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REVIEW ARTICLE

# Reducing environmental impacts through socioeconomic transitions: critical review and prospects

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## HIGHLIGHTS

- Reducing environmental impacts through socioeconomic structural transitions.
- Simulation of looping the dynamic material cycle should be concerned.
- Transboundary effects of socioeconomic transitions need to be analyzed.
- Facilitating interregional cooperation and synergetic control mechanisms.

## GRAPHIC ABSTRACT


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## ABSTRACT

Rapid socioeconomic development has caused numerous environmental impacts. Human production and consumption activities are the underlying drivers of resource uses, environmental emissions, and associated environmental impacts (e.g., ecosystem quality and human health). Reducing environmental impacts requires an understanding of the complex interactions between socioeconomic system and environmental system. Existing studies have explored the relationships among human society, economic system, and environmental system. However, it is unclear about the research progress in the effects of socioeconomic activities on environmental impacts and the potential directions of future research. This critical review finds that existing studies have identified critical regions, sectors, and transmission pathways for resource uses, environmental emissions, and environmental impacts from supply chain perspectives. Moreover, scholars have characterized the impacts of socioeconomic transitions on resource uses and environmental emissions. However, existing studies overlook the dynamic nature of the interconnections among human society, economic system, and environmental system. In addition, the effects of socioeconomic structural transitions on environmental impacts remain unknown. This review proposes four prospects and possible solutions that will contribute to a better understanding of the complex interactions among human society, economic system, and environmental system. They can help identify more effective solutions to reduce environmental impacts through socioeconomic transitions.



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Special Issue—Young Talent

# 1 Introduction

Rapid socioeconomic development leads to a large number of environmental pressures and environmental impacts (Schuur et al., 2015). Environmental pressures in this study mean the resource uses and environmental emissions which directly cross the boundary between socioeconomic system and natural environmental system (Eurostat, 2001). Environmental impacts mean resource depletion and environmental quality changes in the natural environmental system due to environmental pressures, which finally damage human health and ecosystem quality (Huijbregts et al., 2017). For example, the overexploitation and use of resources have caused serious resource scarcity risks (Qu et al., 2018; Wang et al., 2020). Excessive pollutant emissions or releases, under the influence of biogeochemical processes, can adversely affect environmental quality (e.g., water and air quality) (Zhang et al., 2019; Zhang et al., 2022c), human health (e.g., IQ decrement and premature death) (Chowdhury et al., 2022; Li et al., 2020b), and ecosystem quality (e.g., radiative forcing and biodiversity loss) (Du et al., 2021; O'Hara et al., 2021). Scholars have conducted many studies on alleviating these environmental pressures and impacts, such as estimating resource uses (Zhu et al., 2017), compiling environmental emission inventories (Deng et al., 2020), simulating the geochemical diffusion, transport, and transformation of contaminants (Zhang et al., 2016), and accounting for ecosystem services (Shah et al., 2019). These studies focused on the ecological-environmental processes in the natural system. They can provide scientific foundations for environmental measures including end-of-pipe control and ecological restoration.

Human beings closely interact with natural systems, forming the coupled human-natural system (Liu et al., 2007). In this integrated system, the human society, environmental system, and economic system are relatively interdependent and interact with each other (Fig. 1). On one hand, human beings in the society and production activities in the economic system depend on the nature for ecosystem services, including potable water, clean air, nutritious foods, and raw materials. On the other hand, production activities in the economic system have led to large quantities of natural resource depletion and environmental emissions. This further caused global environmental impacts, including ecosystem degradation and human health impacts (Liu et al., 2015). In this sense, measures focusing solely on the natural system cannot adequately address the increasingly complex environmental challenges. Human production and consumption activities are the underlying drivers of environmental emissions and associated environmental impacts (Wang et al., 2018). Therefore, it is indispensable to consider the contributions of human society and economic activities to the environmental impacts. This effort could support more effective and comprehensive strategies for reducing environmental impacts.

Given the negative impacts of human activities on natural system, it is of great significance to investigate the interaction between the socioeconomic system and natural system. Studies have uncovered the supply chain transmission processes that drive resource uses and environmental emissions from multiple perspectives (e.g., production-based, consumption-based, income-based, and betweenness-based perspectives) (Liang et al., 2016a; Mi et al., 2016; Qi et al., 2019). The flow of goods and services among various sectors in a supply chain is accompanied by a large amount of material flows (Graedel, 2019). Identifying the critical supply chain paths that drive resource uses and environmental emissions is conducive to the formulation of targeted emission reduction measures (Owen et al., 2018). Moreover, socioeconomic factors (e.g., economic structure, population size, and technological innovation) can undergo tremendous transitions during industrialization, urbanization, and the aging of population (Lin et al., 2020). Changes in these factors can influence resource uses and environmental emissions, as well as subsequent environmental impacts. Identifying the critical socioeconomic drivers underlying environmental changes is necessary to effectively reduce the environmental impacts of their transitions. In recent years, many scholars have tried to combine multi-disciplinary theories to analyze the coupling between economic systems and environmental systems (Lin et al., 2016; Chen et al., 2019). They have distinguished between critical emission sources and

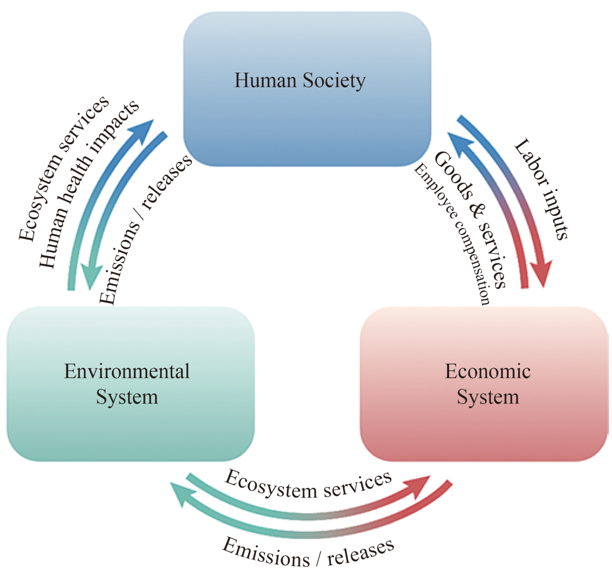


**Fig. 1** Relationships among human society, economic system, and environmental system.

economic drivers that contribute to environmental impacts.

To our knowledge, there lacks a critical review that summarizes the progress in the effect of human society and economic activities on environmental impacts. To fulfill the current knowledge gaps, this review summarizes existing studies on socioeconomic processes driving resource uses, environmental emissions, and environmental impacts. It also identifies future research priorities and proposes potential solutions.

The literature search was performed in three databases: Web of Science, ScienceDirect, and Google Scholar. The keywords used for the search are listed in Table 1. Furthermore, the titles, abstracts, and keywords of resulting articles were reviewed to identify the literature closely related to the topics of this review.

## 2 Socioeconomic processes driving resource uses and environmental emissions

### 2.1 Multiple-perspective identification of critical regions and sectors

Given the increasing impacts of socioeconomic activities on environmental systems, it is essential to understand the complicated connections between economic activities and environmental pressures from a life-cycle perspective (Fig. 2). This can help inform efficient mitigation strategies. Existing studies have investigated the direct and indirect environmental pressures from multiple perspectives, identified the socioeconomic drivers of changing environmental pressures, and analyzed the effects on single and a nexus of elements.

