



China's safe and just space during 40 years of rapid urbanization and changing policies

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Abstract

Context China's high-speed economic development was accompanied by rapid urbanization for forty years, guided by a series of changing policies enacted by the central government. However, did China become more sustainable both economically and environmentally? Or more specifically, did it operate within or towards a safe and just space (SJS)? Although numerous relevant studies exist, these questions have not been adequately addressed, and a multi-scale landscape perspective is needed.

Objectives The main objective of this study was to examine China's urbanization trends, associated institutional changes, and their impacts on the nation's sustainability trajectory during the past four decades.

Specifically, we intended to analyze the impacts of urbanization and related policies on the spatial patterns, temporal trends, shortfalls, and complex nexus of the different dimensions of SJS across scales in China.

Methods We apply the SJS framework, which integrates eight environmental ceilings and seven social justice foundations, to examine China's urbanization, socioeconomic dynamics, and institutional changes, as well as their impacts on sustainability at multiple spatial scales. Segmented regression and correlation analysis were used to analyze the relationship of SJS with landscape urbanization and governance across China.

Results Since the implementation of China's Western Development Plan, China has faced increasing challenges of overshoots in CO₂ emissions, phosphorus and nitrogen loading, ecological footprint, and material footprint on a per capita basis. However, our analysis showed that, by 2015, China met nearly all basic social justice needs. The pattern of SJS showed geospatial gradients of increasing social justice (except material footprint), multi-footprints, and CO₂ from eastern to central, northeastern, and western regions, and from developed to developing provinces. The tradeoffs between social justice, environmental safety, and regional equality remain pronounced across heterogeneous landscapes with different levels of urbanization. The western region's material footprint expanded enormously, but mainly for consumption in the eastern region of China.

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Conclusions China's development in the past four decades is characterized by enormous economic growth, rapid urbanization, much improved living standards, highly fragmented landscapes, and increasing environmental problems. To promote sustainability, China should continue to implement the strategy of high-quality development and promote ecological civilization. Regional landscape-based approaches are needed to explicitly recognize geospatial heterogeneity and disparities, and better understand the urbanization-governance-landscape nexus for promoting a safer and more just China.

Keywords Safe and just space (SJS) · Urbanization · Governance · Landscape · Sustainability

Introduction

The biosphere has been profoundly transformed by increasing human activities as the earth enters the Anthropocene (Steffen et al. 2015; Rockström et al. 2021). Poverty, unemployment, housing shortage, urban/rural slums, water scarcity, health hazards, waste disposal, transportation problems, and urban crimes obstruct social justice and sustainability. To promote global sustainability, Reworth (2012) combined the planetary boundaries (Rockström et al. 2009) and social foundations to develop the doughnut-shaped 'Safe and Just Space' (SJS) framework, which integrates the targets of a safe environment and the goals for social justice. O'Neill et al. (2018) downscaled the planetary boundaries to the national level and found that none of the more than 150 nations under study could meet its people's basic needs at a globally sustainable level of resource use. The situation has gotten worse in recent decades (Fanning et al. 2022). Rockström et al. (2021) recently proposed a "safe and just corridor" framework to facilitate further the integration of the "safe" and "just" targets and help achieve the Sustainable Development Goals (SDGs) at sub-global scales.

Urbanization is usually both a driver and a consequence of economic development, which plays an important role in human-environmental systems' transition toward sustainability on multiple scales, as demonstrated in China during recent decades (Bai et al. 2014; Wu et al. 2014; Bian et al. 2021). By

2030, the global urbanization level is expected to be over 60%, and urban landscapes will increase by 1.2 million km² worldwide, resulting in a considerable loss of biodiversity and natural vegetation (Seto et al. 2012). Urban areas produce over 75% of the world's GDP, but also are responsible for 70% of global greenhouse emissions and energy demand (Elmqvist et al. 2019; Krueger et al. 2022). Hence, urban regions have been widely recognized as critical places to fight against climate change, environmental risk, and social injustice and inequality (Keivani 2010; UN 2020; Bian et al. 2021; Wiedmann and Allen 2021). Importantly, governance plays a key role in achieving urban sustainability through laws, policies, and development and conservation plans. To address the interactions among urbanization, governance, and sustainability, several regional-scale approaches have been proposed in recent decades, such as the integrated landscape approach (Sayer et al. 2013), land system science (Verburg et al. 2013, 2015; Turner et al. 2003, 2007 and 2021), and landscape sustainability science (Wu. 2013, 2021). These approaches provide spatially explicit, context-specific frameworks that can help mitigate tradeoffs and foster synergies between environmental safety and social justice by focusing on regional landscape scales.

As the world's second-largest economy, China has experienced unprecedented urbanization and economic growth during the past four decades, with enormous changes in socioeconomic equality and urban landscape patterns (Fang et al. 2018; Kuang 2020). Meanwhile, China has increasingly been faced with environmental pressures, unsustainable consumption, and increasing vulnerabilities to natural disasters. To meet these challenges, China needs to continually improve urban resilience and sustainability by identifying the shortfalls of SJS at multiple administrative levels, understanding the complex interactions of SJS targets across scales, and promoting the synergy among the SJS targets. Towards this end, Chinese scientists are making significant research advances, including (1) observing, monitoring, and modeling urban sustainability using big earth data (Lu et al. 2015; Gao et al. 2021; Huang et al. 2021); (2) understanding the causes, processes, and consequences of landscape urbanization (Bai et al. 2014; Bian et al. 2021); (3) advocating adaptive landscape governance and planning through institutional reforms and policy initiatives (Bryan et al.

2018; He et al. 2018). However, it remains unclear how urbanization, economic development, and institutional changes (or governance) interact on different scales and what kinds of tradeoffs and synergies exist among sustainability targets. Addressing these questions is imperative for China's sustainable development in the future.

The main goal of this study, therefore, was to systemically examine the trends, shortfalls, spatial patterns, and complex interactions of SJS targets in China during the past 40 years from an urbanization-governance-landscape nexus perspective. Using a set of urbanization and sustainability indicators of SJS (O'Neill et al. 2018; Fanning et al. 2022), the study had the following three specific objectives: (1) To quantify the long-term trajectories of China's national sustainability during rapid urbanization and a series of governance events from 1978 (the beginning of Reform and Opening-Up) to 2020; (2) To assess the shortfalls and spatial pattern of China's SJS across multiple administrative levels; (3) To analyze the tradeoffs and synergies among the SJS targets; (4) To advocate a safer and more just future for China by promoting a landscape sustainability-based approach that closely links SJS, governance, urbanization, and biophysical landscapes.

Methods

Quantifying developmental phases

To analyze the spatiotemporal patterns of, and relationships among, urbanization, governance, and sustainability measures in China, we first examined if there were distinct developmental phases from 1978 to 2020. Urbanization was represented by demographic urbanization levels (% urban population and total urban population) and landscape urbanization (built-up area). We reviewed more than 20 national policies and development programs that were focused on demography (e.g., the One Child Policy in 1979), regional development (e.g., China's Western Development Plan in 2000), economy (e.g., the Establishment of the Socialist-Market Economic System in 1992), and environment (e.g., ecological restoration programs). Based on the long-term trends of several environmental and socioeconomic variables (Fig. 1), we attempted to identify different developmental

phases using the change point detection method (Aminikhanghahi and Cook 2017) and segmented regression models (Toms and Lesperance 2003), with consideration of governance objectives (Bryan et al. 2018), urban transitions (Bai 2008), and progress towards SDGs (Lenzen et al. 2022). Four phases were identified: 1978–1983, 1984–1999, 2000–2013, and 2014–2020. Within each phase, linear regression was used for analyzing the relationships of the indicators of sustainability (e.g., EF and HDI) to urbanization levels, as well as the influences of policy objectives and urbanization on national sustainability over time.

