Food-Energy-Water Nexus for Urban Sustainability: Dynamics and Optimization

Lixiao ZHANG, PhD

Deputy Dean and Professor, School of Environment,

Beijing Normal University

zhanglixiao@bnu.edu.cn

北京師範大學環境學院

School Of Environment, Beijing Normal University

About Me

Education

MSc in Environmental Sciences (Peking University)

PhD in Environmental Sciences (Peking University)

Career

1 years BOKU University of Austria (2004-2005)

16 years BNU (2005-Now)

Interest

Urban ecology---Urban metabolism

Industrial ecology---Sustainable energy

Service

Co-EiC of *Journal of Environmental Management*

Deputy dean of School of Environment

General secretary of environmental geoscience, CSFES

FEW Nexus Projects

- National Natural Science Foundation of China: International Cooperation: ***Integrated Systems Modeling of Food-Energy-Water (FEW) Nexus for Urban Sustainability***

  国家自然基金(国际合作与交流项目):面向可持续发展的城市食物-能源-水关联关系模拟研究

- National Natural Science Foundation of China: ***Crossing Regional System Modeling and Optimizing of Food-Energy-Water (FEW) Nexus For Urban Sustainability***

  国家自然基金面上项目:跨区域视角下城市食物-能源-水关联关系解析与模拟

- National Science and Technology Major Project: ***Transmission process and Coupling Mechanism of Energy-Material-Information Flow in Urban and Regional Areas***

  国家重点研发计划:城市与区域能流-物流-信息流传输过程与耦合机制

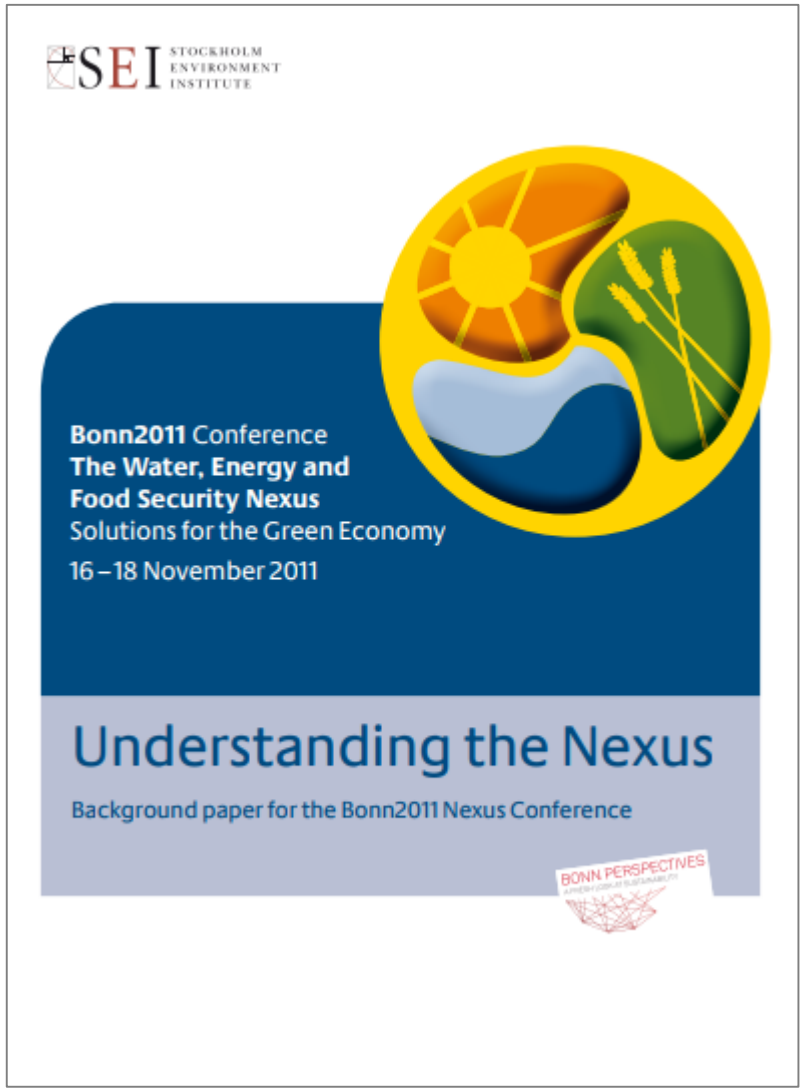
- National Natural Science Foundation of China: ***A Study on the Trade-off Mechanism of Urban Food-Energy-Water Nexus***

  国家自然基金青年项目:城市食物-能源-水关联关系的权衡机制研究

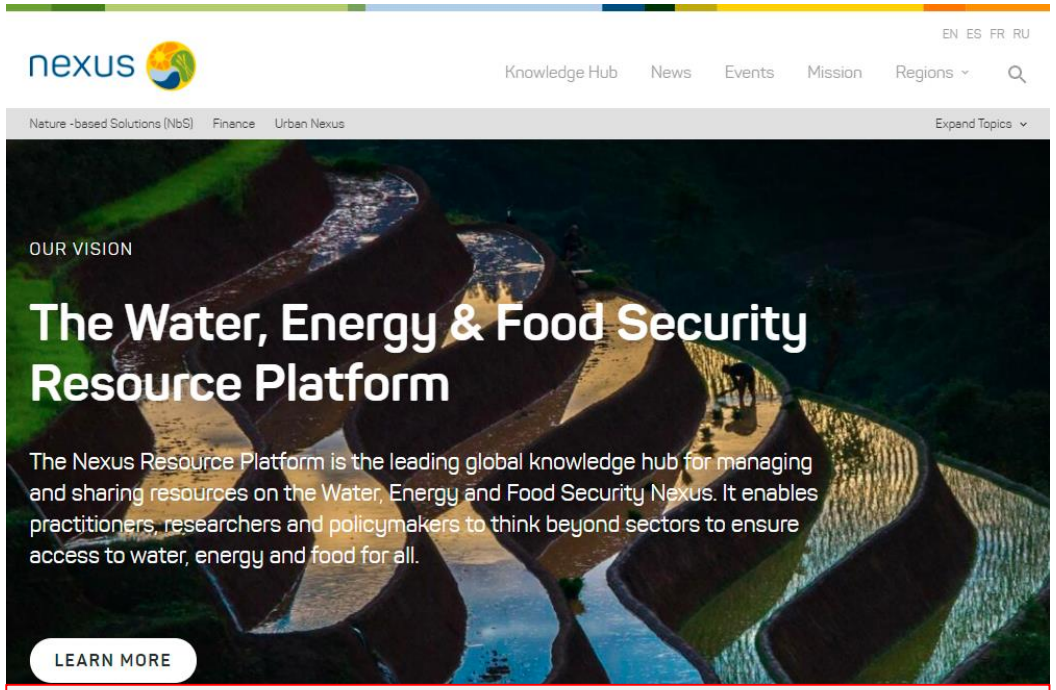
Outline

- Rethinking nexus
- Urban FEW Nexus
- System Dynamics modeling of Urban FEW Nexus
- Sustainable Optimization for Urban FEW Systems
- Real Challenges Facing with Nexus Transition