Environmental pressures are mostly associated with a globalized economic system and widespread human activities. Driven by interregional trade, there is an increasing geospatial separation of production and consumption activities (Wiedmann and Lenzen, 2018). Consequently, commodities produced in one region are usually consumed by other regions, leading to the changes in location and scale of resource uses and environmental emissions (Hong et al., 2022). Studies have traced the production and consumption sources of environmental pressures and identified critical supply chain paths connecting various types of sources (Lenzen and Murray, 2010). They are conducive to the formulation of targeted inter-sectoral and inter-regional management measures and to supporting the strategic trade adjustments that can mitigate environmental pressures.

Sector-specific policies for mitigating environmental pressures along the supply chains require multiple-perspective methods (e.g., production-based, consumption-based, income-based, and betweenness-based methods). Production-based accounting involves the direct resource uses and pollutant emissions within certain administrative/geographic boundaries (Peters, 2008). It helps inform production-side policies such as improving the usage efficiency of resources, implementing cleaner production technologies, and installing pollutant removal facilities (Liang et al., 2015).

The production-based accounting method cannot capture indirect environmental pressures embodied in supply chains. The consumption-based accounting is proposed to quantify both direct and indirect resource uses and environmental emissions driven by the final demand (Rodrigues and Domingos, 2008). It is widely applied to reveal the role of interregional trade in environmental pressures and allocate the mitigation responsibilities to final consumers driving upstream environmental pressures (Steininger et al., 2016). This method can help inform demand-side policymaking through influencing the behaviors of final consumers. Typical demand-side measures include the eco-labeling scheme for consumed products (Lin et al., 2020), consumption behavior optimization (Nielsen et al., 2021), and taxes/subsidies on consumed products (Liang et al., 2015).

Existing studies have also demonstrated the significant role of primary inputs (e.g., labor forces and capital) in enabling environmental pressures through sale chains. The income-based accounting method is proposed to quantify downstream environmental pressures enabled by primary inputs of regions and sectors (Marques et al., 2012). It can help identify critical primary suppliers to support supply-side policymaking. Supply-side measures usually focus on the optimization of primary input

**Table 1** Keywords used in literature search

| Topics | Keywords |
|---|---|
| Socioeconomic process & environmental pressure | "socioeconomic" and "environmental pressure"; |
| | "socioeconomic" and "resource use"; |
| | "socioeconomic" and "environmental emission". |
| Socioeconomic process & nexus | "socioeconomic" and "nexus"; |
| Socioeconomic process & environmental impact | "socioeconomic" and "environmental impact"; |
| Human intervention & environmental impact | "environmental impact" and "human intervention"; |
| | "environmental impact" and "anthropogenic impact". |

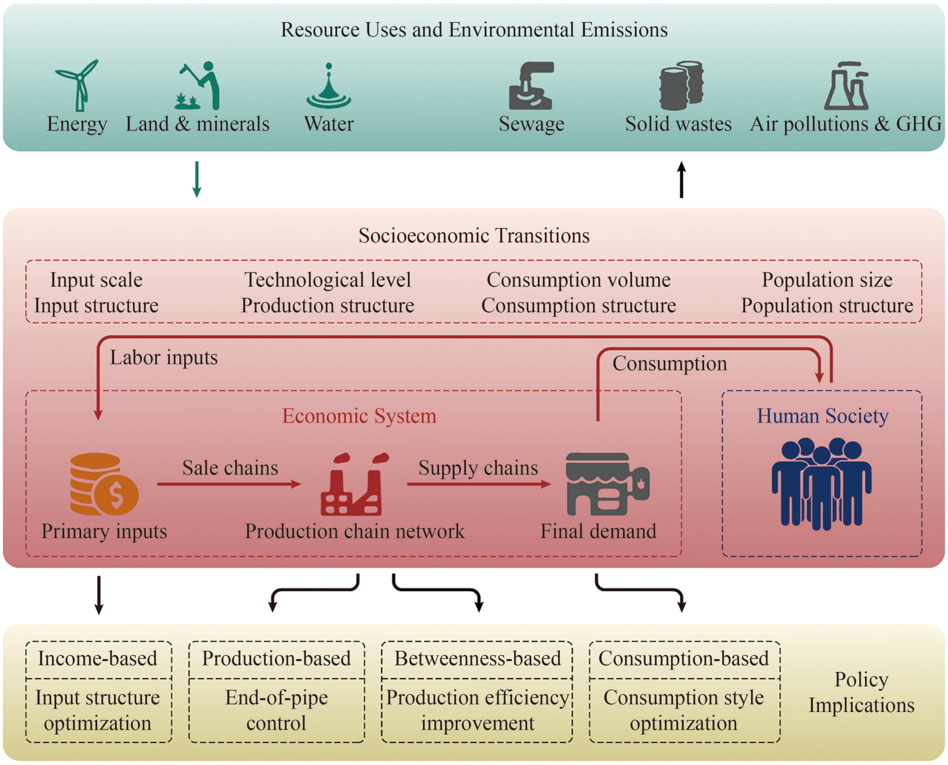


**Fig. 2** Conceptual framework of socioeconomic processes driving resource uses and environmental emissions.

behaviors by administrative and economic tools (Liang et al., 2017).

In addition to primary suppliers, producers, and final consumers, transmission centers are also crucial in controlling supply-chain-wide environmental pressures. The betweenness-based method is proposed to identify important sectors working as transmission centers. Improving the production efficiency of these hotspots can help mitigate environmental pressures of the whole supply chains (Liang et al., 2016a).

The above multiple-perspective methods can capture the whole picture of how environmental pressures originate, pass through, and terminate in sectors and regions. They can lay scientific foundations for fair responsibility-sharing and efficient mitigation policies.

### 2.2 Socioeconomic transitions changing resource uses and environmental emissions

The multiple-perspective methods can identify critical regions and sectors in various stages of supply chain paths driving environmental pressures. The changes in socioeconomic factors in various stages of supply chain paths (i.e., socioeconomic transitions) would lead to changes in environmental pressures. Globally, the current rapid socioeconomic transitions in demographic, economic, technological, and behavioral dimensions pose huge challenges to sustainable development (Wiedmann and Lenzen, 2018). Specifically, socioeconomic transitions have a macro-level impact on economic development, technological progress, and demographic changes, as well as a micro-level impact on suppliers' resource allocation, producers' industrial structure, and consumers' behavior patterns (Wei et al., 2022). For example, the global urban area has expanded at the cost of occupying other valuable land resources such as agricultural land, grasslands, wetland, and forests (Liu et al., 2020). In the context of the aging population, the seniors' contribution to greenhouse gas emissions has increased by 6.5 % during 2005–2015 in some developed countries, due to a growing population of the aged group and their carbon-intensive expenditure pattern (Zheng et al., 2022).

Existing studies have quantified relative contributions of socioeconomic factors to environmental pressure changes. The change in the intensity of environmental pressures is usually found to be a critical factor contributing to changes in resource uses and environmental emissions (Liang et al., 2013a). The socioeconomic development and technological advances have significantly increased resource use efficiency and reduced environmental emission intensity (Wang et al., 2017). However, it is increasingly difficult to further reduce resource uses and environmental emissions through end-of-pipe measures at a relatively low cost (Wu et al., 2018). Studies begin to concern the importance of structure optimization for global, national, city, and community-scale environments (Wang et al., 2017; Li et al., 2018; Fan et al., 2022). It is found that the actions on production structure, final demand structure, and primary input structure can contribute to reducing greenhouse gas emissions (Liang et al., 2016b). Given that final consumption is the underlying driver of resource uses and environmental emissions, optimizing consumption patterns has huge potentials to reduce environmental pressures (Yang et al., 2020). Consequently, recent studies have evaluated the variable contributions of consumer behavior heterogeneity (e.g., different age groups, income groups, and rural-to-urban gaps) to environmental emission changes (Shi et al., 2020; Wei et al., 2020), which calls for greater public mitigation efforts.