Assessment of China's safe and just space on multiple scales

The safe and Just Space (SJS) concept integrates environmental ceilings (i.e., planetary boundaries) and social foundations (i.e., food, water, energy, housing, and education) to define a safe and just space within which humanity can sustainably live (Raworth 2012). This study was focused on the following environmental ceilings all of which are related to the United Nations' Sustainable Development Goals (SDGs): CO₂ emissions per capita (SDG 13: climate action), cumulative CO₂ emissions (SDG 13), phosphorus and nitrogen loading (SDG 2: zero hunger; SDG 6: Clean water and sanitation; SDG 14: life below water), ecological footprint per capita (SDG 12: responsible consumption and production; SDG 14; SDG 15: life on land), material footprint per capita (SDG 12), land use changes (SDGs 13 and 14), and blue water footprint per capita (SDG 6: clean water and sanitation). To assess climate change, we consider both CO₂ emissions per capita and cumulative CO₂ emissions. We also accounted for biogeochemical flows, including the nitrogen and phosphorus cycles. The transformation of land systems and freshwater resources is evaluated using the human appropriation of net primary production (HANPP) and the blue water footprint. Moreover, we used ecological and material footprints as metrics to quantify human demand for natural resources and the allocation of extracted raw materials to meet an economy's demand (Fig. 2). To assess environmental safety, we utilized the down-scaled thresholds defined by O'Neill et al. (2018) at the per capita level (Supplementary Table 1). If an environmental indicator's value falls below 0.8, it is considered "Safe"; if it falls between 0.8 and 1, it is

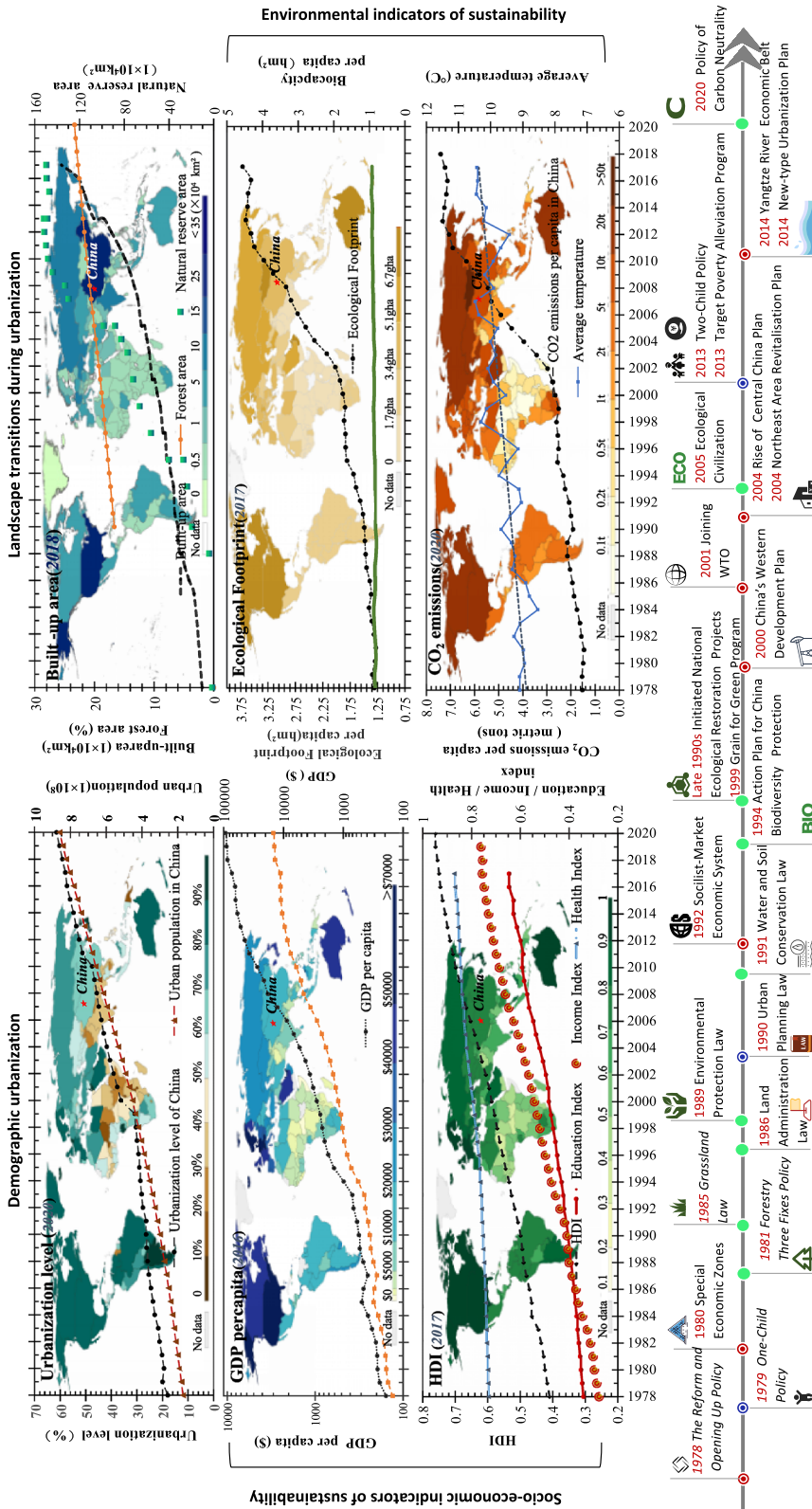


Fig. 1 Trajectories of China’s urbanization, sustainability-related indicators, and key governance events during the past 40 years. Urbanization includes demographic urbanization (% urban population and total urban population) and landscape urbanization (built-up area). Sustainability indicators cover the dimensions of the economy (red circles), environment (green circles), and human well-being (blue circles). Data on urbanization level, urban population, GDP, CO₂, and forest area were compiled from the World Bank (<https://data.worldbank.org/country/>). The dynamics of HDI, education index, income index, and health index were from Human Development Reports (UNDP, <http://hdr.undp.org/en/data.worldbank.org/country/>). The ecological footprint (EF) and biocapacity data were from the Global Footprint Network (<https://www.zuijiwangluo.org/ecological-footprint-results/>). The average temperature and nature reserves area data were from China’s Environmental Protection Administration and China Meteorological Administration (<http://data.cma.cn/data>). The global pattern of the indicators was produced by Our World in Data (<https://ourworldindata.org>) and Global Footprint Network (<https://ourworldindata.org>)

considered “Potential Risk”; and if it exceeds 1, it is considered “Risk” (Fig. 2).

Social foundations represent social justice benchmarks, encompassing the multiple facets of objective well-being, including nutrition (NU), education (ED), employment (EM), access to energy (EN), equality (EQ), income (IN), and healthy life expectancy (LE). These indicators are also aligned closely with SDGs, including zero hunger (SDG 2), good health and well-being (SDG 3), quality education (SDG 4), no poverty (SDG 1), reduced inequality (SDG 10), and affordable and clean energy (SDG 7). The SJS boundaries adopted are downscaled at both the per capita and national scales, as defined by O’Neill et al. (2018) (for specific threshold details, please refer to Supplementary Table 1). For socio-economic indicators, values between 0 and 0.8 are categorized as “disparity”; those between 0.8 and 1 as “increasing justice”; and values reaching 1 as “just” (Fig. 2B). For the indicators of SJS at the provincial (31 provinces in mainland China, excluding Hongkong, Macau, and Taiwan) and regional scales (i.e., western, northeastern, central, and eastern China), the values are normalized to the range between -1 to 1. Negative values indicate relatively higher levels of environmental safety but relatively lower levels of social justice, whereas positive values denote higher levels of social justice but higher environmental risks (Fig. 3).