Rethinking nexus

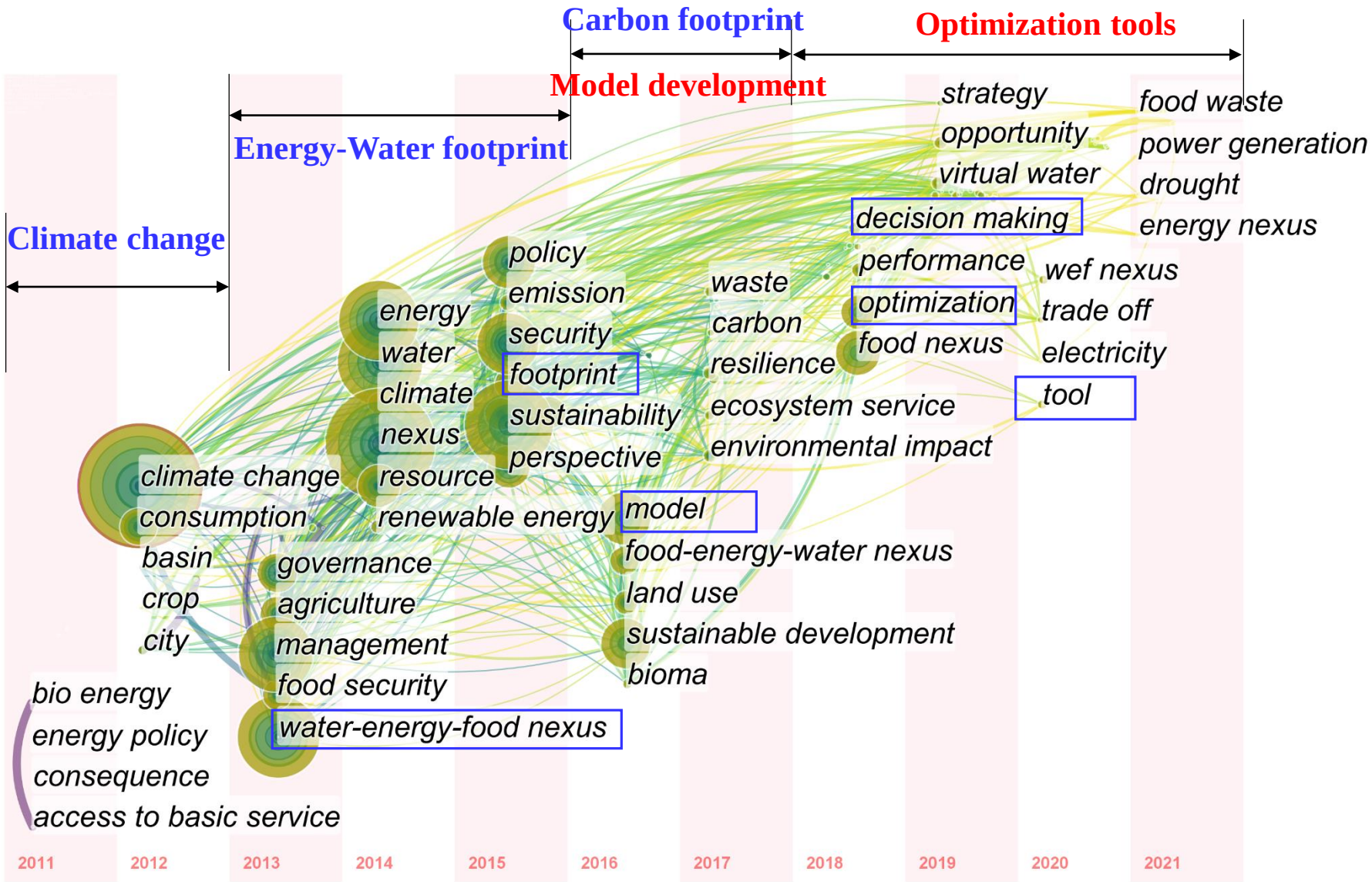


November 16-18, 2011

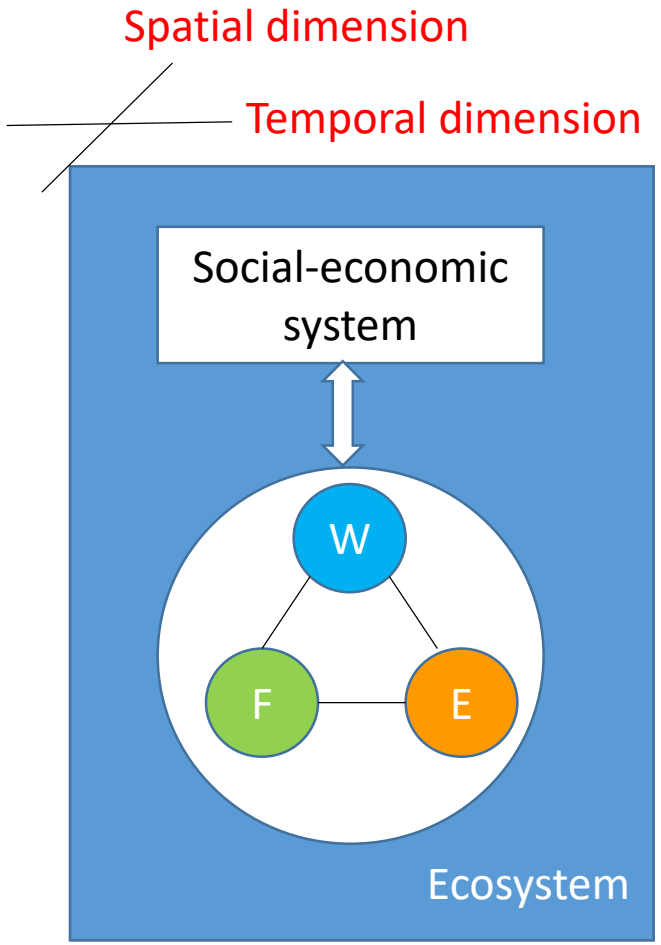


Bonn report explains the Nexus and presents initial evidence for how a nexus approach can enhance water, energy and food security in a green economy by increasing efficiency, reducing trade-offs, and building synergies across sectors.

Rethinking nexus



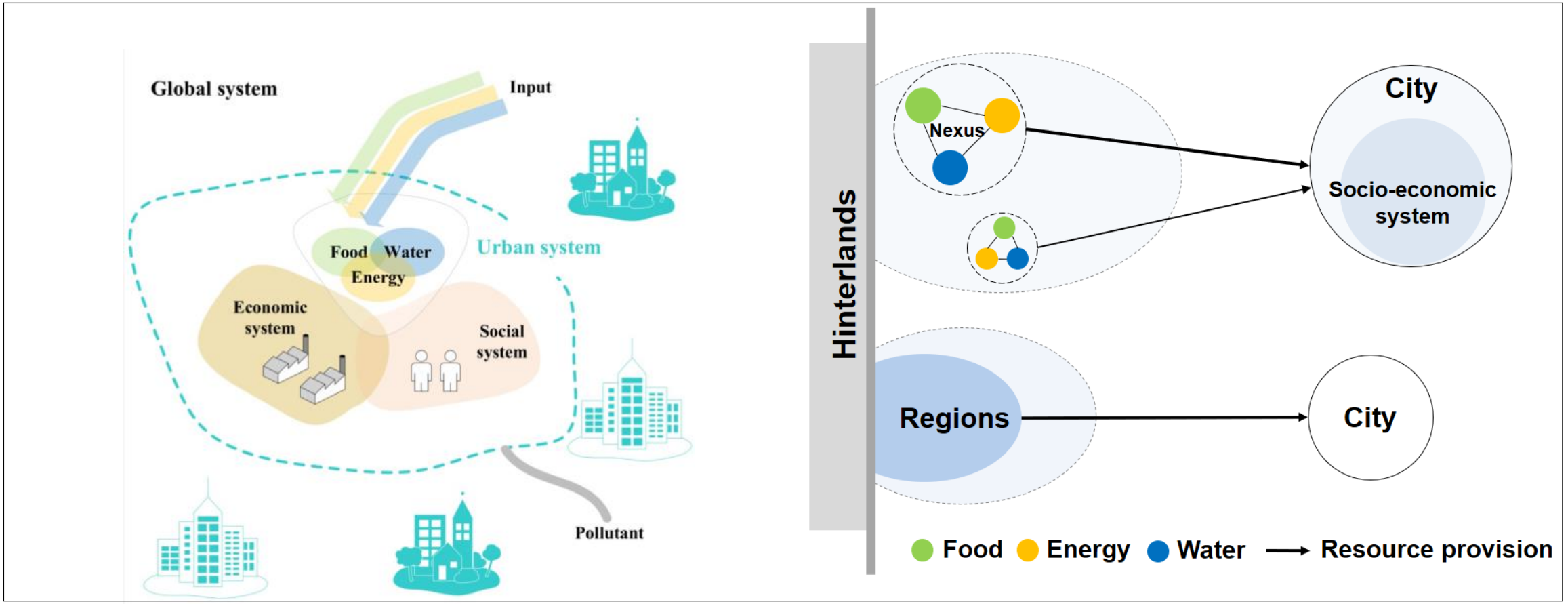
Rethinking nexus



Nexus of nexuses— extensions

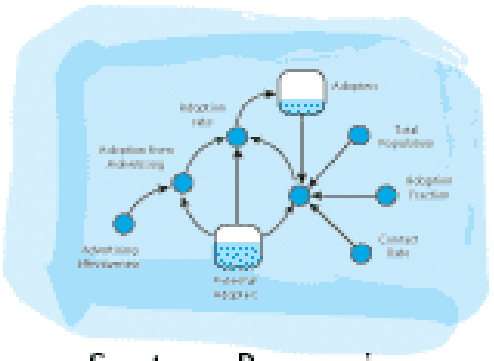
- Element nexus
- Supply chain cascade
- Tele-connection

Urban FEW Nexus

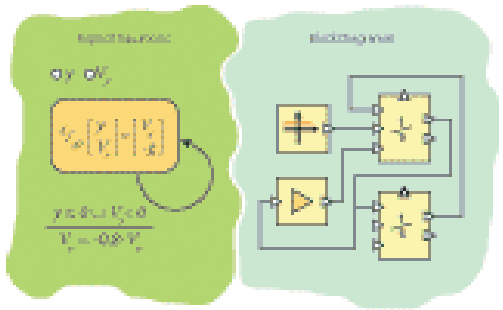


- Cities are sites of FEW distributions, consumption and, to a lesser extent, production and reuse
- Urban systems mainly draw on FEW resources outside of their physical boundaries and create environmental impacts that extend beyond city borders