### 2.3 Effects of socioeconomic transitions on the nexus of elements

The studies mentioned above have mostly focused on a single resource or environmental pollutant. Actually, there are complex linkages among various resource uses and environmental emissions. Holistic studies to explore such linkages are necessary to support practical solutions for environmental issues (Bleischwitz et al., 2018). Thus, the nexus concept has been proposed to characterize the linkages among different entities. It can identify the synergies, co-benefits, and trade-offs in the complex dynamics of coupled systems (Liu et al., 2018). Nexus-related studies can help promote inter-sectoral cooperation and achieve coordinated management of multiple environmental pressures (Endo et al., 2017).

According to the number of the “entities” involved, there are two-pronged and multi-pronged nexus. Many studies have explored two-pronged nexus, since the connection between two entities is relatively straightforward. Given that the increased global demand for foods is putting unprecedented pressure on natural resources, food-related nexus (e.g., food-water, food-land, and food-carbon nexus) has received extensive attention (D’Odorico et al., 2018). These studies explored the resource uses and pollutant emissions of various food subsystems (e.g., food production, food consumption, and food wastes) at different spatiotemporal scales.

In addition, in response to the global climate change, achieving carbon neutrality is one of the most pressing tasks globally (Yang et al., 2022). Some land-use change activities, such as agricultural abandonment and afforestation, act as carbon sinks (Piao et al., 2022). The existing study has explored the grassland-carbon nexus, emphasizing the importance of sustainable grassland management to enhance soil carbon storage in grasslands and reduce carbon emissions (Chang et al., 2021). Meanwhile, reducing anthropogenic carbon emissions is an important component of achieving carbon neutrality (Chen, 2021). Since the transformation of energy systems is an important pathway for carbon emission mitigation, energy-carbon nexus has attracted much attention (Zhang and Hanaoka, 2022a; Zhang and Chen, 2022b). Furthermore, existing studies have found that carbon neutrality is closely linked to economic activities such as food production, wastewater treatment, and metal production (Wang et al., 2021a; Li et al., 2022a; Wang et al., 2022). Studies on the nexus of these elements and carbon (e.g., food-carbon, water-carbon, and metal-carbon nexus) can be strengthened to provide more comprehensive information for achieving carbon neutrality.

Multi-pronged nexus is much more complex than the two-pronged nexus (Albrecht et al., 2018). The interdependencies among food, energy, and water systems are regarded as core sustainable development issues, and these three systems interconnect with each other directly and indirectly (Fuso Nerini et al., 2018). Consequently, the food-energy-water nexus has become a focal point for interdisciplinary studies (Huntington et al., 2021). Some studies quantified direct food-energy-water linkages within a specific region based on material flow analysis from the production perspective (Liang et al., 2019). Actually, food-energy-water systems are not only directly interlinked via production activities but also intertwine with activities such as capital investment and consumption within the socioeconomic network. With the maturity of multi-perspective accounting methodologies, scholars have explored the indirect linkages of food-energy-water systems from supply and demand perspectives based on the input-output models (Guan et al., 2019; Liang et al., 2020).

Moreover, socioeconomic factors such as economic growth, upturning living standards, and urbanization have been verified to have significant impacts on resource nexus (Pastor et al., 2019). By exploring the impact of socioeconomic transitions on resource nexus, policy recommendations can be made for reducing the use of multiple resources simultaneously through certain optimization measures. Table 2 lists some studies related to the socioeconomic impacts on the nexus. For the two-pronged nexus, many studies have decomposed the changes in resource uses over a time period into the contributions of various socioeconomic factors. For instance, Duan and Chen (2020) investigated the contribution of several drivers (e.g., changes in energy intensity, production structure, consumption pattern, and population) to the water-energy nexus in China. However, for multi-pronged nexus, a few studies have examined multiple factors simultaneously (Zhao et al., 2018; Lee et al., 2021); most studies quantified the relationship between socioeconomic factors and resource nexus by statistical and data analysis techniques (Ding et al.,

**Table 2** Studies related to the impact of socioeconomic transitions on the nexus

| Categories | Nexus | Regions | Time | Methods | References |
|---|---|---|---|---|---|
| Energy-related | Energy-water | China | 1990–2014 | MRIO-SDA[a] | Duan and Chen, 2020 |
| | Energy-carbon | Europe | 1995–2010 | LMDI[b] | Moutinho et al., 2015 |
| | Energy-carbon-water | Provinces-China | 2000–2016 | LMDI[b] | Li et al., 2021a |
| | Energy-carbon-water-land | Provinces-China | 2005–2013 | LMDI[b] | Zhao and Chen, 2014 |
| Food-related | Food-water | USA | 1995–2010 | MRIO-SDA[a] | Avelino and Dall'erba, 2020 |
| | Food-carbon | Guangdong-China | 1993–2013 | LMDI[b] | Zhen et al., 2017 |
| | Food-water-land | Provinces-China | 2002–2012 | MRIO-SDA[a] | Cai et al., 2020 |
| | Food-energy-water | China | 2012–2017 | IO-SDA[c] | Lee et al., 2021 |
| Air pollutants | PM, $CO_2$ | Provinces-China | 2007–2012 | MRIO-SDA[a] | Shao et al., 2020 |
| | $SO_2$, $NO_x$ | China | 2003–2014 | LMDI[b] | Jia et al., 2018 |
| | $SO_2$, $NO_x$, PM, $CO_2$ | China | 2014 | LMDI[b] | Qian et al., 2021 |

Abbreviations: a. MRIO-SDA, Multi-Regional Input-Output model and Structural Decomposition Analysis; b. LMDI, Logarithmic Mean Divisia Index; c. IO-SDA, Input-Output model and Structural Decomposition Analysis.

2019b). Correlations between socioeconomic factors and the nexus are complex and far from being simple linear relationships. Thus, more studies are needed to reveal the holistic impacts of different socioeconomic factors on multi-pronged nexus. Recent developments in artificial intelligence technologies (e.g., machine learning) have facilitated the study on the correlations between socioeconomic factors and environmental pressures (Li et al., 2021b; Magazzino et al., 2021), which can also be applied to the nexus research.