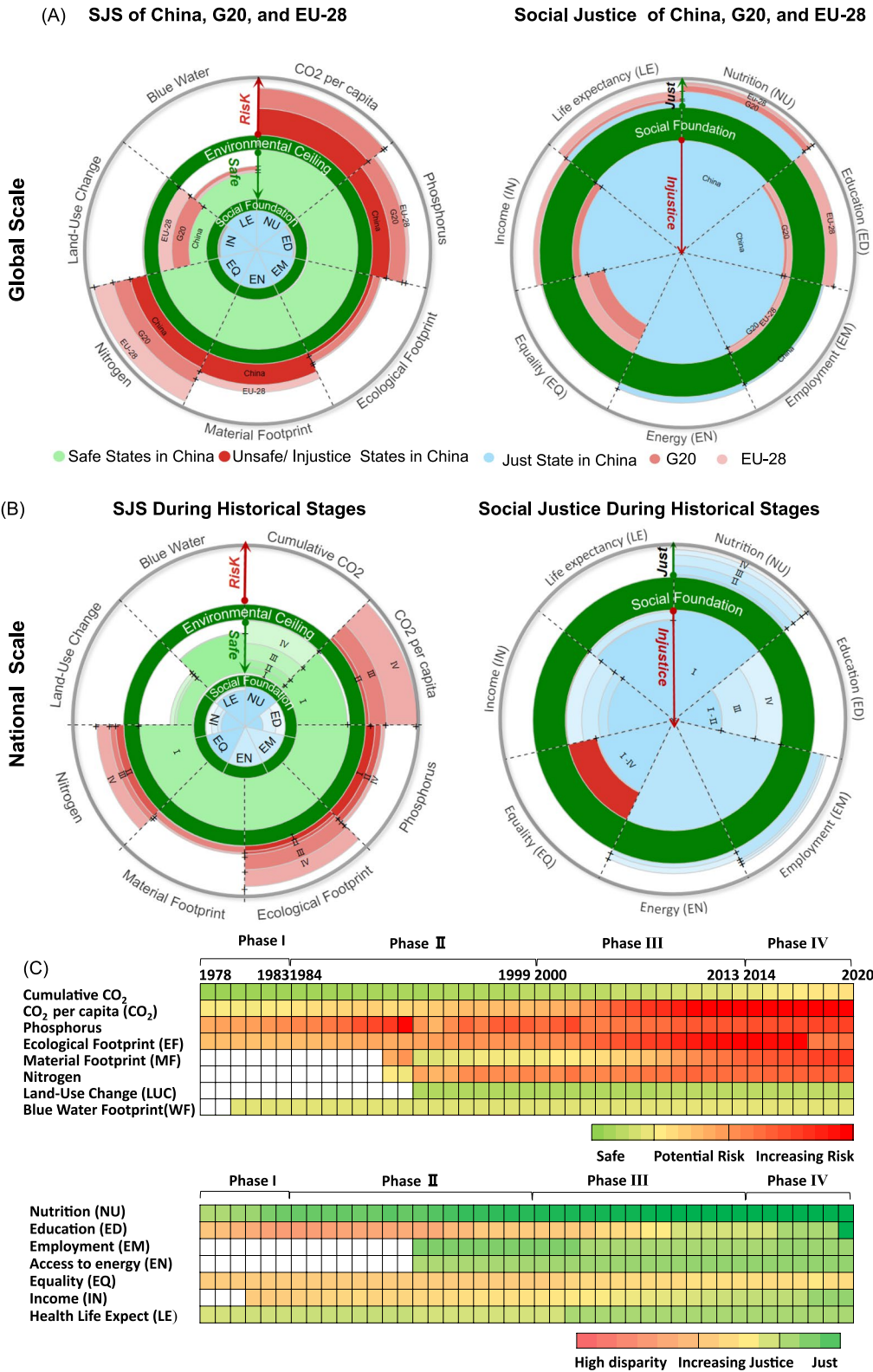
China’s sustainability trajectories under urbanization and governance on multiple scales

Since the Reform and Opening-up Policy in 1978, China experienced enormous changes in the environment, socioeconomic conditions, and landscape patterns, driven by rapid urbanization and a series of problem-oriented and priority-based governances in different stages (Fig. 1). From 1978 to 2020, China’s urbanization level increased from 18.92 to 61.43%, urban population from 171 to 861 million, built-up areas from 1.94×10^4 to 24.53×10^4 km², GDP per capita from US\$149.54 to US\$14,723, HDI from 0.41 to 0.76, education index from 0.34 to 0.65, health Index from 0.73 to 0.87, and income index from 0.28 to 0.76. These impressive socioeconomic developments had enormous environmental consequences. For example, during 1978–2020,

the average temperature of China rose from 9.01 to 10.48 °C, EF per capita increased from 1.31 to 3.71 hm², and CO₂ emission per capita from 1.46 to 7.41 metric tons.

Changes in national policies, development programs, and other governance-related factors were main drivers for China’s rapid economic growth, urbanization, and landscape transformations across the country, together affecting its sustainability trajectory during the past four decades (Fig. 1). Our analysis, using the change point detection method and the segmented regression between urbanization and sustainability-related indicators, revealed that China’s development could be divided into four phases: 1978–1983: Phase I—the start-up phase, 1984–1999: Phase II—the regulation and restoration phase, 2000–2013: Phase III—the take-off phase, and 2014–2020: Phase IV—the adaptive planning phase (Fig. 1 and Supplementary Table 1).

Driven by the ‘Reform and Opening-up Policy’ (1978), during Phase I China began to focus on socioeconomic development as the national priority. Moderate urbanization rates in this stage (rising from 18.92% to 21.62%) were due largely to the household registration system, restricting rural residents from moving to cities. The urban development policy of Phase II changed from ‘strictly controlling the scale of large cities, rationally developing medium cities, and actively developing small cities and towns’ to ‘coordinated development of the large, medium, and small cities’, macro-regulated by the urban planning law (1990) (Fig. 1) (Bai et al. 2014; Fang. 2018). In the late 1990s, China suffered a number of disasters, such as drought along the Yellow River Basin (1997), flooding along the Yangtze River Basin (1998), and severe dust storms in northern China (2000), all of which were attributed to ecosystem destruction and unsustainable landscape management (Bryan et al. 2018). Then, the central government initiated a series of policies and programs of ecological restoration to combat climate change impacts, deforestation, ecosystem degradation, and overcultivation on sloping land in the late 1990s, such as ‘The National Land Consolidation Program’ (1997), ‘National Forest Conservation Consolidation Program’ (1998), ‘Grain for Green Program’ (1999), and other national ecological projects (Bryan et al. 2018). During Phase II, China’s forest area increased from 16.67 to 23.34%, and the number of nature reserves increased from



◀**Fig. 2** Environmental safety and social justice in China during 1978–2020, represented by Safe and Just Space (SJS) on a per capita basis. **A** The shortfalls of SJS in 2011, **B** Changes in the SJS of China during the four phases, and **C** Temporal dynamics of environmental risks and social justice from 1978 to 2020. The environmental ceiling and social foundation of SJS per capita were defined by O'Neill et al. (2018) and Fanning et al. (2022). The original data were compiled from the University of Leeds, the World Bank, the IFA, the State Statistical Bureau of the PRC, and Jiang et al. (2019a, b)

34 to 2750 (the total area grew from 1.26×10^4 to $147.33 \times 10^4 \text{ km}^2$) (Fig. 1).

After the ‘Western Development Plan’ (2000), China entered into the take-off phase (i.e., Phase III: 2000–2013), with the priority of developing the inland regions, followed by ‘The Rise of Central China Plan’ (2004), ‘Northeast Area Revitalization Plan’ (2004), and ‘Targeted Poverty Alleviation Program’ (2013) (Fig. 1). Driven by these strategies and large-scale urbanization, China’s wealth soared, but environmental pressures also built up quickly, resulting in resource overexploitation and extensive landscape fragmentation and degradation. ‘Ecological Civilization’ (2005) and ‘Carbon Neutrality’ (2020) have been prioritized for promoting national sustainability in Phase IV, the adaptive planning stage (2014–2020). China established the Pioneering and Demonstration Belt for Ecological Civilization—the Yangtze River Economic Belt (YEB) (2014) to alleviate the risks of ecosystem degradation and climate change in China’s longest river. To help mitigate climate change, China has promised to reach its carbon peak by 2030 and achieve carbon neutrality in 2060 (Fig. 1). ‘New-Type Urbanization’ (2014) in particular provided another impetus to develop green GDP, improve human well-being, and increase urban resiliency through innovative technologies, adaptive planning, and integrated management. The positive consequences of these policy interventions in improving the environment and society were still time-lagged and on a limited scale, requiring more research and extensive cooperation between multiple sectors in the future.