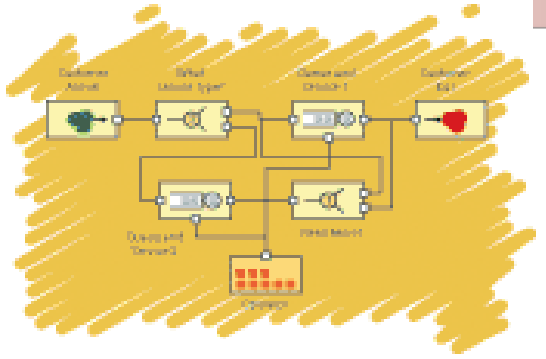
Urban FEW Nexus—System dynamics



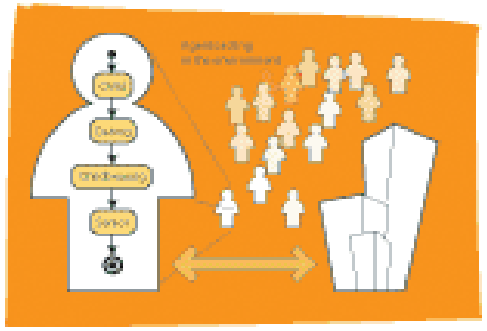
System Dynamics



Dynamic Systems



Discrete Event

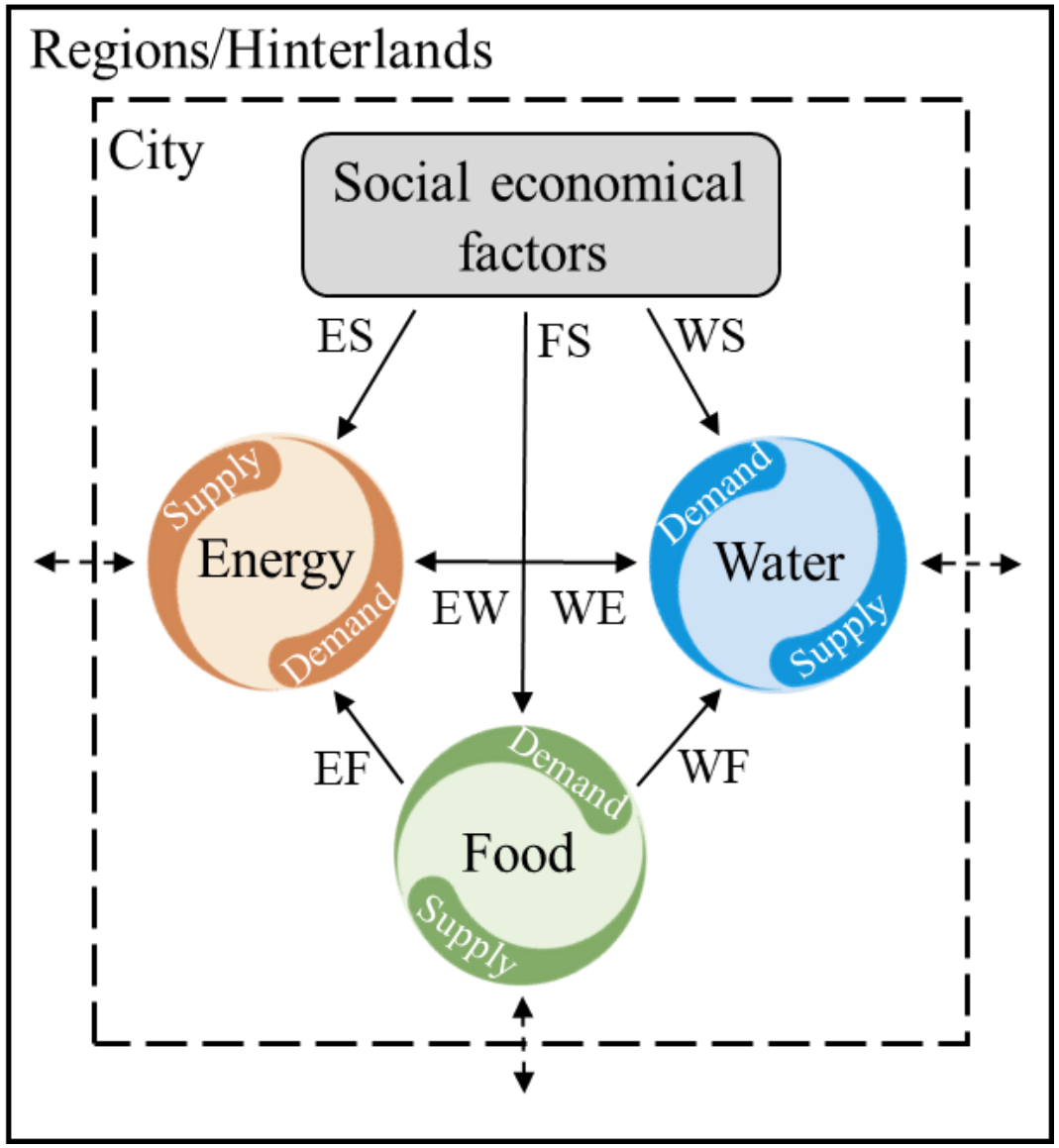


Agent Based

- Track the interactive mechanism of trans-disciplinary and cross-sector performance of FEW system
- Contribute to collaborative management, which is a continuous and progressive long-term process in practice

☞☞ Great efforts engaged in dynamic simulation

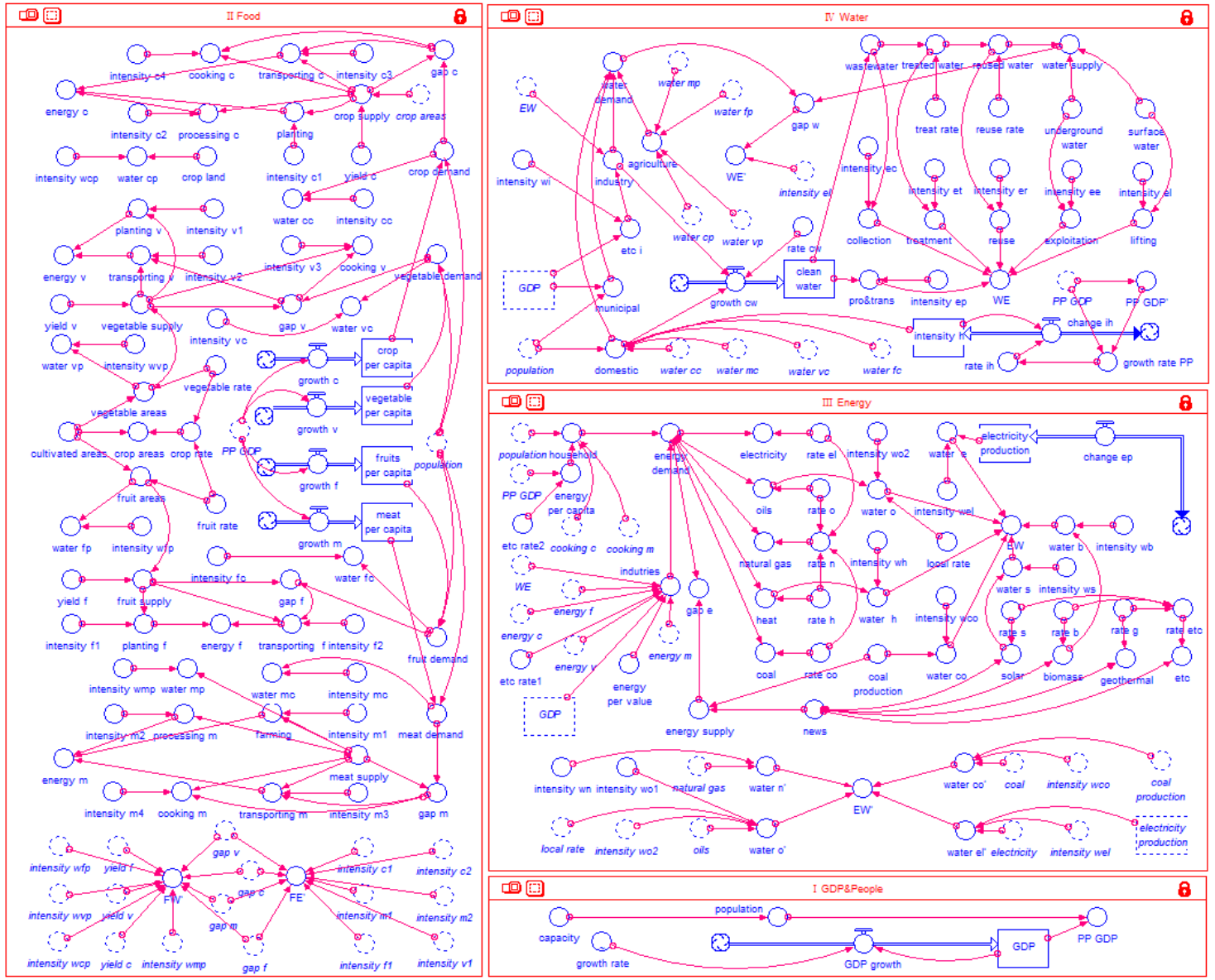
FEW Nexus—Conceptual framework



- The city-wide FEW demand is met through local in-boundary and trans-boundary productions.
- The city has the local FEW interactions enabled by co-location within its boundaries
- The demand-supply gap has to rely on trans-boundary provision that may have different FEW nexus features
- To reflect such complexity, the consideration of supply delineation into in- and trans-boundary components is necessary

