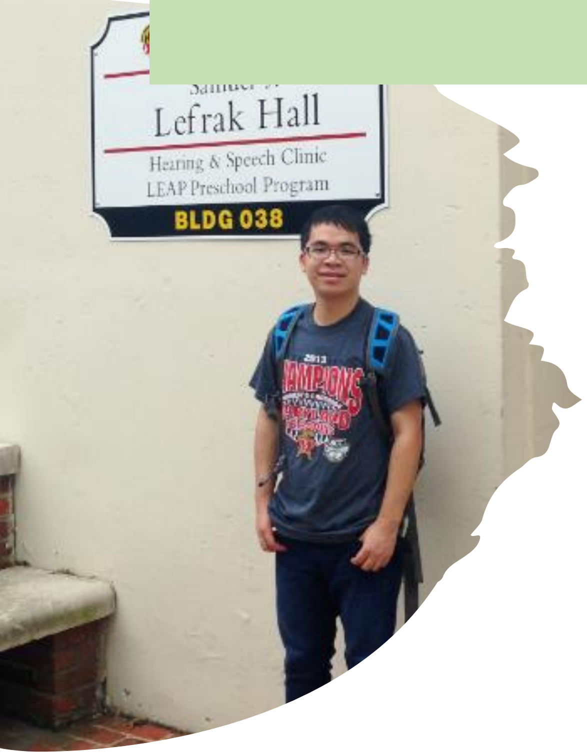

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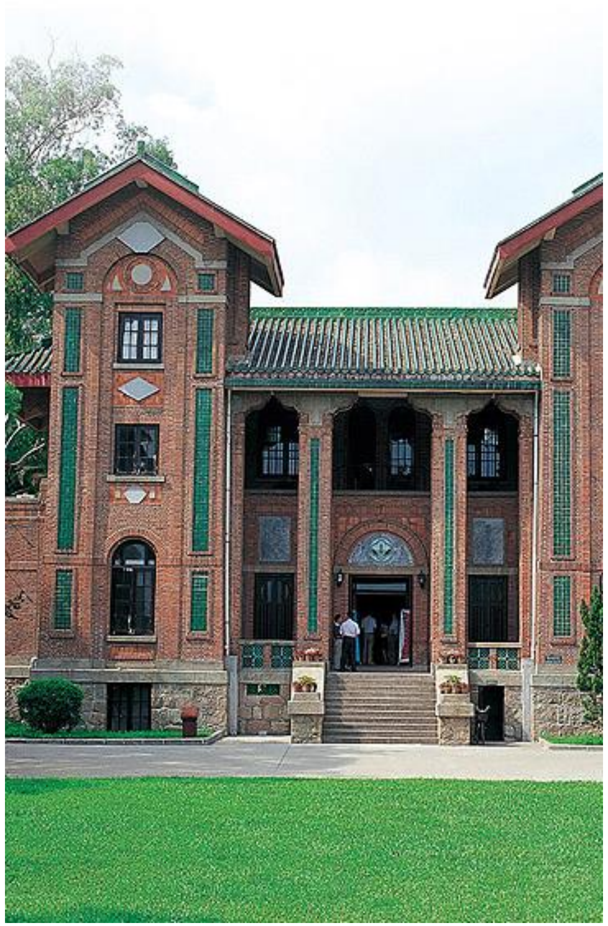

Thank you!