China’s safe and just space at multiple scales

China faces tremendous challenges to achieve high levels of human well-being for 914.25 million urban

and 598 million rural inhabitants, while simultaneously improving environmental safety. From a global perspective, the world is faced with similar challenges, transgressing environmental boundaries faster and earlier than achieving social justice goals (Fig. 2B-1 and B-2). In 2020, China transgressed environmental ceilings in terms of CO₂ emissions, nitrogen and phosphorus loading, material footprint (MF), and ecological footprint (EF) at the per capita level, while cumulative CO₂ emissions, blue water, and land-use change were all within the environmental ceiling (Fig. 2A). Comparatively, China’s environmental risk was about 1/3–3/5 of G20 and EU-28, but with high levels of social justice per capita (about 90%) in terms of ED, NU, and EQ (Fig. 2A). Nevertheless, China achieved almost all the targets of social justice (except EQ) on a per capita basis by 2015 during the adaptive planning stage. Urbanization and governance-related changes may have contributed to these transformations.

The prominent challenges in terms of the national SJS changed from low levels of social justice to overshooting the boundaries of environmental safety over the past four stages, especially after Phase III (Fig. 2B and C). During Phase I, CO₂ emissions per capita did not overshoot the environmental ceiling, with an average value of 96% threshold. Meanwhile, EQ, IN, and LE per capita were at 44–96% levels. During Phase III, encouraged by a series of regional development strategies (e.g., the Western Development Plan, the Rise of Central China Plan, and the Targeted Poverty Alleviation Program), GDP per capita experienced an 11-fold increase (Fig. 1), poverty ratio decreased from 26.9% to 0, and the ratio of secondary school enrollment increased from 60.3 to 90%. However, during this period, EF per capita almost doubled, rising from 219 to 399%. Both CO₂ per capita and MF tripled, increasing from 166 to 458% and from 90 to 270%, respectively, with only phosphorus loading relatively stable but still overshooting the environmental ceiling (260–290%) (Fig. 2B and C). In the adaptive planning stage, although the environmental risk increased continuously, their increasing ratios of overshoot environmental indicators decreased. EF per capita decreased from 453 to 255%, maybe indicative of the beginning of a transformation from extensive development to high-quality development.

Across China, the more developed provinces in eastern China had higher levels of social justice (i.e.,

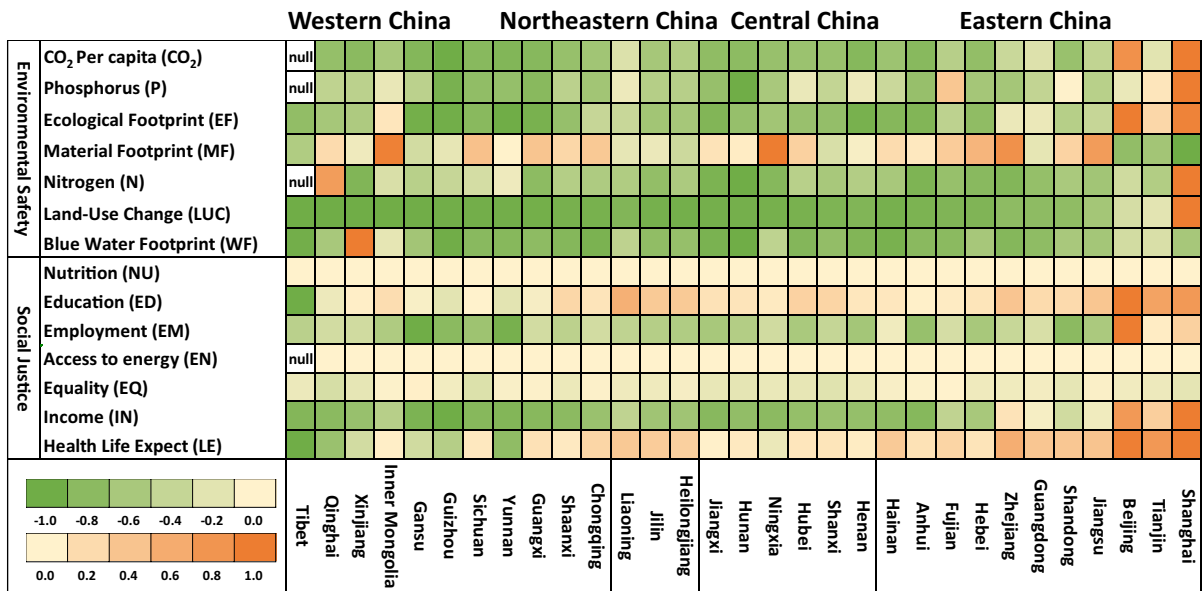


Fig. 3 The spatial patterns of SJS at the provincial scale in 2010. The color scale shows the scores of SJS. The negative value (green) shows high levels of environmental safety and

low levels of social justice, while positive values (orange) indicate high degrees of social justice and high environmental risks

LE, IN, EM, ED) but lower levels of environmental safety (i.e., CO₂ emissions, phosphorus and nitrogen loading, EF) than the less developed provinces in central, northeastern, and western regions of China in 2010 (Fig. 3). For environmental safety, MF had almost the opposite pattern as compared to other footprints and CO₂ emissions. The less developed provinces in western China (e.g., Inner Mongolia, Qinghai, Ningxia, and Shaanxi) had higher MF levels than the more developed provinces in eastern China (e.g., Shanghai, Beijing, and Tianjin). In addition, WF was higher in Xinjiang, Inner Mongolia, Gansu, Ningxia, Beijing, and Tianjin (Fig. 3). For social justice, NU, EN, and EQ exhibited the lowest level of heterogeneity among the indicators of SJS in the 31 provinces, and all met the basic thresholds of social justice. Although China implemented the nine-year compulsory primary and secondary education policy throughout the nation, eastern China had higher education enrollments, more investments, and better infrastructure than the other regions (Fig. 3).

China is faced with a number of sustainability challenges similar to those of other developing countries around the world. O’Neill et al. (2018) and Fanning (2022) found that most countries exceeded the per capita thresholds for environmental boundaries,

particularly CO₂ emissions per capita for which 66% of countries exceeded the limit. Additionally, 55% of countries overshot in terms of EF, phosphorus and nitrogen loading, land use change, and MF. In addition, nations tend to increase environmental risks faster than improve social justice. Furthermore, by applying a decision-based method to downscale the SJS framework for assessing the sustainability of South Africa, Cole et al. (2014) identified several risks in biodiversity loss, WF, carbon emissions, safety, IN, and EM, thus underscoring the utility of the SJS in informing national policies at national scale.

The SJS-urbanization-governance-landscape nexus across scales

Tradeoffs and synergies within the SJS-urbanization-governance-landscape nexus

China’s governance systems, urbanization, and landscapes are closely interconnected with one another, which together determine the targets and thresholds of environmental safety, social justice, and drivers for sustainability across scales. We simplified the

complex SJS-urbanization-landscape nexus by distinguishing the synergies and tradeoffs among SJS targets, urbanization, and landscape transformations to derive practical suggestions for integrated and synergic governance. Pearson correlation coefficients were selected to examine the synergies and tradeoffs at the national, regional, and provincial scales (Fig. 4). For China as a whole, the elements of environmental safety and social justice showed obvious tradeoffs during the past 40 years as the urbanization level and landscape urbanization rapidly increased, such as improving income and reducing CO₂ across national, regional, and provincial scales (Fig. 4A-2, B-2, and C-2). Meanwhile, these two sets of sub-targets were closely related, such as the footprint family indicators (e.g., ecological footprint, blue water footprint, nitrogen footprint, and material footprint), and indicators

related to social justice (e.g., HDI, income, as well as health life expect) (Fig. 4A-1).