Basic feedback loops of FEW resources within urban system

System Dynamics—Model disaggregation



Food

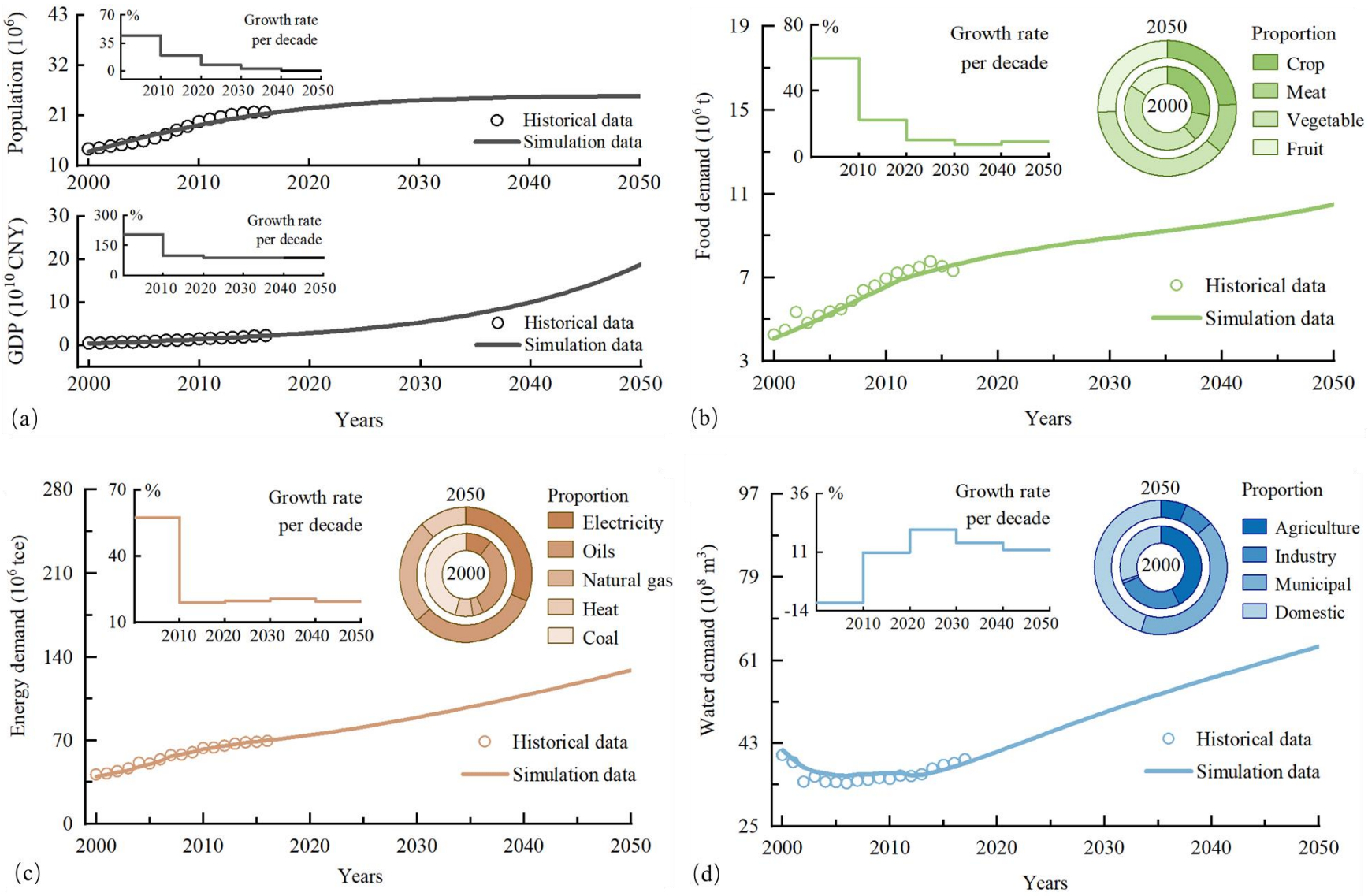
Water

Energy

GDP & People

Stella model for urban FEW nexus

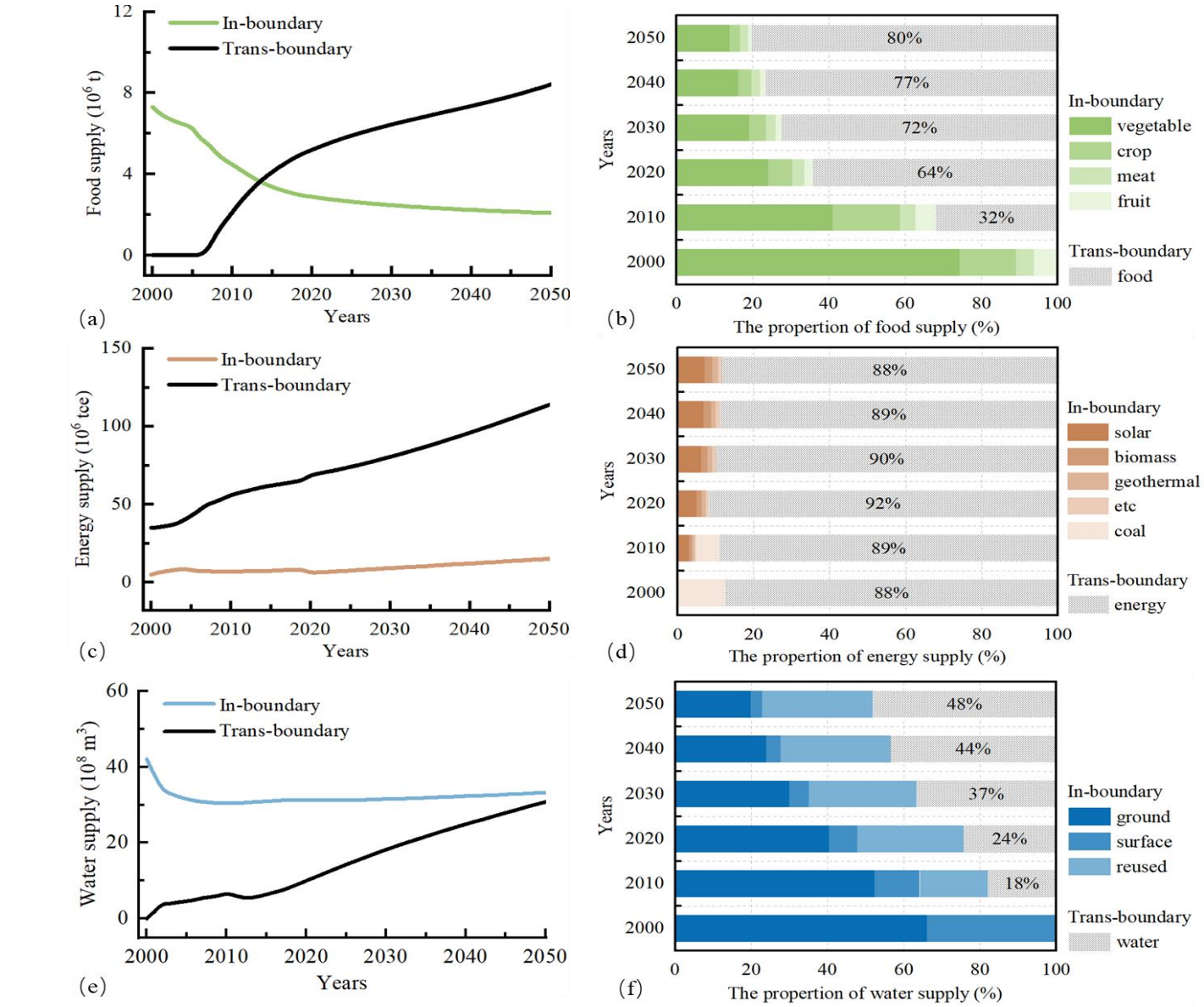
Dynamics of urban FEW demand



Simulation results of socio-economic elements (a) and the demand of food (b), energy (c) and water (d) in Beijing

- The validation results indicated that the behavior of the BJ-FEW was acceptable and the slight error observed was not in contrast with the trends and behaviors of the variables.
- Under the baseline scenario, the total demand of food, energy and water in Beijing will increase to 10 million tons (Mt), 129 million tons of standard coal (Mtce) and 6.4 billion cubic meters (Bm3) respectively in 2050

Changes of urban FEW supply sources



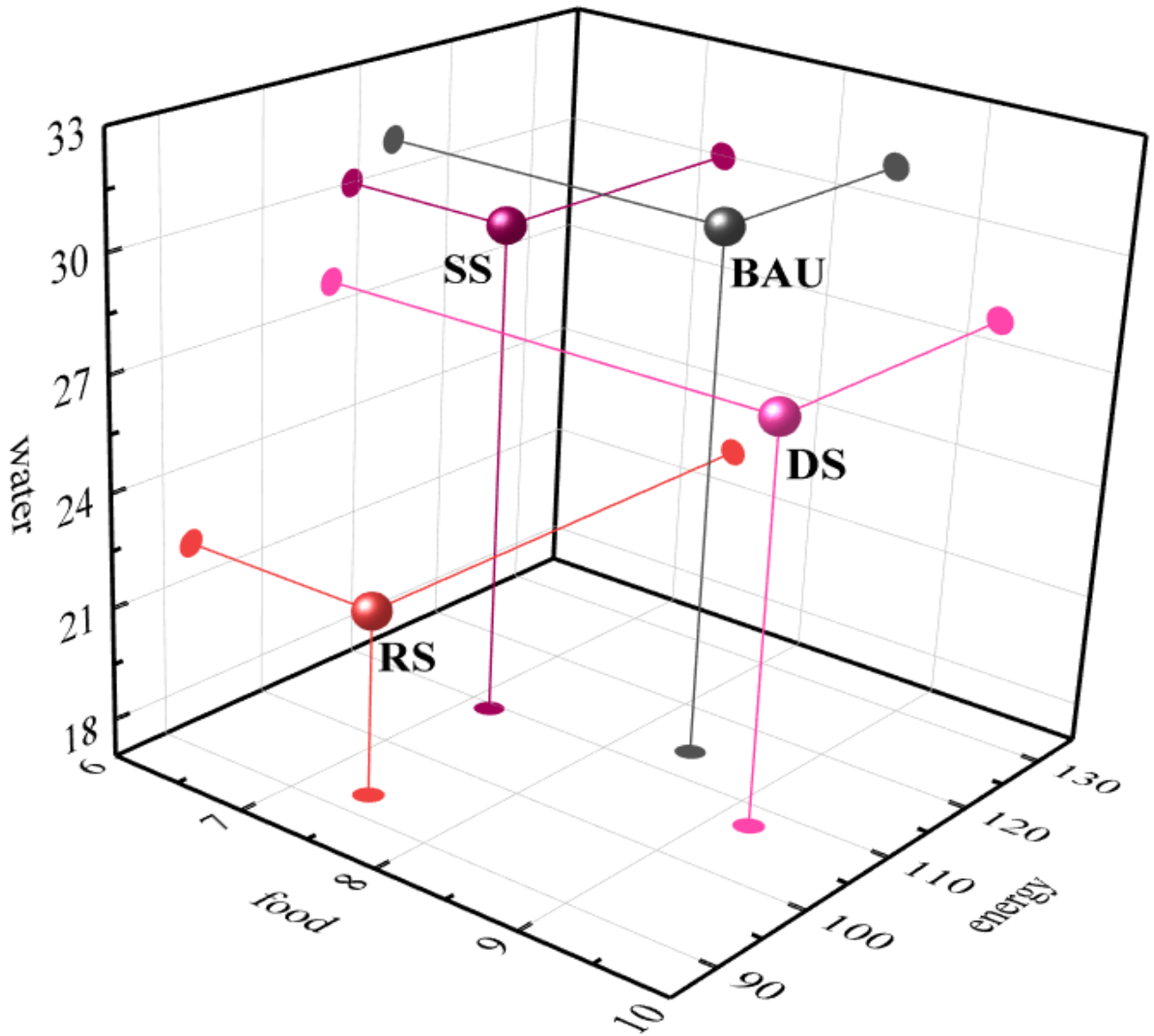
- There is increasing trend of EFW resources from trans-boundary provision
- There will be 80% of food, 88% of energy and 48% of water depending highly on trans-boundary supply.
- According to the modeling result, the total water demand will be 6.4 Bm3 in 2050, and there will be still a large gap of 1.6 Bm3 water demand, roughly another SNWD project.
- t is obvious that as urban FEW nexus is expanding outside, the tele-connections between megacity and its hinterland regions have being intensified

Simulation results the supply of food (a-b), energy (c-d) and water (d-e) in Beijing

Scenario analysis

Scenarios	Definition	Implications
SS	Supply Scenario	This scenario is to enhance urban local production capacity. It will retain 0.15 hectares of arable land at least to guarantee agricultural activities. Sewage treatment rate will improve 3%. Besides, the new energy utilization will add an extra of 0.1 million tce to the annual growth during 2020-2035 and 0.2 million tce during 2036-2050.
DS	Demand Scenario	This scenario is to optimize urban resource consumption behaviors. The utilization efficiency of energy and water will change with a small increment of 5% comprehensively. The dietary behavior is expected to be healthier and greener by increasing 10% plant-sourced foods intake and decreasing 10% animal-sourced foods intake per capita.
RS	Relocation Scenario	This scenario is mainly inspired by the planning of Xiong'an New Area (XNA), which is a national-level strategy aimed at alleviating the pressures of Beijing. Considering the relocation of population and industries, we assume Beijing's 2 million population will settle in XNA, and its growth rate of GDP will adjust to 6% during 2020- 2035 and 5.5% during 2036-2050.