In addition to the nexus among resources, there are close linkages among environmental emissions. One of the most typical topics is the nexus between $CO_2$ and air pollutant emissions. Previous studies have demonstrated that $CO_2$ emission mitigation and air pollutant control can be achieved simultaneously through optimization measures (Qian et al., 2021). For example, it is possible to reduce $SO_2$ emissions while reducing $CO_2$ emissions through carbon capture and storage (Singh et al., 2012). Many studies on the co-benefits and ancillary impacts of policies in reducing $CO_2$ emissions and air pollutants have focused on developed economies (Dong et al., 2015). In fact, it is even more important for developing countries, because their rapid socioeconomic development is often accompanied by substantial pollutant emissions. China has experienced rapid economic development in recent decades. The massive production activities in China have put tremendous pressures on air pollutant control and $CO_2$ emission mitigation. In this context, a growing number of studies have explored the synergistic effects of $CO_2$ emission mitigation and air pollutant control in regions and sectors of China (Dong et al., 2019; Bo et al., 2021). In addition to quantitative studies based on synergistic analyses, exploring the socioeconomic factors driving $CO_2$ and air pollutant emissions is particularly important for developing effective emission control strategies. Numerous studies have explored the influence of socioeconomic transitions on $CO_2$ or air pollutant emissions separately. However, there are relatively fewer studies analyzing the synergistic effects of socioeconomic transitions on $CO_2$ and air pollutant emissions, which cannot fully reveal the substantial co-benefits of specific interventions.

### 2.4 Problems to be solved

#### 2.4.1 Studies with higher spatial resolutions are needed

Most of existing studies analyzing the impacts of socioeconomic transitions on environmental pressure changes are based on administrative units (e.g., nations, provinces/states, and cities). However, both environmental pressures and economic activities are highly localized, with significant spatial heterogeneity. Studies with higher spatial resolutions (e.g., at the grid scale) are needed, which can provide spatially explicit policy implications for environmental management. The construction of database with high spatial resolutions is the major challenge. It requires the joint efforts of official statistics and research institutions from various regions. Introducing the remote sensing technology is a promising way to provide high-spatial-resolution raw data for related databases (He and Weng, 2018).

#### 2.4.2 Inter-regional cooperation needs to be strengthened

Regions are closely linked through interregional trade. Goods and services consumed in one region usually lead to resource uses and environmental emissions in other regions (Lin et al., 2019; Zhong et al., 2022). Inter-regional cooperation along supply chains (e.g., production regions and consumption regions) are needed to address the environmental pressures caused by interregional trade. Moreover, there is significant socioeconomic heterogeneity among regions with different political regimes. Thus, the challenges and opportunities for improving the environment are not evenly distributed around the world (West et al., 2014). Region-specific and feasible policies should be proposed based on the unique characteristics of nations and regions.

#### 2.4.3 Understanding of multi-element nexus needs to be deepened

Existing policies mostly focus on individual sectors and environmental pressures, which cannot fully capture the co-benefits of integrated resource and environmental management strategies. In this context, multi-element nexus studies offer a breakthrough by breaking down the boundaries across disciplines and sectors. It is necessary to establish a joint assessment mechanism across sectors. This mechanism can help uncover potential co-benefits and unintended consequences of sectoral measures focusing on individual elements (Liang et al., 2014; Zhang et al., 2018a).

## 3 Socioeconomic processes influencing environmental impacts

Resource uses and environmental emissions lead to environmental impacts (e.g., ecosystem quality and human health) through a series of ecological-environmental processes across environmental media in the natural system. Taking the resource uses and environmental emissions as the endpoint cannot adequately characterize environmental impacts. Consequently, scholars begin to investigate the effects of socioeconomic processes on environmental impacts, such as human health and ecosystem quality impacts caused by air pollutant emissions (Hill et al., 2019).

### 3.1 Critical drivers of environmental impacts

Excessive resource uses and environmental emissions can lead to various environmental impacts, which can be summarized into midpoint environmental impacts (including resource depletion and environmental quality degradation) and endpoint environmental impacts (including human health impacts and ecosystem quality degradation) (Fig. 3). Based on the resource use and environmental emission inventories, scholars have made efforts to clarify the emission-to-impact and use-to-impact pathways, as well as evaluated environmental impacts at various spatial scales (Brauer et al., 2012; Feng et al., 2019). Furthermore, by coupling socioeconomic processes and ecological-environmental processes, some studies have identified critical drivers and receptors of environmental impacts (Table 3).

Excessive resource uses and environmental emissions firstly lead to midpoint environmental impacts. Environmental emissions can damage environmental quality (e.g., air quality, soil quality, and water quality). Environmental quality degradation is caused by both local emissions and long-distance transport of emissions from remote regions. Numerous studies have explored the temporal-spatial changes of environmental quality and traced the direct emission sources (Chen et al., 2014; Gao