Our results show that, during the past 40 years, China’s rapid urbanization and economic growth, as well as human well-being improvements, were accompanied with equally rapid expansion of footprints in terms of carbon emissions, phosphorus and nitrogen loading, resource consumption, and environmental pollution (Fig. 4A-1 and A-2). This was especially true for carbon and ecological footprints (Fig. 2B-1 and B-2). The decoupling between environmental safety and social justice has not happened on a national scale in China (Lu et al. 2019). Governance has always aimed at reducing tradeoffs between social justice, environmental safety, and improving environmental resiliency through the cooperation of stakeholders, the public, and scientists from multiple

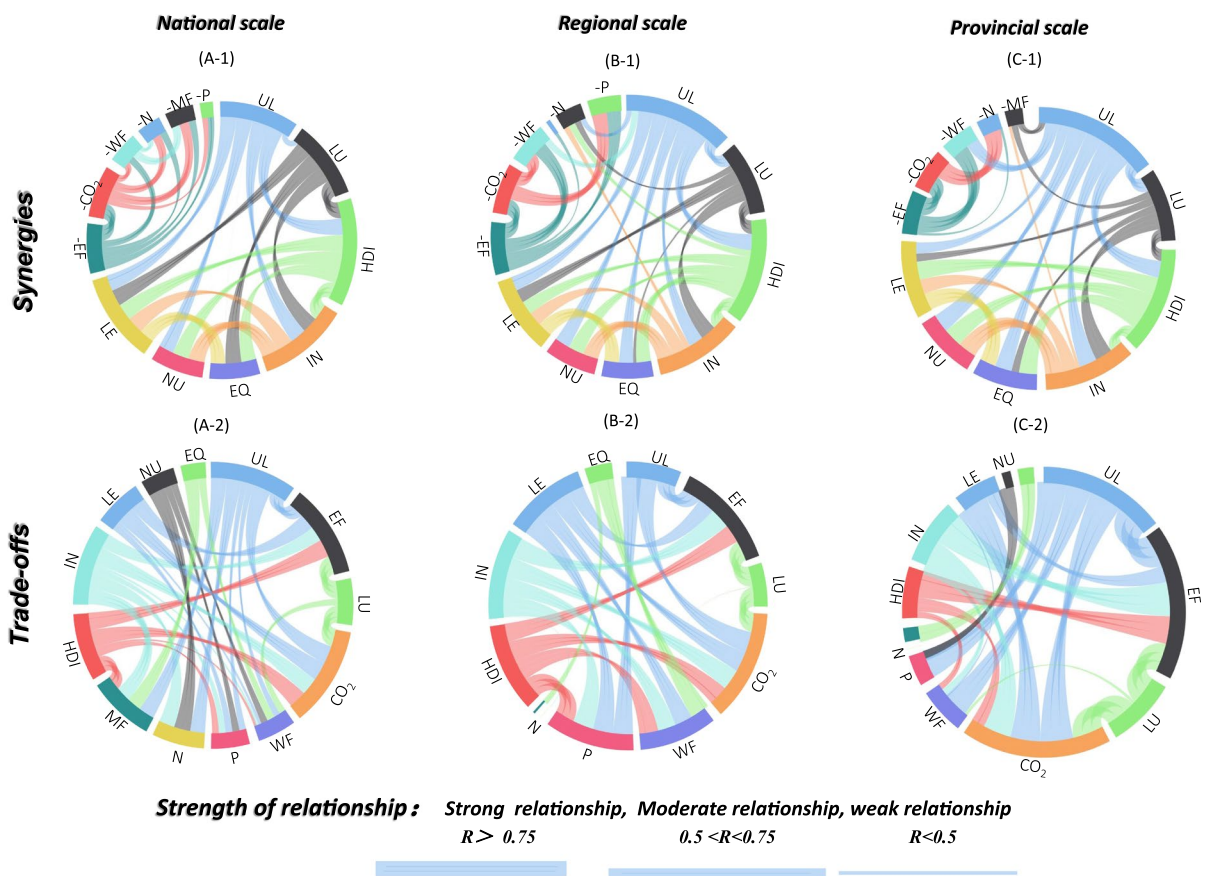


Fig. 4 Tradeoffs and synergies among the targets of Safe and Just Space (SJS) and urbanization at the national (A-1 and A-2), regional (B-1 and B-2), and provincial (C-1 and C-2)

scales. *UL* Demographic urbanization; *LU* Landscape urbanization; *IN* Income index; *CO₂* CO₂ per capita; *P* Phosphorus; and *N* Nitrogen

sectors and scales (Bowen et al. 2017; Alcamo et al. 2020). Among the policies, ‘Targeted Alleviation Program’ (2013) has achieved significant success in elevating rural human well-being through ecological restoration in some regions of China, such as the Karst landscapes in southwestern China (Wang et al. 2019).

Kroll et al. (2019) found notable synergies among the SDGs that are related to targets of social justice, such as income (SDG1: poverty alleviation), health life expects (SDG3: ensuring healthy lives and promoting well-being), access to energy (SDG7: affordable and clean energy), employment (SDG8: decent work and economic growth), and infrastructure, innovation, and industrialization (SDG9:). However, tradeoffs were inevitable among cities and communities (SDG11), just, peaceful, and inclusive societies (SDG16), and climate action (SDG13) (Kroll et al. 2019). Fuso Nerini et al. (2018) also reported tradeoffs between access to energy (SDG7) and the need for renewable resources reducing the footprint, and advocating integrated pathways that consider social justice (Sovacool and Dworkin 2014). To achieve sustainability across scales, social justice should be maximized, while reducing human consumptions (e.g., ecological footprints) through effective governance and improving local and regional self-sufficiency (Dorninger et al. 2017).

Synergies between mitigating material footprint, social justice, and urbanization

At the regional and provincial scales, synergies were observed between the reduction of MF, improvement of social justice (e.g., HDI and income index), and urbanization (Fig. 3 and Fig. 4 B-1 and C-1). Seemingly, in some more developed provinces, MF and socioeconomic improvement were decoupled to a large extent, probably attributable to various forms of environmental governance. For example, more developed provinces tend to reduce their material extraction through domestic and international trade with less developed provinces and countries (Wiedmann et al. 2015). Jiang et al. (2019a, b, 2022) also reported spatial synergy between the reduction of MF and socioeconomic improvement, as the northwestern region with low levels of urbanization and income (e.g., Xinjiang, Inner Mongolia, and Qinghai) exported a large amount of raw materials (e.g., fossil fuels, biomass,

and non-metal) to the eastern provinces which had the highest levels of urbanization and social justice (e.g., Beijing, Shanghai, and Guangdong).

Based on our analysis, the trajectory of China’s 40 years of development across national, regional, and provincial scales is aligned with the concept of weak sustainability (i.e., allowing for substitution between natural and manufactured capital), making it difficult to adhere to the principles of strong sustainability (i.e., natural capital is not substitutable) about SJS (Neumayer 2003; Pelenc and Ballet, 2015; O’Neill et al. 2018). In the absence of domestic and international trade, the tradeoffs between environmental safety and social justice, as well as the preference for weak sustainability, are amplified in developed regions and urban landscapes in China compared to developing regions and rural/natural landscapes. In the long term, the strong sustainability perspective is needed, and landscape approaches can help achieve that goal.

The SJS-urbanization-governance-urban landscape nexus in China

Scaling-down per capita overshoot in the environmental ceiling from global to national scales is necessary (O’Neill et al. 2018; Fanning et al. 2022) because of the geospatial heterogeneity of environmental and socioeconomic conditions across regions that include urban, rural, and natural landscapes. Landscapes result from the interactions between human activities and the natural environment, representing a core operating scale for achieving SJS targets through design, planning, and management (Sayer et al. 2013). This is particularly pronounced in urban landscapes, where the dynamics of SJS, urbanization, and governance are intricately intertwined across temporal and spatial scales. This integration is a result of the agglomeration of population, resource consumption, and fluxes of natural and material capital from distant places facilitated by complex transportation networks (Kennedy et al. 2011).