Scenario analysis



Simulation results of scenario analysis

- The scenario analysis verify the positive effects by adjusting social-economic drivers, and illustrate that the improved spaces of regulation from production and consumption sides are limited
- Over the long term, Xiong'an New Area plan, which is a national-level strategy aimed at moving non-capital functions out of Beijing, will excellently help it relieve 12%, 18% and 29% local supply-demand pressure of food, energy and water
- The spillover effects associated with FEW resource outsourcing outside of their immediate geographies should be considered in urban planning and policy making

How to design integrated model for FEW nexus

the UN SDGs

- Zero hunger
- Clean water and sanitation
- Affordable and clean energy
- Sustainable cites and communities
- Responsible consumption and production
- …

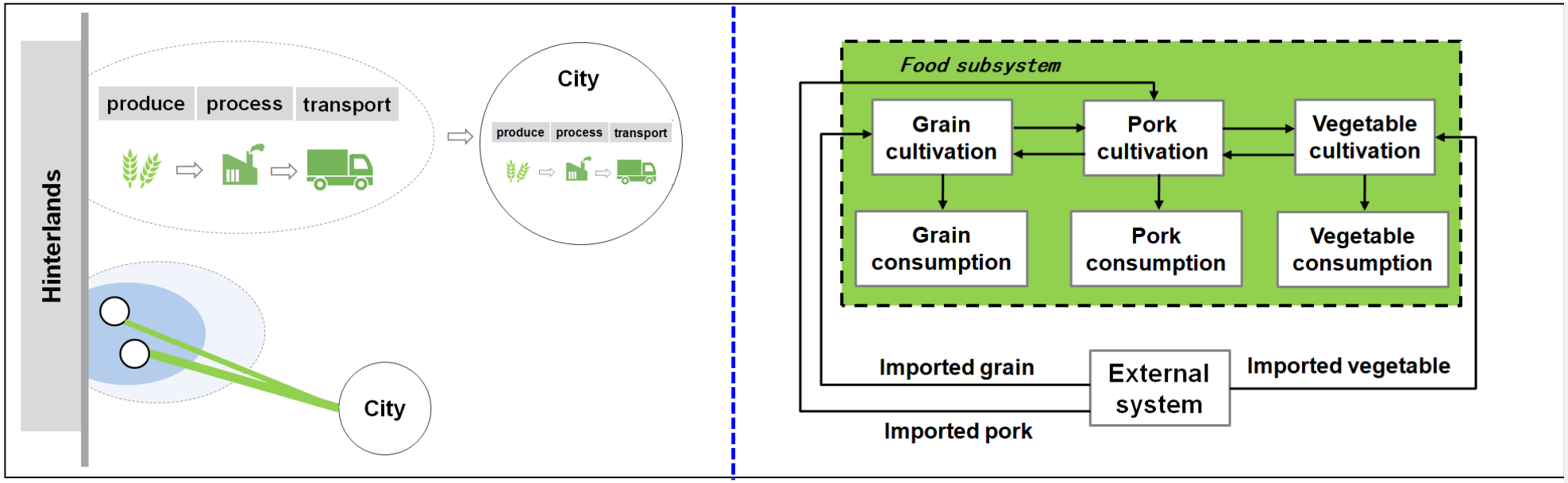
- **Agricultural development**

- **Development potential of renewable energy (cooperation between cities and their surrounding areas)**

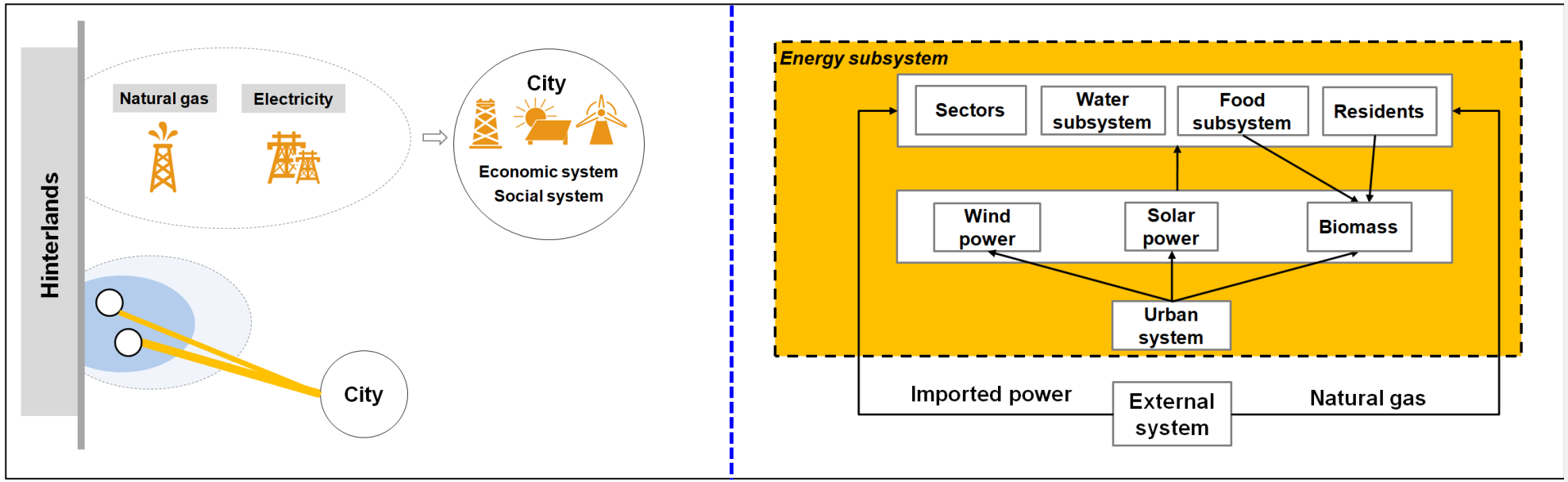
- **Management strategies**

Design models for urban FEW subsystems

Food subsystem

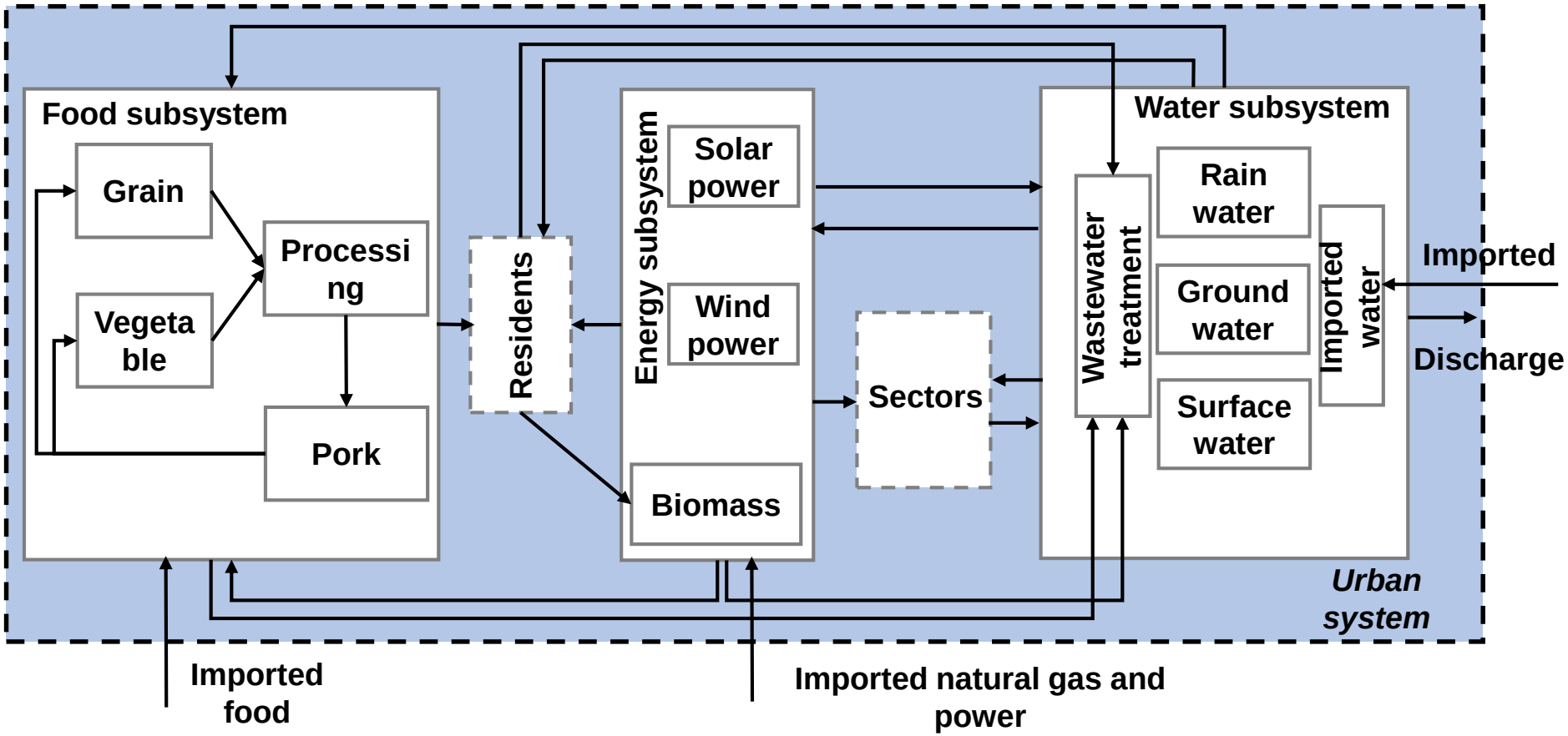


Energy subsystem



- To devise a systematic and integrated optimization model to explore the resources coordinated management
- To bump up the sustainability of cities and their hinterlands.
- To construct the FEW subsystems optimization models, with the exchanges among these three subsystems