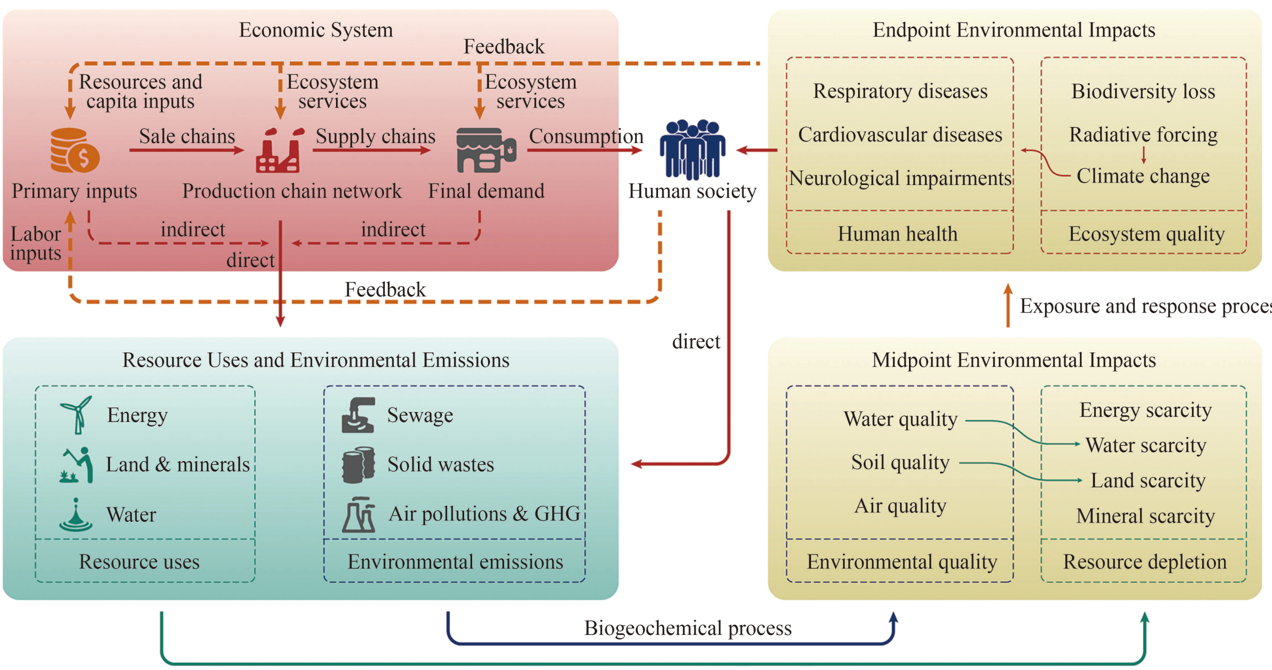


**Fig. 3** Processes from socioeconomic activities to environmental impacts.

**Table 3** Selected studies on critical socioeconomic drivers of environmental impacts

| Environmental impacts | Detailed impacts | Models | Time | Regions | Key driver-receptor relationships | References |
|---|---|---|---|---|---|---|
| Resource depletion | Fossil fuel scarcity | MRIO[a] | 2012 | China | Central and Northwest-Central Coast | Wang et al., 2020 |
| | Land & mineral scarcity | MRIO[a] | 2007 | World | Developed regions-Developing regions | Font Vivanco et al., 2017 |
| Environmental quality | $PM_{2.5}$ concentration | InMAP[b], MRIO[a] | 2003–2015 | USA | Non-Hispanic white-Black and Hispanic | Tessum et al., 2019 |
| | Atmospheric Pb concentration | CanMETOP[c], MRIO[a] | 2012 | China | Eastern and southern-Central and western | Wang et al., 2021b |
| Human health | IQ decrement, Fatal heart attack | GEOS-Chem, MRIO[a] | 2010 | China | USA Western Europe, and Japan-China | Li et al., 2020b |
| | Premature death | GAINS[d], MRIO[a] | 2010 | India | Higher income groups-Lower income groups | Rao et al., 2021 |
| Ecosystem quality | Biodiversity loss | GLOBIO[e], MRIO[a] | 2007 | World | Developed economies-Other economies | Wilting et al., 2017 |
| | Radiative forcing | OSCAR, MRIO[a] | 2007–2012 | China | Beijing-Tianjin, East Coast, and South Coast-less developed regions | Du et al., 2021 |
| Resource, economic, and labor loss | Economic loss | CMAQ[f]; WRF-ARW[g]; MRIO[a] | 2010 | Asia | Wealthy consumption countries-low income producers | Nansai et al., 2020 |

Abbreviations: a. MRIO, Multi-Regional Input-Output model; b. InMAP, Intervention Model for Air Pollution; c. CanMETOP, Canadian Model for Environmental Transport of Organochlorine Pesticides; d. GAINS, Greenhouse Gas-Air Pollution Interactions and Synergies Integrated Assessment model; e, GLOBIO, Global Terrestrial Biodiversity model; f. CMAQ, Community Multiscale Air Quality model; g. WRF-ARW, Weather Research and Forecasting-Advanced Research.

et al., 2018). These studies revealed the geographical relocation of environmental quality caused by cross-border emission transport (e.g., from Heibei and Tianjin to Beijing, from East Asia to North America). However, they only focus on the environmental processes in the natural system, but cannot reveal the impacts of socioeconomic processes on environmental quality changes.

Subsequent studies have identified critical socioeconomic drivers of environmental quality changes by integrating the socioeconomic processes with biogeochemical processes (Li et al., 2016b; Wang et al., 2021b). These studies mainly focus on the driving effects of consumers and explore the environmental quality changes embodied in trade. The trade of goods and services can lead to virtual (or say embodied) transfer of environmental quality changes (Li et al., 2016b). Compared with physical emission transport, the trade even has larger contribution to environmental quality changes (Zhang et al., 2017; Wang et al., 2021b). For instance, Wang et al. (2021b) found that half of Pb concentrations in less-developed regions were driven by the consumption of well-developed regions. In Northwestern China, 61 % of the atmospheric Pb concentration was driven by the consumption of other regions, while 10 % of the atmospheric Pb concentration came from physical emission transport. Distinct driver-receptor relationships also exist at the social-group scale. Tessum et al. (2019) revealed the "pollution inequity" among racial-ethnic groups. They found that the groups causing $PM_{2.5}$ exposure and the groups exposed to $PM_{2.5}$ are different. On the whole, non-Hispanic whites possessed a "pollution advantage". Revealing such driver-receptor relationships is of great importance for interregional cooperation governance to control environmental pollution and improve equality.

Meanwhile, excessive resource uses and poor environmental quality can lead to resource depletion (e.g., energy scarcity, water scarcity, land scarcity, and mineral scarcity) (Jia et al., 2019; Ma et al., 2020). Existing studies have established indicators (e.g., water stress index and scarcity-weighted indicators) to quantify resource scarcity and explore its socioeconomic drivers (Wang and Zimmerman, 2016; Font Vivanco et al., 2017; Wang et al., 2020). In the context of resource endowment discrepancies, considering scarcity can reverse the flows of resources embodied in trade of some regions as compared with non-weighted footprints (Font Vivanco et al., 2017). The uneven distribution of resources across regions highlights the importance of resource scarcity over resource uses. Enriching such studies by incorporating scarcity into resource evaluation can help to manage resources from the perspective of resource endowments.

Midpoint environmental impacts would further cause human health impacts (e.g., respiratory diseases, cardiovascular diseases, and neurological impairments) and ecosystem quality degradation (e.g., biodiversity loss, radiative forcing, and climate change) (Li et al., 2016a; Cohen et al., 2017; Hemmativaghef, 2020; Jiang et al., 2021). Ecosystem quality degradation also exacerbates human health impacts by changing the exposure environment (Hong et al., 2019). Numerous studies have evaluated the diseases and premature deaths caused by different pollutant emissions at the global and regional levels (Cohen et al., 2017; Landrigan et al., 2018; Hemmativaghef, 2020). Physical transport of emissions and interregional trade further lead to the transboundary human health impacts (Zhang et al., 2017; Ma et al., 2021). Human health impacts are caused by both pollution exposure and people's vulnerabilities. Disparities in vulnerability further differentiate drivers and receptors, and lead to "health inequality" (Rao et al., 2021). For instance, Rao et al. (2021) revealed the different distributions of contributions and impacts among income groups. They found that low-income groups bore disproportionate health risks induced by indirect emissions of households. Only focusing on environmental emissions and environmental quality cannot reveal such driver-receptor relationships. It is necessary to model the lengthy pathways of socioeconomic processes leading to endpoint environmental impacts. Similarly, distinct driver-receptor relationships also exist in the context of ecosystem quality degradation (Wilting et al.; Du et al., 2021). For instance, Lenzen et al. (2012) revealed the driving effects of consumers in developed countries on biodiversity loss in developing countries. Environmental impact inequality is of great importance and requires more attention at multiple scales.

Furthermore, human health impacts and ecosystem quality degradation can lead to the losses of labor forces, economic production, resources, and ecosystem services (Pichery et al., 2012; Feng et al., 2019; Oswald et al., 2020). These losses would then feed back to the socioeconomic system. In this way, the socioeconomic system and environmental system form a cycle. Some studies have quantified labor and economic losses due to particular environmental impacts (Feng et al., 2019; Nansai et al., 2020). The driver-receptor relationships are also revealed (Nansai et al., 2020). For instance, Nansai et al. (2020) revealed the adverse economic impacts of wealthy consumption countries on low-income production countries. Fig. 3 shows the pathways of the feedback. Specifically, labor losses caused by human health impacts will influence the primary inputs of the economic system by reducing labor availability. Labor losses will further lead to cascading economic losses along supply chains (Nansai et al., 2020). Ecosystem quality degradation can also lead to economic losses due to extreme climate events and ecological restoration (Franzke and Czupryna, 2020). Similarly, economic losses will influence the primary inputs via capital inputs. Moreover, ecosystem quality degradation leads to the decline in the availability of resources (e.g., water, minerals, and land), which also influences the inputs of the economic system. Such feedback on primary inputs can lead to cascading effects on downstream production and consumption behaviors through supply chains. Ecosystem quality degradation can also feed back to production activities and final demand. For example, climate change and biodiversity loss (e.g., extinction of pollinators) can influence agricultural production activities (Jordan et al., 2021). Tourism industry depending on the biodiversity and landscape would significantly be affected by ecosystem quality degradation. However, little is known about the knock-on response of such feedbacks to the socioeconomic system. Bridging this gap depends on the dynamic simulation of looping the socioeconomic-environmental cycle.