We used the regression analysis and segmented linear regression to analyze the long-term dynamics of the complex SJS-urbanization-governance-landscape nexus using urbanization, EF, income index, and HDI as indicators (Fig. 5B). The relationship between landscape urbanization and EF per capita fit the left part of an Inverted-U shape (i.e., environmental

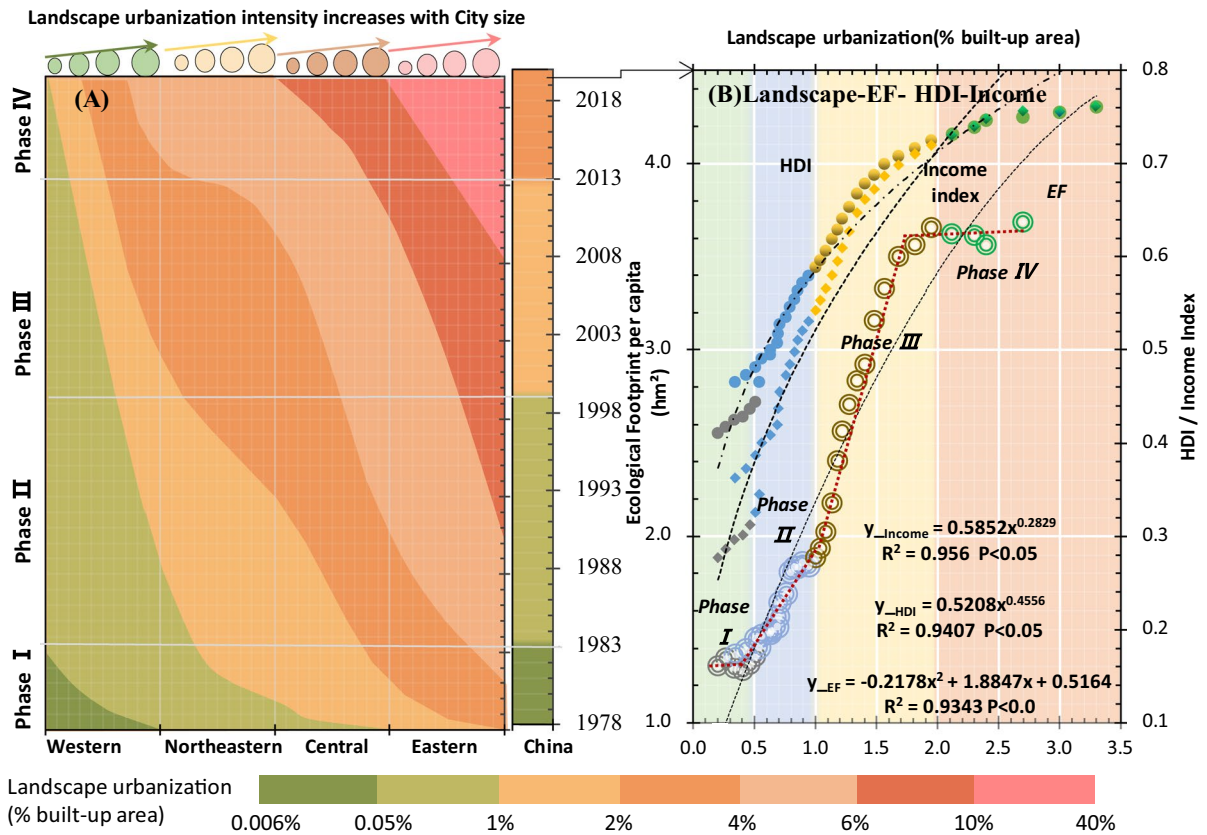


Fig. 5 Landscape urbanization and sustainability indicators in China during the four developmental phases. **A** The overall spatiotemporal pattern of China’s landscape urbanization during Phase I (grey circles), Phase II (blue circles), Phase

III (yellow circles), and Phase IV (green circles), and **B** The scatterplots of HDI, Income index, and EF against landscape urbanization at the national scale during 1978–2020

Kuznets curve) ($p < 0.05$), and segmented linear regression revealed three separation points (i.e., 1983, 1999, 2013). The relationship of landscape urbanization with HDI and income index exhibited power-law relationships in the past four decades (Fig. 1 and Fig. 5 B). During the four phases, governance regulated the urbanization-SJS-landscape nexus through controlling the speed and scale of landscape urbanization: Low speed (Phase I: $< 0.05\%$ built-up area)-increasing speed (Phase II: $< 1\%$ built-up area)-high speed (Phase III: $< 2\%$ built-up area)-decreasing speed (Phase IV: $< 4\%$ built-up area). Meanwhile, the environmental risks and social justice also changed (Fig. 5 B).

Based on our study, China’s SJS exhibited some degree of synchronicity with the temporal dynamics of landscape urbanization (Fig. 5A and B), indicating that the spatial complexity of the relationship

between urbanization and SJS at the national level can be simplified hierarchically through the analysis of urban landscapes (Fig. 4 and Fig. 5B). Previous studies that downscaled SJS to landscape scales (e.g., CO_2 , EF, GDP) (Duren et al., 2012; Wang and Sun 2022 Hori et al. 2023) also found highly positive spatial correlations between indicators of land use, footprints, and social justice. The overall spatial pattern of SJS (e.g., EF per capita, CO_2 per capita, LE, EQ, and IN) of China is characterized by an east–west gradient, interwoven with the urban hierarchies (Fig. 5A). Further studies should focus more on modeling and analyzing SJS on finer resolutions in a spatially explicit manner. This should integrate landscape sustainability science, remote sensing, and various downscaling models of SJS, benefiting the identification of place-based and problem-driven challenges, and facilitating scientific and

adaptive design, planning, and management (Hori et al. 2023; Miller et al., 2013).

Planning for a safer and more just future

To plan for a safer environment and more just society, a convergence science perspective is needed (Lobo et al. 2021), which integrates diverse disciplines, including economy, economic geography, regional sciences, sociology, landscape planning, landscape ecology, sustainability sciences, and complexity science. In particular, landscape sustainability science provides a transdisciplinary platform that can facilitate dialogue among sustainability science, landscape ecology, policy, and society to codesign a safer and more just future through adaptive transformations of landscape systems through the cooperation of scientists, landscape planners, and the public. Such regional landscape approaches emphasize place-based, problem-driven, and used-inspired methodologies so as to solve the context-specific tradeoffs between ecosystem services and human well-being, between national goals and local implementation, between rural and urban areas, and between developing and developed regions (Verburg et al. 2015 and 2015; Wu et al., 2013; Alcamo et al. 2020; Lobo et al. 2021).

Regional landscapes, such as metropolitan regions and urban agglomerations, represent a pivotal scale domain for addressing sustainability issues (Fang and Yu 2020; Meyfroidt et al. 2022; Wu 2022). They exhibit complex interactions with targets of SJS, usually leading to inevitable tradeoffs (Fig. 4). The composition, configuration, efficiency, and socioeconomic attributes of landscapes are leverages for shifting the state of environmental safety and social justice. Meeting the targets of SJS should consider spatial complexity, which can be simplified by recognizing multiple hierarchical levels, such as national, regional, provincial, city, and local community levels. Also, landscape-specific adaptive management and governance are needed, which optimize the composition and configuration of protected areas, different land uses, and environmental subsidies and regulations for regional sustainability.

To promote a safer and more just future for China, we advocate a convergence framework that couples SJS, sustainability science, landscape sustainability,

governance, and land system planning and helps facilitate interactions among government, scientists, and stakeholders of different kinds for achieving sustainability goals (Fig. 6). Sustainability science provides transdisciplinary knowledge and the principles of “strong sustainability” for assessing the shortfalls of SJS across spatial scales, which can help identify future sustainability priorities (the first column in Fig. 6). These assessments can assist the central and local governments with the making and implementation of policies, strategies, and programs to promote safer and more just human-environmental systems from national to landscape scales. To ensure effective and just governance, views and values of the public, stakeholders, and scientists need to feed back to the decision makers (the third column in Fig. 6).