Design models for urban FEW subsystems



- The FEW subsystems combined with socio-economic systems, an integrated optimization analysis can be carried out

Mathematical formulation for integrated system

Food subsystem objective function

$$TCExF = \sum_{d\in D} ex_d^{local} F_d^{local} + \sum_{d\in D} ex_d^{moved\ in} F_d^{moved\ in} + \sum_{c\in C} ex_c^{local} A_c^{local} + \sum_{c\in C} ex_c^{moved\ in} A_c^{moved\ in}$$

Food subsystem constraints

$$\sum_{d\in D} f_d^{\min} \times p \times 365 \le F^{dem} \le \sum_{d\in D} f_d^{\max} \times p \times 365$$

$$\sum_{d\in D} F_d^{local} + \sum_{d\in D} F_d^{moved\ in} = \sum_{d\in D} F_d^{dem}$$

$$F_{c,d}^{local} = A_c^{local} cf_{c,d}$$

$$\sum_{c\in C} L_c^{local} \le L_{c,current}^{local}$$

$$\sum_{i'\in I'} N_{i'}^{moved\ in} + \sum_{i''\in I''} N_{i''}^{local} = N^{dem}$$

Energy objective function

$$TCExE = \sum_{r\in R} ex_r M_r + \sum_{x\in X} ex_x^{el} ELD_x$$

Energy subsystem constraints

$$\sum_{x\in X} ELD_x = ELD^{dem}$$

$$ELD^{dem} = ELD^{local} + ELD^{moved\ in}$$

$$ELD^{dem} \le ELD^{current}$$

$$\sum_{x\in X} M_r \le M_r^{av}$$

$$\sum_{x\in X} ELD_x = \sum_{r\in R} \eta_{x,r}^{el} M_{r,x}$$

$$ELD_{bio}^{ns} \le \frac{K \times M_{bio}^{av} \times C_c}{T} \times \beta_{ns}$$

Cross-subsystems objective function

$$TCExC = TCExF + TCExE + TCExW$$

Cross-subsystems constraints

$$ELD_d^t = eld_{ag}^{local} A_{ag} + eld_{pro} (F_d^{moved\ in} + F_d^{local})$$

$$W_d^{dem} = w_c^{local} A_c^{local} + w_l^{local} A_l^{local} + w_d^{pro} F_d^{dem}$$

$$ELD_{wa}^t = \sum_{a\in A} eld_a W_a^{dem}$$

$$W_x^{dem} = \sum_{x\in X} w_x ELD^t$$

- Owing to the different nature of these resources, it is essential to choose a unified quantity for integrated optimization
- Exergy could provide a unified way to measure various natural resources
- Considering the life cycle processes of FEW consumption, minimizing the total cumulative exergy consumption is a better objective function

Scenarios—FEW systems

Food supply: local meat and eggs decrease 1/3 and1/4, respectively

Food supply: local vegetable supply increases 10%

Energy supply: coal to electricity

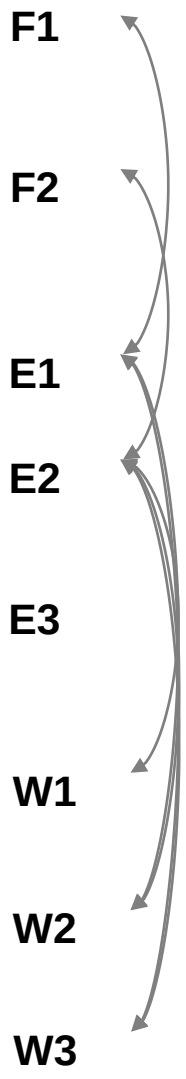
Energy supply: coal to natural gas

Energy supply : increase the share of renewable energy

Water supply: increase the share of wastewater reuse

Water supply: rainwater collection

Water supply: regional diversion

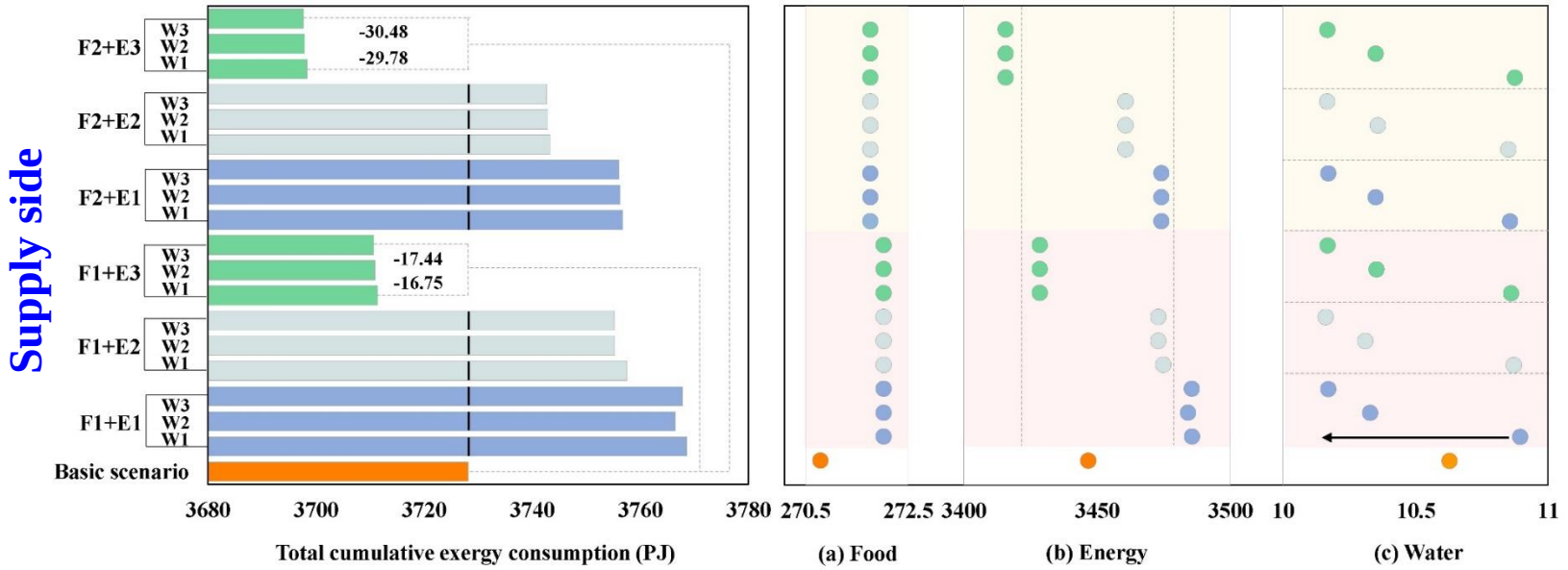


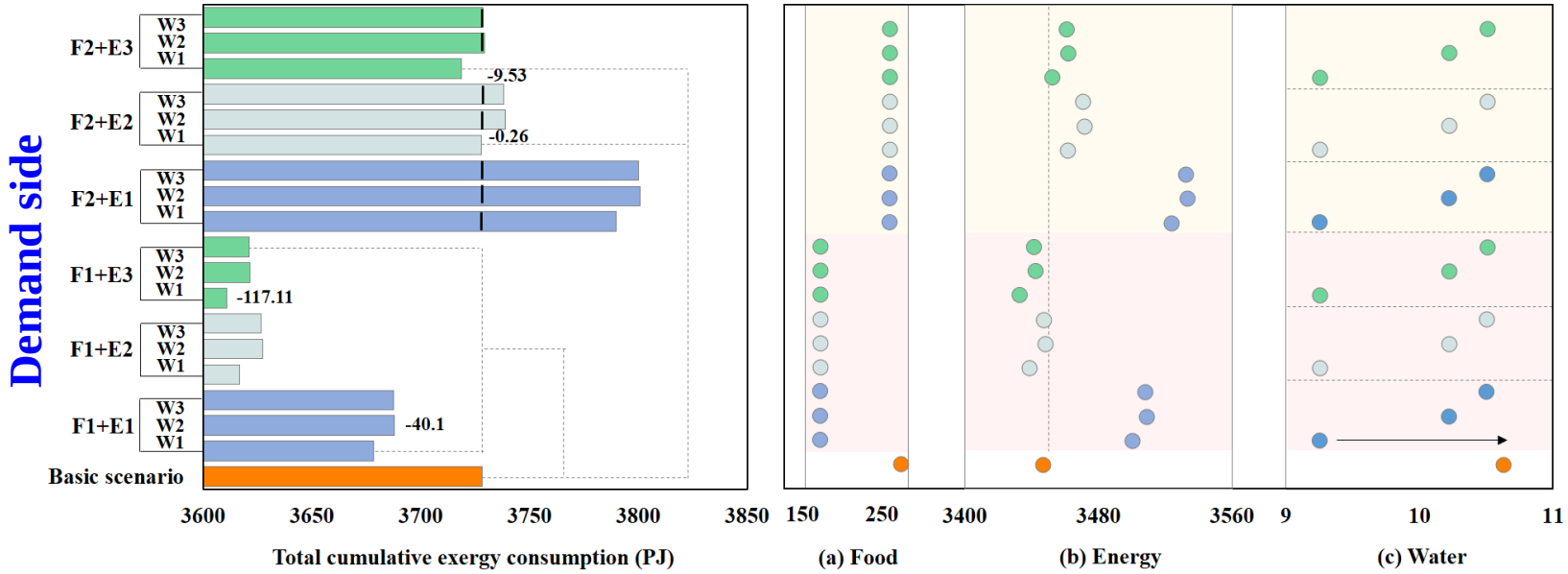
Supply side: 18 scenarios

F1+E1+W1	F2+E1+W1
F1+E1+W2	F2+E1+W2
F1+E1+W3	F2+E1+W3
F1+E2+W1	F2+E2+W1
F1+E2+W2	F2+E2+W2
F1+E2+W3	F2+E2+W3
F1+E3+W1	F2+E3+W1
F1+E3+W2	F2+E3+W2
F1+E3+W3	F2+E3+W3