### 3.2 Effects of human interventions on environmental impacts

Identifying the key factors affecting environmental impact changes can provide hotspots for environmental impact control. Previous studies find that anthropogenic factors (e.g., end-of-pipe control) are the primary factors (contributing ~90 %) in reducing $PM_{2.5}$-related impacts, compared to natural factors such as meteorological conditions (Ding et al., 2019a; Zhang et al., 2019). Therefore, it is necessary to explore the contribution of key socioeconomic factors to environmental impact changes. This can help mitigate the adverse environmental impacts via human interventions.

Since end-of-pipe control is recognized as one of the determinants in mitigating environmental quality degradation, many studies have explored the influence of various end-of-pipe control measures on environmental impacts. For example, improving the efficiency of scarce water uses is the primary factor in reducing food-related scarce water uses in China, contributing 27.5 Gt of scarce water savings during 2007–2012 (Liang et al., 2021b). Furthermore, numerous studies have evaluated the contributions of various end-of-pipe control measures for air pollutants to reduce environmental impacts. For instance, Lin et al. (2019) found that $PM_{2.5}$ pollution control policies (including strengthening industrial emission standards, phasing out outdated technologies, and upgrading industrial boilers) significantly contributed to air quality improvement in China. Moreover, installing efficient air pollutant removal devices and improving power generation efficiency could lead to significant mercury-related health benefits (Li et al., 2020a).

However, only end-of-pipe control measures are not enough to alleviate the increasingly complex environmental impacts. For instance, it is found that only the end-of-pipe control (i.e., technological improvements) will be insufficient to prevent the increase in pharmaceutical concentration of the freshwater ecosystems (Acuña et al., 2020). The end-of-pipe control measures need to be combined with source mitigation actions (e.g., per capita consumption reduction). Consequently, many studies have made preliminary attempts to reveal the influence of other socioeconomic factors (including population size, urbanization rates, and economic growth) on environmental impact changes (Marques et al., 2019; Zhang et al., 2019b). Specifically, most of them explored the relationships between socioeconomic factors and environmental impacts using econometric methods (e.g., linear regression and coupling coordination) (Liao et al., 2020; Wolf et al., 2022). Regarding the resource scarcity, population growth has exacerbated global water scarcity risks (He et al., 2021). Liao et al. (2020) investigated the coordination relationship between urbanization and environmental carrying capacity in China. However, such single-perspective correlation studies cannot describe the whole picture of socioeconomic impacts. Some studies have further explored the relationships between multiple socioeconomic factors (e.g., population, urbanization, and economic growth) and multiple environmental impacts (e.g., air pollution and related health risks) (Chen et al., 2018; Zhang et al., 2019b).

The above studies based on the correlation analysis cannot fully reveal the influencing mechanisms. Subsequently, scholars have tried to decompose the socioeconomic system to uncover related mechanisms. Geng et al. (2021) decomposed the socioeconomic system into eight factors (including economic growth, economic structure, energy and climate policies, etc.) to evaluate their contributions to the changes in $PM_{2.5}$-related premature deaths in China. Their study highlighted the importance of economic structure transition in further air quality improvements. Liu et al. (2021a) found that population aging (with a contribution of 16 %) and the growth in GDP per capita (18 %) caused the $PM_{2.5}$-related health costs to remain high in China during 2013–2018. In addition to human health impacts, scholars have also explored the effects of socioeconomic factor changes on the declining ecosystem quality, such as the influence of population growth, economic development, and technological progress on the losses of biodiversity and ecosystem services (Marques et al., 2019).

In summary, existing studies on the effects of socioeconomic transitions on environmental impacts have gradually developed from end-of-pipe control to source mitigation (Fig. 4). However, relatively few studies have concerned the impacts of structural transitions in the socioeconomic system, such as production structure, consumption structure, and population structure. It is important to further explore how to mitigate adverse effects through socioeconomic structural transitions.

### 3.3 Problems to be solved

#### 3.3.1 Socioeconomic structural transitions influencing environmental impacts

Numerous studies have explored the effects of policy interventions (mainly including end-of-pipe control measures and partial socioeconomic system regulations) on environmental impacts (Zhang et al., 2019; Guo et al., 2022). However, the impacts of changes in structural factors such as production structure, consumption structure, and population structure in socioeconomic system on environmental impacts have not been fully revealed. These structural factors would continuously change in the context of economic transition, green consumption, poverty eradication, and population aging. Their changes would have substantial influences on environmental impacts. Quantifying the effects of such structural transitions can help uncover more hotspots and potentials for reducing environmental impacts. Interdisciplinary efforts are required to incorporate multiple methods, such as the input-output models, structural decomposition analysis, and biogeochemical cycle models, to describe the effects of structural transitions based on the emission-to-impact and use-to-impact pathways.

#### 3.3.2 Dynamic simulation of looping the socioeconomic-environmental cycle

Environmental impacts resulting from socioeconomic processes would probably feed back to the socioeconomic system. Some studies have quantified the economic and

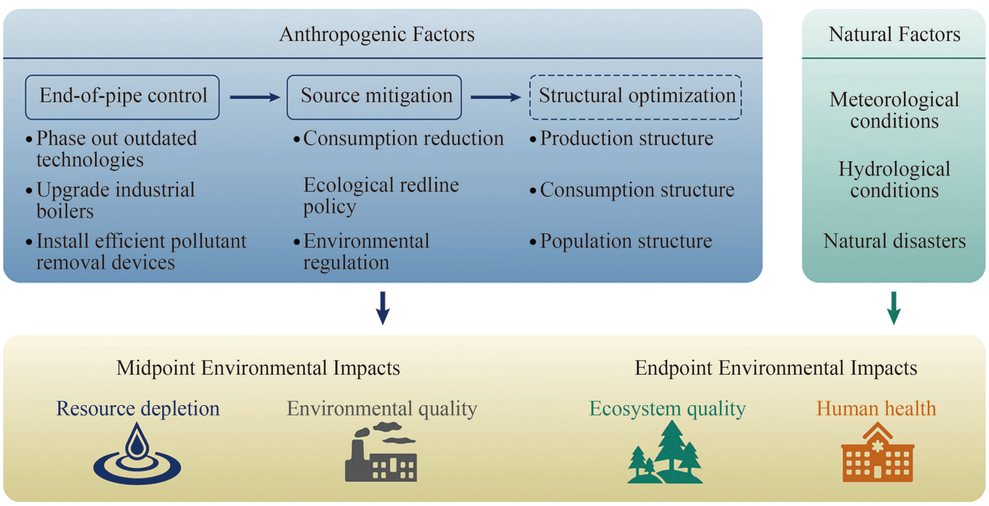


**Fig. 4** Natural and anthropogenic factors affecting environmental impacts.

labor losses due to ecosystem quality degradation and human health impacts. (Feng et al., 2019; Nansai et al., 2020). However, the subsequent cascading effects in the socioeconomic system due to such feedbacks have not been well characterized. Specifically, the feedbacks influence socioeconomic system by directly changing the primary inputs (e.g., the inputs of labor forces, capital, and natural resources), production activities (e.g., agricultural activities related with pollination insects), and consumption behaviors (e.g., medical services and tourism). The direct effects would lead to cascading influences on production and consumption activities through economic supply chains. Subsequently, the environmental impacts associated with socioeconomic activities will change accordingly. However, the mechanism of such cascading effects still remains unknown. Revealing this is conducive to realizing the dynamic simulation of looping the socioeconomic-environmental cycle and improving the effectiveness of policymaking.