The regional landscape scale is the pivotal scale for achieving SJS because it connects the global and local scales. Landscape sustainability science provides a platform for studying and monitoring the SJS trajectory and understanding the spatial heterogeneity and complexity of the SJS-governance-landscape nexus, so that tradeoffs can be minimized and sustainable pathways can be identified through codesign and adaptive planning (the second column in Fig. 6). As sustainable development is a continuous process, and can only be achieved through adaptive feedback loops. We identify three main feedback loops in this framework: (1) the feedback loop of the assessment of SJS from national to landscape scales, setting sustainability priorities, analyzing the SJS-governance-landscape nexus, and adaptive landscape planning; (2) the feedback loop between landscape sustainability and governance; and (3) the feedback loop among the public, stakeholders, and government (Fig. 6). These feedback loops can only be understood through learning by doing and through the cycle of goal setting, policy formulation, and implementation evaluation for sustainability (Walters and Holling 1990; Folke et al. 2005; Ahern et al., 2013).

Conclusions

This study has examined China’s sustainability trajectory in the past four decades from the SJS-urbanization-governance-landscape nexus perspective. China’s rapid economic growth and urbanization have greatly reduced poverty and substantially

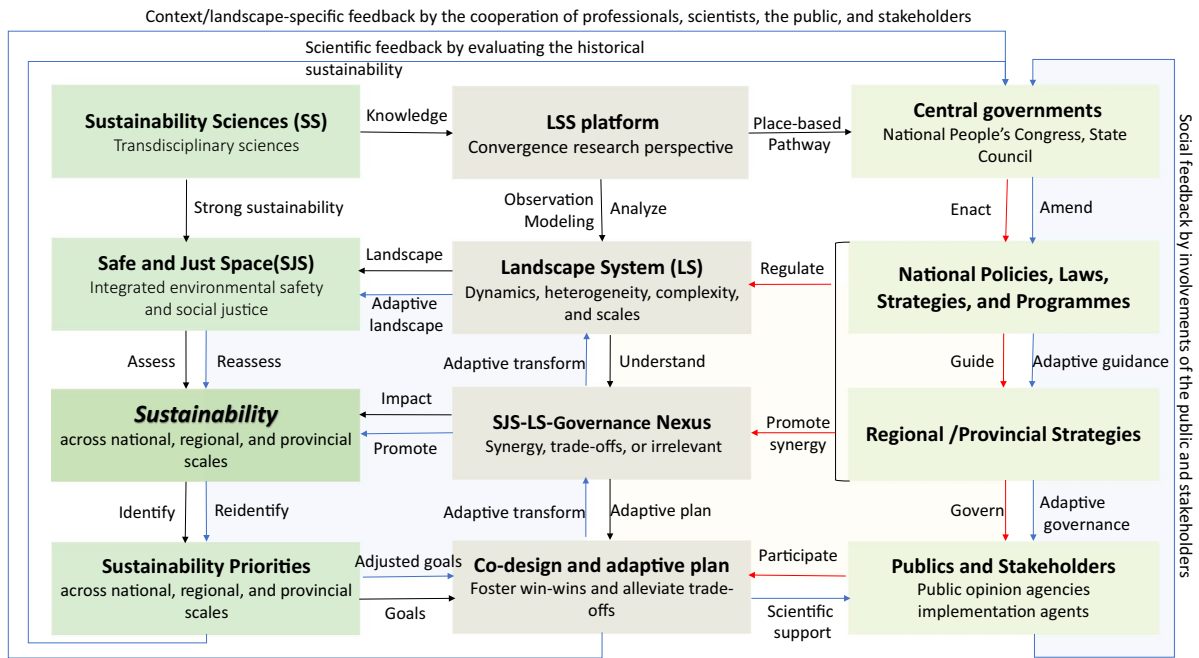


Fig. 6 The convergence framework of sustainability that integrates sustainability science, landscape approaches, and multiscale governance through cooperation among government, scientists, and the public. The three interlinked loops are identified among assessment of the coupled human-environmental system (the first column), adaptive landscape planning (the second column), and adaptive governance (the third column)

improved people’s living standards and social justice. However, some environmental boundaries have been transgressed at the national level, especially after the ‘Western Developing Plan’ (2000). There are environmental shortfalls during rapid urbanization, with excessive CO₂ emissions and increasing EF, MF, and phosphorus and nitrogen loading at the per capita level. Geospatial disparities of SJS across China are pronounced: the developed provinces in eastern China have higher levels of social justice (i.e., LE, IN, EM, ED), but lower levels of environmental safety (as indicated by CO₂ emissions, phosphorus and nitrogen loading, EF) than developing provinces in central, northeastern, and western China. However, synergies also exist among the targets of environmental safety (e.g., EF, WF, CO₂, nitrogen and phosphorus loading), and also among the targets of social justice (e.g., IN, EQ, NU, ED, and LE), especially at the national scale. Although China has enacted a series of policies to promote sustainable development, their effects on national environmental safety have been scale-limited and time-lagged. However, China’s advancement towards economic prosperity coupled with

sustainability offers valuable insight for other nations. To move forward, we advocate for landscape-based sustainability approaches which provide a transdisciplinary and context-specific platform to help mitigate tradeoffs, foster synergies, and facilitate cooperation among scientists, the government, and stakeholders of different kinds.

Author contributions HB was responsible for designing the study and conducting a significant portion of the data synthesis, analysis, initial writing, and editing. JG contributed to the project by writing the initial draft, reviewing and editing the manuscript, and providing interpretation of the data, formal analysis, and conceptualization. YL and DY provided valuable expertise and guidance regarding the statistical analyses. JW helped with the writing and editing of the manuscript.

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Data availability Data on urbanization level, urban population, GDP, CO₂, and forest area were compiled from the World

Bank (<https://data.worldbank.org/country/>). The dynamics of HDI, education index, income index, and health index were from Human Development Reports (UNDP, <http://hdr.undp.org/en/data>). The ecological footprint (EF) and biocapacity data were from the Global Footprint Network (<https://www.zujiwangluo.org/ecological-footprint-results/>). The phosphorus footprints were sourced from Jiang et al (2019a, b). The average temperature and nature reserves area data were from China's Environmental Protection Administration and China Meteorological Administration (<http://data.cma.cn/data>). Our World in Data (<https://ourworldindata.org/>) and Global Footprint Network (<https://ourworldindata.org>) produced the global pattern of the indicators. The original data of landscape urbanization from <http://data.ess.tsinghua.edu.cn>.