- **Scenarios were set from production and consumption sides**
- **Single scenario in FEW subsystems**
- **Group scenarios based on the combination method**
- **Supply side: 18 scenarios**
- **Demand side: 18 scenarios**

Results—supply and demand sides





- Only 6 scenarios play positive role in reducing the total CExC
- Saving 30.5 PJ
- Coal to electricity/natural gas could increase the total CExC

- 11 scenarios play positive role in reducing the total CExC
- Saving 117 PJ
- Energy and food subsystems become the larger contributors to decrease the total CExC

Scenarios—integrated system

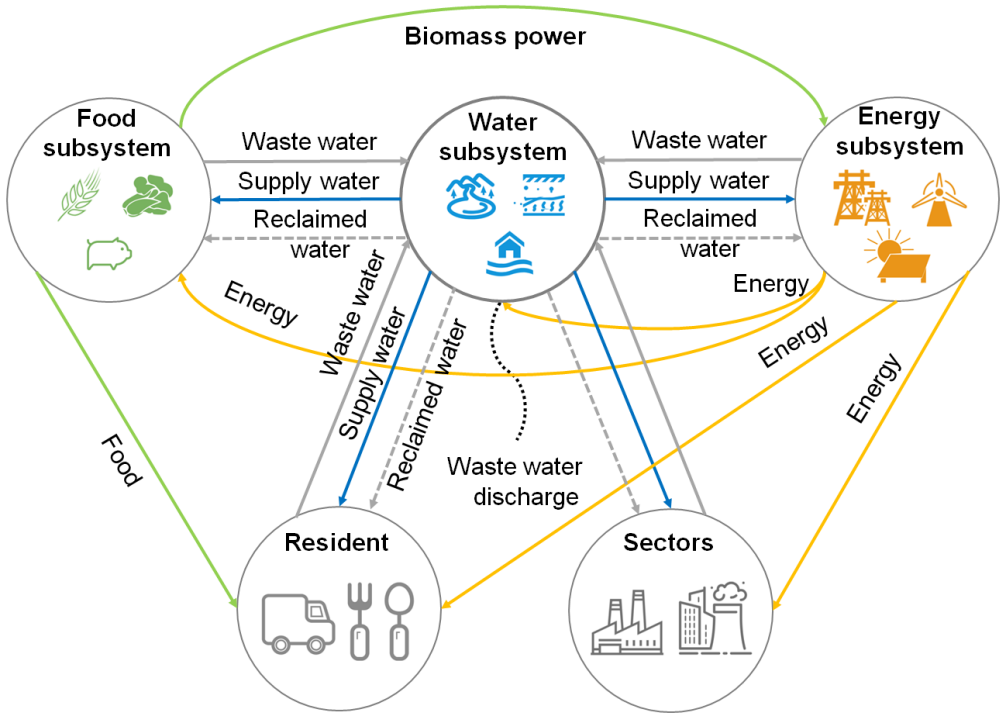


Diagram of integrated system optimization

We selected the scenarios of better performance from supply and demand sides, and then combined into 10 integrated scenarios. For example, this is the content of scenario I1, including FEW supply and demand.

Supply+Demand: 10 scenarios

Food supply: meat and eggs supply reduce 1/3 and 1/4, respectively; vegetable supply increase 10%;

Food demand: based on the Chinese Dietary Guidelines (minimum level)

Energy supply: coal to natural gas, local renewable energy increase, imported green power from other provinces (100kWh)

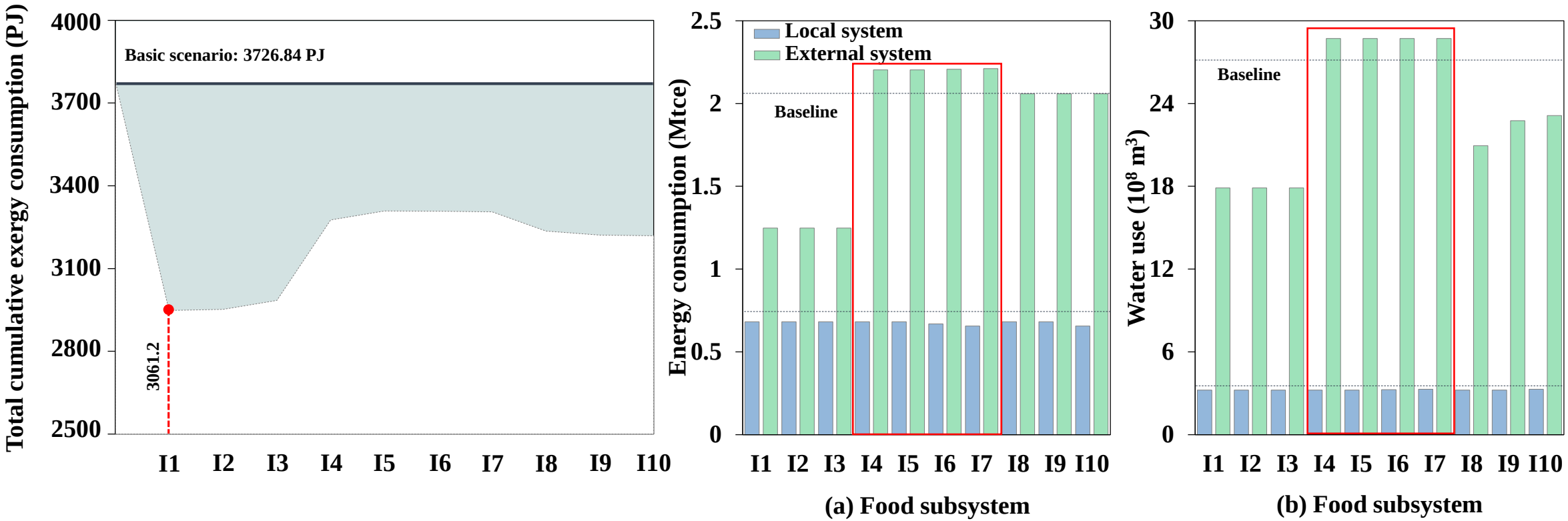
Energy demand: household saving

Water supply: increase rainwater collection and South-to-North Water Diversion

Water demand: household saving

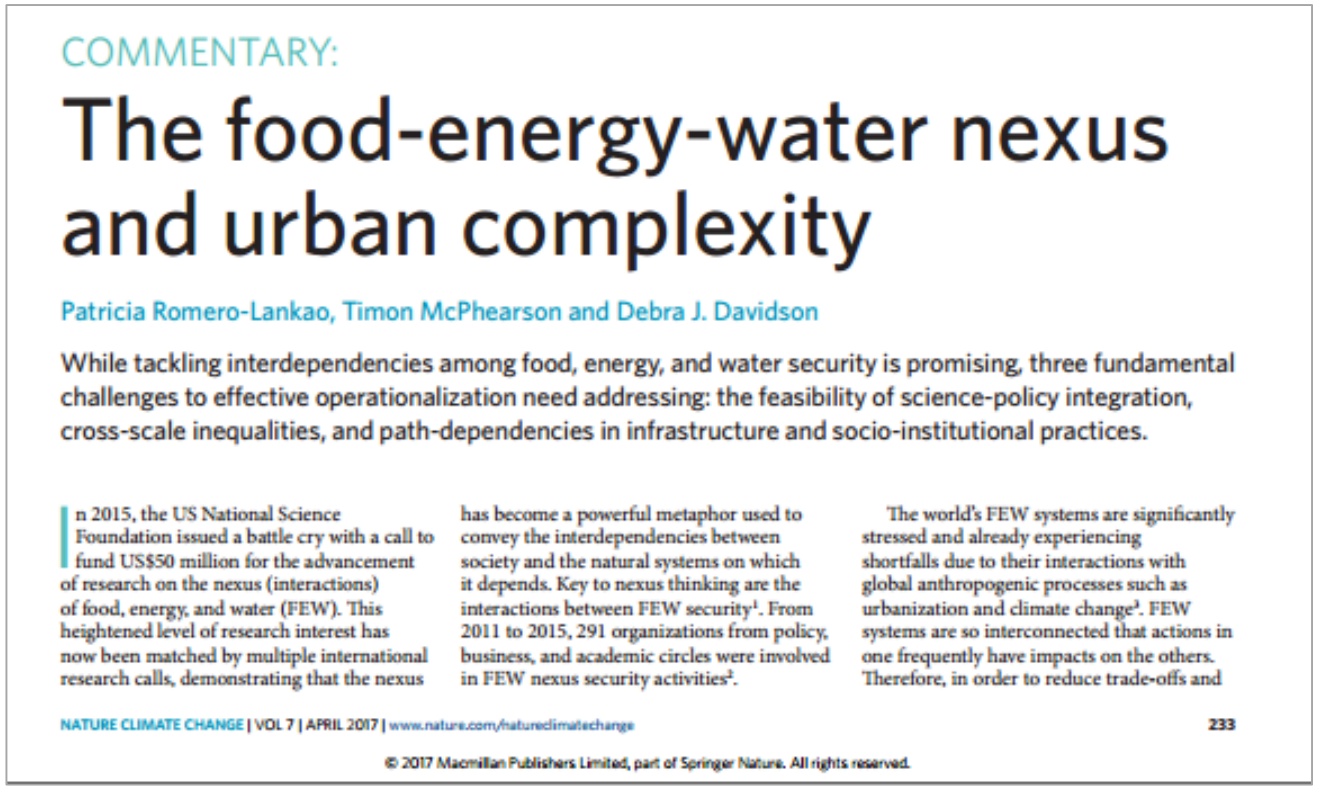
I1

Results—integrated system optimization



- All of the total cumulative exergy consumption (I1-I10) are less than BAU，**I1 is the better choice**
- The total cumulative exergy consumption could **decrease 665.6PJ (18%)**
- **Greater contribution:** food and energy subsystems (Scenario I1)
- **Trade-offs:** scenarios (I4-I7) show the trade-offs (energy and water footprint increase in food subsystem), due to the changes in food consumption

Real challenges facing with nexus transition



COMMENTARY:

The food-energy-water nexus and urban complexity

Patricia Romero-Lankao, Timon McPhearson and Debra J. Davidson

While tackling interdependencies among food, energy, and water security is promising, three fundamental challenges to effective operationalization need addressing: the feasibility of science-policy integration, cross-scale inequalities, and path-dependencies in infrastructure and socio-institutional practices.