#### 3.3.3 Synergetic control of multiple environmental impacts through socioeconomic transitions

Only focusing on single environmental impacts would probably cause the effects of co-benefits or unintended consequences to other environmental impacts (Liang et al., 2013b). Synergetic control of multiple environmental impacts is required in the context of socioeconomic transitions. It is conducive to improving the environmental regulation efficiency. Existing studies have focused on the synergetic control of greenhouse gases and air pollutants (Peng et al., 2018; Yang and Teng, 2018). Moreover, some studies have explored the synergistic control of multiple environmental impacts brought about by various control measures and policies (Bryan et al., 2016; Peng et al., 2021a). However, few studies have investigated the synergistic effects of socioeconomic transitions on multiple environmental impacts. Revealing this can provide scientific foundations for synergistically controlling environmental impacts during the processes of socioeconomic transitions.

## 4 Uncertainties and potential measures

### 4.1 Uncertainties related to socioeconomic processes

Uncertainties related to socioeconomic processes are primarily caused by statistics and modeling. The findings of these studies are greatly affected by the accuracy of statistics. For example, several studies reported large differences in $CO_2$ emissions calculated using different socioeconomic datasets (Guan et al., 2012; Shan et al., 2018). The errors in socioeconomic statistics are primarily from the statistical system and artificial factors (Hong et al., 2017). Most international statistics are currently based on bottom-up reporting, which challenges cross-validation of the data (Hong et al., 2017). Specifically, different statistical guidelines (i.e., standards and processes used in collections and measurements) lead to different interpretations and definitions of data by reporters, resulting in inconsistencies and double counting of statistics (Chen et al., 2022). Furthermore, artificial errors in measurements, recording, and transmissions would reduce the accuracy of statistics. Therefore, statistics can be made more reliable by standardizing statistical guidelines and strengthening the data review process in the future.

The multiple assumptions used in the integrated assessment models lead to uncertainties of socioeconomic processes. For example, the input-output model assumes that the output of a sector is a linear function of its inputs (Miller and Blair, 2009). In fact, the relationships between inputs and outputs in various sectors of socioeconomic system can be affected by social factors such as politics and technologies (Peng et al., 2021a). In addition, existing integrated assessment models assign monetary values to environmental impacts (i.e., human lives and ecosystem services), leading to greater uncertainties in the determination of damage (Ackerman et al., 2009). Nowadays, integrated assessment models are still at the early stages of fully depicting the interrelationships between various links in socioeconomic systems. It is necessary to incorporate more knowledge of social sciences into future reforms of the integrated assessment models, such as psychology and political science (Peng et al., 2021b). Bringing the model closer to real life and serving the development of appropriate policies are the most important goals (Ramanathan et al., 2022).

### 4.2 Uncertainties related to environmental processes

Uncertainties related to environmental processes are mainly from the compilation of environmental emission or resource use inventory, the geochemical diffusion, transport, and transformation of contaminants, as well as the environmental impact evaluation.

Uncertainties in environmental inventories are one of the primary factors influencing the accuracy of simulation studies. The uncertainties mainly arise from imperfect or incomplete data sources (Zhu et al., 2017; Deng et al., 2020). Taking the atmospheric mercury (Hg) emissions as an example, the uncertainties mainly include the variations in the estimates of the Hg contents in fuel/raw materials (Zhang et al., 2012), the lack of actual measurements of the Hg emissions from combustion chambers (Wu et al., 2006), and the Hg removal efficiency of air pollution control devices (Wang et al., 2010). More systematic and harmonized measurements are required to reduce the uncertainties of data sources, given that reliable data are essential for obtaining accurate results with environmental simulation models.

For the geochemical diffusion, transport, and transformation of contaminants, uncertainties are mainly attributed to variations in the emission inputs of the chemical transport model and the model representation of tropospheric chemical processes, especially chemistry and physical processes such as vertical transport and wet scavenging (Chen et al., 2014). Moreover, uncertainties arise from limited data on contamination concentrations in wildlife for simulating biological processes in food webs (Lavoie et al., 2013; Clayden et al., 2013). To reduce these uncertainties, future research should make more efforts to have a clear understanding of the specific mechanisms in the biogeochemical cycle.

The environmental impact evaluation includes the evaluation of environmental quality, ecosystem quality, and human health. The uncertainties mainly exist in the parameters used in the evaluation. For example, in the evaluation of human health impacts, the uncertainties are attributed to the selection of some epidemiological empirical parameters (Massányi et al., 2020).

## 5 Prospects and possible solutions

This section summarizes the theoretical and technical limitations of existing studies and proposes possible solutions (Fig.5).

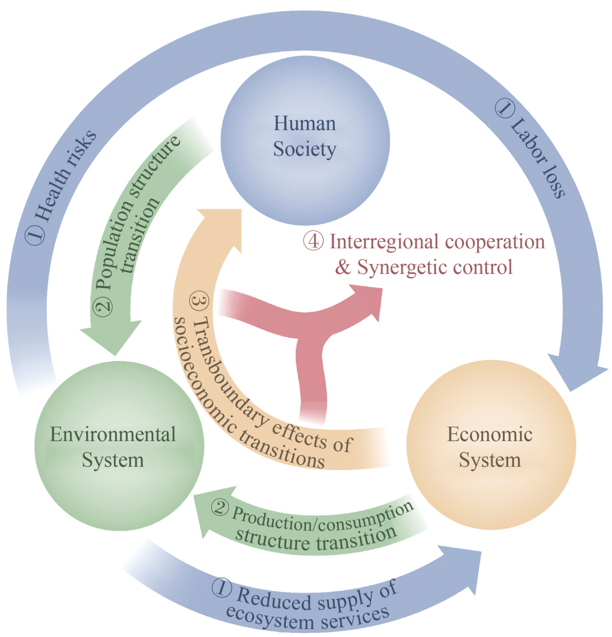


**Fig. 5** Prospects for future research (The numbers in the circles represent four prospects: ① Simulation of looping the dynamic material cycle, ② Socioeconomic structural transitions influencing environmental impacts, ③ Transboundary effects of socioeconomic transitions, and ④ Interregional cooperation mechanisms for synergetic control of multiple environmental impacts).

### 5.1 Simulation of looping the dynamic material cycle

Most existing studies on the material cycle have primarily investigated the one-way chain of resource depletion, environmental emissions, and environmental impacts caused by economic activities (Moss et al., 2010). In reality, human and natural systems are interconnected, and the feedbacks between them must be integrated into a complete material cycle (Ferraro et al., 2019). Future studies should capture the cascading effects of environmental impacts along the economic supply chains. Specifically, environmental impacts (e.g., human health risks and ecosystem quality degradation) affect the primary inputs (e.g., labor forces, capital, and land) to the economic production network (Barbier and Hochard, 2018; Zhang et al., 2018b). This will further lead to cascading effects on production activities, consumption activities, resource uses, environmental emissions, and environmental impacts through economic supply chains. For example, the human health risks associated with pollution may cause a decrease in the quantity (e.g., premature deaths caused by air pollution) (Lelieveld et al., 2015), quality (e.g., intelligence quotient loss from mercury exposure) (Zhang et al., 2021), and productivity (e.g., chronic respiratory diseases due to haze) (Guan et al., 2016) of the workforce. Due to the labor force decline in economic systems, production and consumption behaviors are negatively influenced. Furthermore, pollutant emissions and related health risks would change and further influence the workforce. Meanwhile, human behaviors will change in response to dynamic environmental perception (Beckage et al., 2018), which would further influence upstream production and emissions. These processes form a dynamic and looped socioeconomic-environmental cycle. Future research needs to change from static modeling of the material cycle to dynamic and looped modeling.