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- Ahern J (2013) Urban landscape sustainability and resilience: the promise and challenges of integrating ecology with urban planning and design. *Landsc Ecol* 28:1203–1212
- Alcamo J, Thompson J, Alexander A et al (2020) Analyzing interactions among the sustainable development goals: findings and emerging issues from local and global studies. *Sustain Sci* 15:1561–1572
- Aminikhanghahi S, Cook DJ (2017) A survey of methods for time series change point detection. *Knowl Inf Syst* 51:339–367
- Bai X (2008) The urban transition in China: trends, consequences and policy implications. *New Global Front Urban*. Routledge, London, pp 339–356
- Bai X, Shi P, Liu Y (2014) Society: realizing China's urban dream. *Nature* 509:158–160
- Bian H, Gao J, Wu J et al (2021) Hierarchical analysis of landscape urbanization and its impacts on regional sustainability: a case study of the Yangtze River Economic Belt of China. *J Clean Prod* 279:123267
- Bowen KJ, Cradock-Henry NA, Koch F et al (2017) Implementing the “Sustainable Development Goals”: towards addressing three key governance challenges—collective action, tradeoffs, and accountability. *Curr Opin Environ Sustain* 26:90–96
- Bryan BA, Gao L, Ye Y et al (2018) China's response to a national land-system sustainability emergency. *Nature* 559:193–204
- Cole MJ, Bailey RM, New MG (2014) Tracking sustainable development with a national barometer for South Africa using a downscaled “safe and just space” framework. *Proc Natl Acad Sci* 111:E4399–E4408
- Dorninger C, Abson DJ, Fischer J, von Wehrden H (2017) Assessing sustainable biophysical human-nature connectedness at regional scales. *Environ Res Lett* 12:10
- Duren RM, Miller CE (2012) Measuring the carbon emissions of megacities. *Nat Clim Change* 2:560–562
- Elmqvist T, Andersson E, Frantzeskaki N et al (2019) Sustainability and resilience for transformation in the urban century. *Nat Sustain* 2:267–273
- Fang C (2018) Important progress and prospects of China's urbanization and urban agglomeration in the past 40 years of reform and opening-up. *Econ Geogr (chinese Version)* 38:1–9
- Fang C, Yu D (2020) China's Urban Agglomerations, 1–32. Springer, Cham
- Fanning AL, O'Neill DW, Hickel J et al (2022) The social shortfall and ecological overshoot of nations. *Nat Sustain* 5:26–36
- Folke C, Hahn T, Olsson P, Norberg J (2005) Adaptive governance of social-ecological systems. *Annu Rev Environ Resour* 30:441–473
- Fu B, Wang S, Zhang J et al (2019) Unraveling the complexity in achieving the 17 sustainable development goals. *Nat Sci Rev* 6:386–388
- Fuso Nerini F, Tomei J, To LS et al (2018) Mapping synergies and tradeoffs between energy and the sustainable development goals. *Nat Energy* 3:10–15
- Gao J, Zhang Z, Li W et al (2021) Urban sustainable development evaluation with big earth data: data, indicators, and methods. *Bull Chin Acad Sci (chin Version)* 36:940–949
- He BJ, Zhao DX, Zhu J et al (2018) Promoting and implementing urban sustainability in China: an integration of sustainable initiatives at different urban scales. *Habitat Int* 82:83–93
- Hori K, Shirahama S, Hashimoto S et al (2023) Development of a method for downscaling ecological footprint and biocapacity to a 1-km square resolution. *Sustain Sci* 18:1549–1568
- Huang C, Sun Z, Jiang H et al (2021) Big earth data supports sustainable cities and communities: progress and challenges. *Bull Chin Acad Sci (chinese Version)* 36:914–922
- Jiang M, Behrens P, Wang T et al (2019a) Provincial and sector-level material footprints in China. *Proc Natl Acad Sci* 116:26484–26490
- Jiang S, Hua H, Sheng H et al (2019b) Phosphorus footprint in China over the 1961–2050 period: historical perspective and future prospect. *Sci Total Environ* 650:687–695
- Jiang M, Behrens P, Yang Y et al (2022) Different material footprint trends between China and the world in

- 2007–2012 explained by construction and manufacturing-associated investment. *One Earth* 5:109–119
- Keivani R (2010) A review of the main challenges to urban sustainability. *Int J Urban Sustain Dev* 1:5–16
- Kennedy C, Pincetl S, Bunje P (2011) The study of urban metabolism and its applications to urban planning and design. *Environ Pollut* 159:1965–1973
- Kroll C, Warchold A, Pradhan P (2019) Sustainable development goals (SDGs): are we successful in turning tradeoffs into synergies? *Palgrave Commun* 5:1–11
- Krueger EH, Constantino SM, Centeno MA et al (2022) Governing sustainable transformations of urban social-ecological-technological systems. *Npj Urban Sustain* 2:1–12
- Kuang W (2020) National urban land-use/cover change since the beginning of the 21st century and its policy implications in China. *Land Use Policy* 97:104747
- Lenzen M, Geschke A, West J et al (2022) Implementing the material footprint to measure progress towards sustainable development goals 8 and 12. *Nat Sustain* 5:157–166
- Lobo J, Alberti M, Allen-Dumas M et al (2021) A convergence research perspective on graduate education for sustainable urban systems science. *Npj Urban Sustain* 1:1–5
- Lu Y, Nakicenovic N, Visbeck M et al (2015) Policy: Five priorities for the UN sustainable development goals. *Nature* 520:432–433
- Lu Y, Zhang Y, Cao X et al (2019) Forty years of reform and opening up: China's progress toward a sustainable path. *Sci Adv* 5:equ9413
- Meyfroidt P, de Bremond A, Ryan CM et al (2022) Ten facts about land systems for sustainability. *Proc Natl Acad Sci* 119:e2109217118
- Miller TR (2013) Constructing sustainability science: emerging perspectives and research trajectories. *Sustain Sci* 8:279–293
- Neumayer E (2003) *Weak versus strong sustainability: exploring the limits of two opposing paradigms*. Edward Elgar Publishing, London
- O'Neill DW, Fanning AL, Lamb WF et al (2018) A good life for all within planetary boundaries. *Nat Sustain* 1:88–95
- Pelenc J, Ballet J, Dedeurwaerdere T (2015) Weak sustainability versus strong sustainability. *Brief for GSDR United Nations*, 1–4.
- Raworth K (2012) *A safe and just space for humanity: can we live within the doughnut?* Oxfam, Nairobi
- Rockström J, Steffen W, Noone K et al (2009) Planetary boundaries: exploring the safe operating space for humanity. *Ecol Soc* 14:1–33
- Rockstrom J, Gupta J, Lenton TM et al (2021) Identifying a safe and just corridor for people and the planet. *Earth's Future* 9:e202000EF1866
- Sayer J, Sunderland T, Ghazoul J et al (2013) Ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses. *Proc Natl Acad Sci* 110:8349–8356
- Schultz L, Folke C, Österblom H et al (2015) Adaptive governance, ecosystem management, and natural capital. *Proc Natl Acad Sci* 112:7369–7374
- Seto KC, Güneralp B, Hutyra LR (2012) Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proc Natl Acad Sci* 109:16083–16088
- Sovacool BK, Dworkin MH (2014) *Global energy justice: problems, principles, and practices*. Cambridge Univ Press, Cambridge
- Steffen W, Richardson K, Rockström J et al (2015) Planetary boundaries: guiding human development on a changing planet. *Science* 347:1259855
- Toms JD, Lesperance ML (2003) Piecewise regression: a tool for identifying ecological thresholds. *Ecology* 84:2034–2041
- Turner BL, Matson PA, McCarthy JJ et al (2003) Illustrating the coupled human-environment system for vulnerability analysis: three case studies. *Proc Natl Acad Sci* 100:8080–8085
- Turner BL, Lambin EF, Reenberg A (2007) The emergence of land change science for global environmental change and sustainability. *Proc Natl Acad Sci* 104:20666–20671
- Turner BL, Lambin EF, Verburg PH (2021) From land-use/land-cover to land system science. *Ambio* 50:1291–1294
- UN (2020) *The sustainable development goals report 2020*. United Nations, New York
- Verburg PH, Erb KH, Mertz O, Espindola G (2013) Land system science: between global challenges and local realities. *Curr Opin Environ Sustain* 5:433–437
- Verburg PH, Crossman N, Ellis EC et al (2015) Land system science and sustainable development of the earth system: a global land project perspective. *Anthropocene* 12:29
- Walters CJ, Holling CS (1990) Large-scale management experiments and learning by doing. *Ecology* 71:2060–2068
- Wang T, Sun F (2022) Global gridded GDP data set consistent with the shared socioeconomic pathways. *Sci Data* 9:221
- Wang K, Zhang C, Chen H et al (2019) Karst landscapes of China: patterns, ecosystem processes and services. *Landsc Ecol* 34:2743–2763
- Wiedmann T, Allen C (2021) City footprints and SDGs provide the untapped potential for assessing city sustainability. *Nat Commun* 12:1–10
- Wiedmann TO, Schandl H, Lenzen M et al (2015) The material footprint of nations. *Proc Natl Acad Sci* 112:6271–6276
- Wu J (2013) Landscape sustainability science: ecosystem services and human well-being in changing landscapes. *Landsc Ecol* 28:999–1023
- Wu J (2021) Landscape sustainability science (II): core questions and key approaches. *Landsc Ecol* 36:2453–2485
- Wu J (2022) A new frontier for landscape ecology and sustainability: introducing the world's first atlas of urban agglomerations. *Landsc Ecol* 37:1721–1728
- Wu J, Xiang W-N, Zhao JZ (2014) Urban ecology in China: historical developments and future directions. *Landsc Urb Plan* 125:222–233

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