In 2015, the US National Science Foundation issued a battle cry with a call to fund US$50 million for the advancement of research on the nexus (interactions) of food, energy, and water (FEW). This heightened level of research interest has now been matched by multiple international research calls, demonstrating that the nexus has become a powerful metaphor used to convey the interdependencies between society and the natural systems on which it depends. Key to nexus thinking are the interactions between FEW security[1]. From 2011 to 2015, 291 organizations from policy, business, and academic circles were involved in FEW nexus security activities[2].

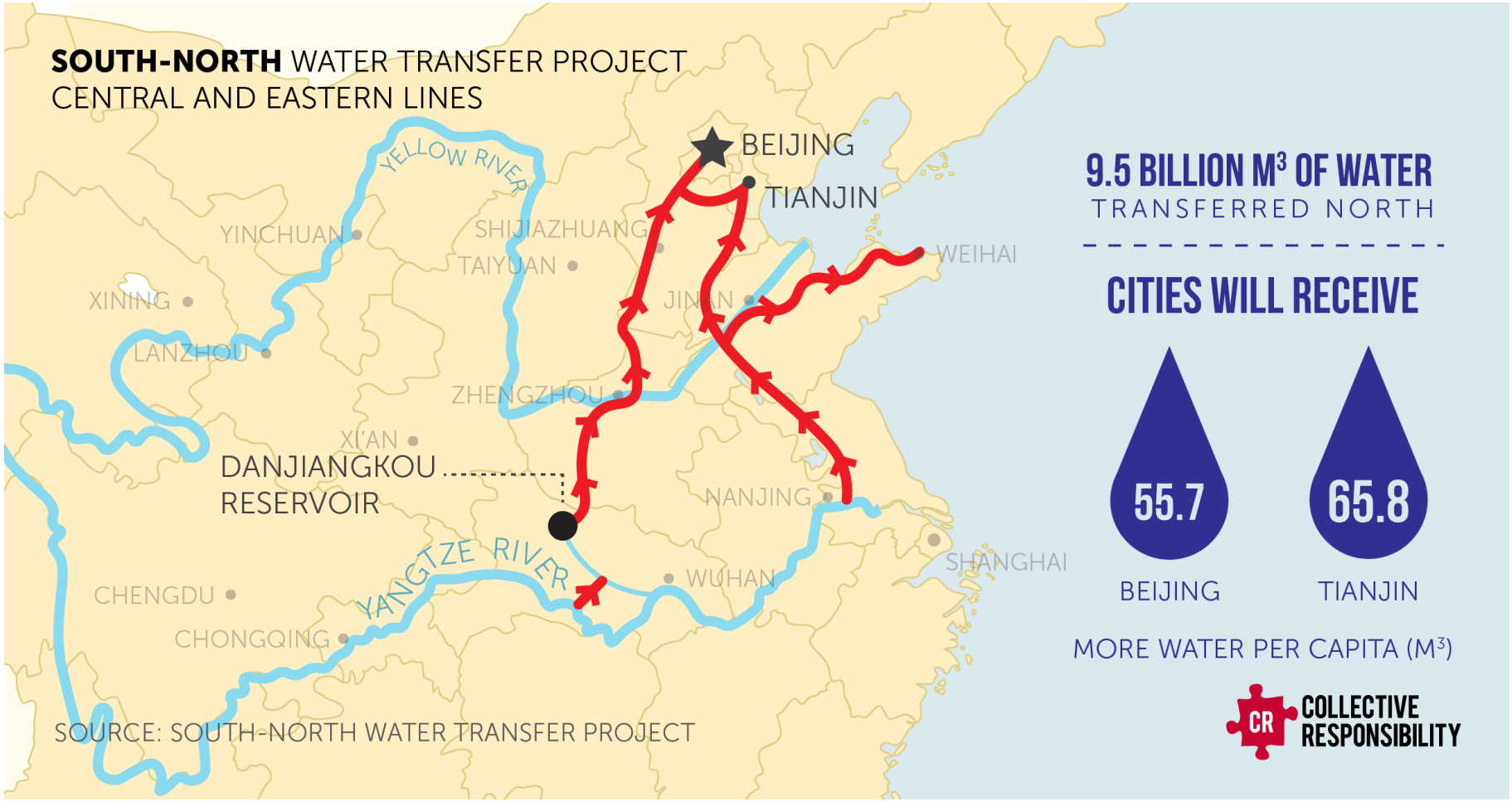
The world's FEW systems are significantly stressed and already experiencing shortfalls due to their interactions with global anthropogenic processes such as urbanization and climate change[3]. FEW systems are so interconnected that actions in one frequently have impacts on the others. Therefore, in order to reduce trade-offs and

- Feasibility of science-policy integration
- Cross-scale inequalities
- Path-dependency

Feasibility of science-policy integration

- Science-policy integration faced with the challenge of moving decision-makers beyond their accustomed ways of framing and managing
- Science-policy integration involves a collective engagement of disparate interests, values, and power relations.
- There is also frequently a mismatch between geographical and topical areas of concern and the jurisdiction or knowledge necessary to manage FEW security.

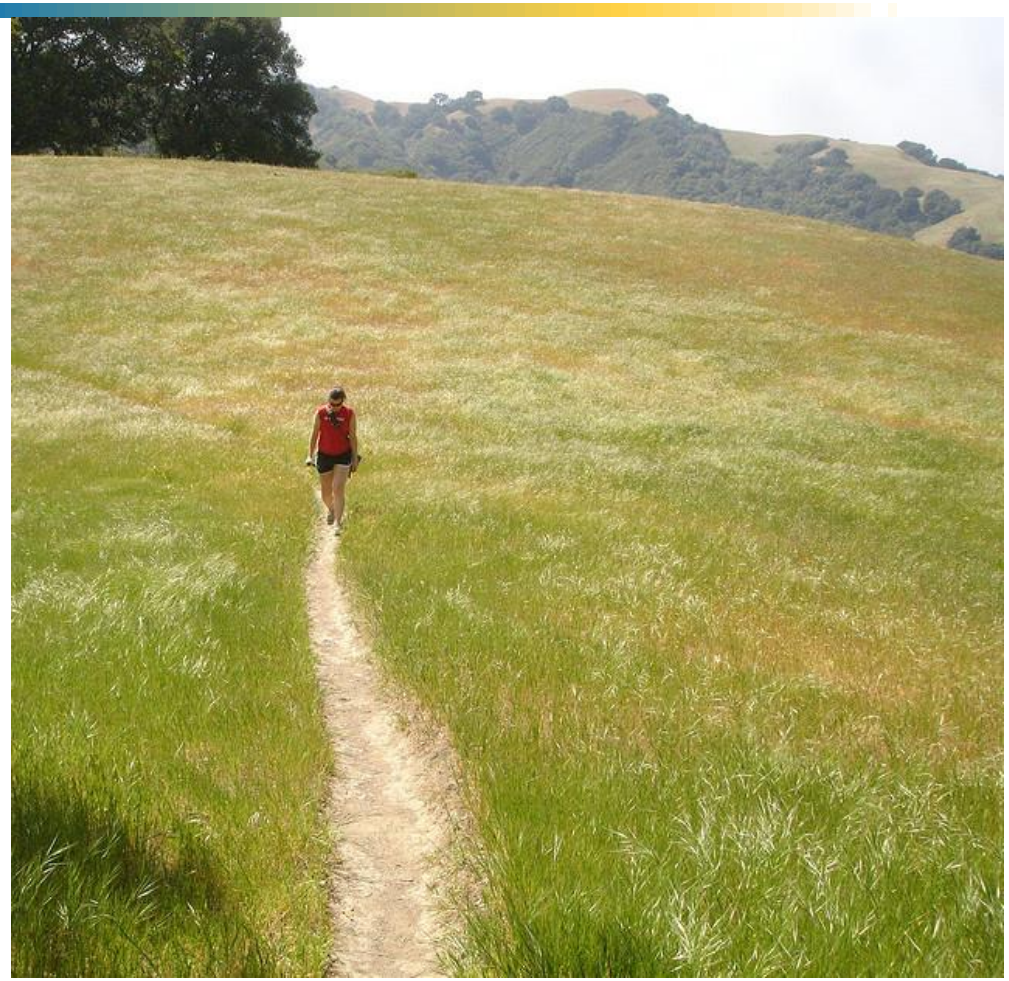
Cross-scale inequalities



By and for whom are FEW system being secured?

Path-dependence

Once adopted, very enduring and costly to change



Infrastructural and governance regimes shaping urban FEW security may be dynamically stable, with a high degree of path-dependency that makes them difficult to change

At worst, we will run the risk of perpetuating the very dysfunction we are try to repair!

----Romero-Lanko et al.,2017

Thanks for your attention!

Prof. Lixiao Zhang

zhanglixiao@bnu.edu.cn