Integrated modelling is important to loop the dynamic material cycle. The input-output models and computable general equilibrium models can be used to quantify the cascading feedback effects of environmental impacts to the economic system (Li et al., 2022b). On the basis of the preliminary exploration of existing studies, exogenous feedback effects can also be quantified, such as human behavior changes and extreme events. For example, the climate-society model (Moore et al., 2022) and the integrated social-energy-ecology-climate model (Ramanathan et al., 2022) can be utilized to simulate the feedback effects of psychological, social, economic, legal, and political factors in the looped material cycle.

### 5.2 Socioeconomic structural transitions influencing environmental impacts

Existing studies have investigated the impacts of socioeconomic structural factors on resource uses and environmental emissions (Kovanda and Hak, 2008; Liang et al., 2021a). However, resource uses and environmental emissions are midpoints in the looped material cycle. Policies developed based on midpoint indicators are less effective than those using endpoints (e.g., ecosystem quality and human health). For example, Samset et al. (2020) found that declining emissions of greenhouse gases will not lead to a decrease in global temperature in the short term. In other words, the decline in greenhouse gas emissions does not absolutely diminish the impact of global warming on the environment. Consequently, future research should take environmental impacts as the endpoint to investigate the effects of socioeconomic structural transitions on environmental changes. Achieving this goal must address two research gaps: (1) accurate assessment of the environmental impacts caused by the human system and (2) constructing integrated models to simulate the interconnections between socioeconomic structural transitions and environmental impacts.

The causal chain linking socioeconomic structures to human health and ecosystem quality is complicated. For example, there are complex interactions among hazardous substances (e.g., secondary pollutants) and disparities in receptor response time (e.g., shorter response time in susceptible populations) (Chartres et al., 2019). To uncover the causal chain, it is necessary to utilize a multidisciplinary approach. First, it is necessary to establish monitoring networks for water, soil, and atmosphere, through which environmental chemical modeling can be used to accurately quantify the nexus of elements and reveal potential new pollutants. Second, it is necessary to employ clinical medicine and ecological investigation to reveal vulnerable populations and biota of risky substances. Finally, it is necessary to quantify the relationships between hazardous substances and human health as well as ecosystem quality. In terms of the health effects of risky substances, toxicological and epidemiological studies can be used to estimate dose-response relationships. The impact of risky substances on ecosystem quality (e.g., biodiversity loss and ecosystem service loss) can be quantified by ecological network models.

Structural decomposition analysis and logarithmic mean divisia index decomposition analysis have been widely used to identify the critical socioeconomic factors leading to changes in resource uses and environmental emissions. Similarly, based on the causal chain linking socioeconomic structures to environmental impacts, the structural decomposition analysis and logarithmic mean divisia index can be used to estimate the contributions of socioeconomic structural transitions on environmental impact changes. However, the number of decomposed factors in the structural decomposition analysis and logarithmic mean divisia index depends on the model's setup, which would usually overlook certain exogenous factors (e.g., the spatial structure of the population). Econometric models can be used to complement the structural decomposition analysis and logarithmic mean divisia index (Guang et al., 2019), which can more comprehensively investigate the effects of socioeconomic structural transitions on environmental impact changes with reference to existing studies.

### 5.3 Transboundary effects of socioeconomic transitions

Socioeconomic transitions generate transboundary environmental impacts through interregional trade (Qi et al., 2019) and physical transport processes (e.g., atmospheric and water cycle) (Liu et al., 2021b). For example, China has become an emerging market for ruminant products in recent years. The imports of ruminant products and livestock feed contribute to 12 Tg $CO_2$-eq and 42.8 Gg of greenhouse gas emissions and nitrogen emissions respectively in other countries (Du et al., 2018). Moreover, emissions can be transported through atmospheric movement to regions outside their origins, where they cause negative environmental impacts. Existing studies have investigated the transboundary environmental impacts along economic supply chains in specific time points. However, the cross-border environmental impacts of socioeconomic transitions over a time period still remain unknown. Investigating this point in future research can help evaluate the potential effectiveness of policy interventions on environmental impacts.

The environmentally extended multi-regional input-output model and structural decomposition analysis have been used to quantify the contributions of socioeconomic transitions to environmental emission changes (Liang et al., 2021a). Meanwhile, existing studies have used atmospheric transport models (e.g., GEOS-Chem chemical transport model) and hydrological models (e.g., hydrodynamic models) to simulate the transboundary flows of pollutants in environmental media (Kwon et al., 2018; Wu et al., 2019). By combining them with environmental health evaluation models and ecosystem service evaluation models, the transboundary environmental impacts of socioeconomic transitions can be captured in the future. Furthermore, the robustness of simulation results highly depends on the quality of raw input data. For example, the environmentally extended multi-regional input-output model and GEOS-Chem model depend on the input-output databases and pollutant emission databases. It is imperative to improve the data quality of existing databases based on interdisciplinary techniques (e.g., data mining and remote sensing).

### 5.4 Interregional cooperation mechanisms for synergetic control of multiple environmental impacts

Targeted legislation, regulations, emission standards, and permits have achieved outstanding results in environmental management, such as the Clean Air Act in the United States and the Air Pollution Prevention and Control Action Plan in China. Existing studies find that strict environmental policies have increased the cost of controlling environmental impacts, and interregional cooperation can save governance cost and enhance policy effectiveness (Xue et al., 2019). Therefore, interregional cooperation mechanisms are urgently needed.

Restructuring the interregional trade is an important interregional cooperation mechanism to reduce environmental impacts. However, existing studies only consider certain types of environmental impacts, which cannot fully capture the co-benefits or unintended consequences. For example, increasing China's imports of EU dairy products and U.S. beef can reduce greenhouse gas emissions but increase the land footprint of Latin American nations (Zhao et al., 2021). Thus, synergetic control of environmental impacts in interregional cooperation mechanisms can reduce environmental management costs. Policies and measures to prevent pollution can affect multiple pollutants simultaneously, which makes it more difficult to assess policy effectiveness. Multi-system near-real-time decision models are needed in the future to facilitate the interregional cooperation and synergetic control mechanisms.

A top-down approach can be used to construct such system-coupling models. First, the near-real-time geographic information system of multiple environmental impacts can be constructed based on remote sensing satellite data and environmental monitoring data. Second, socioeconomic and physical-geographic models can be utilized to explore the source-receptor relationships of environmental impacts. Third, future research can incorporate social sciences (e.g., political sensitivity and psychology) and scenario analysis methods (e.g., artificial intelligence networks, multi-objective optimization, and agent-based models) to explore short-term interregional cooperation strategies, as well as analyze historical trends to propose long-term stable cooperation strategies. Finally, uncertainty and validity analyses are necessary for the accuracy of results, which is a growing concern of modelers (Trutnevyte et al., 2019). The cross-validation of results based on empirical studies or macro- and micro-databases can help improve their robustness.

## 6 Conclusions

Human beings interact closely with natural systems. Integrating various processes of the coupled human-natural system is critical to understanding the effects of human society and economic activities on the environmental system. This review, for the first time, summarizes existing progress on the impacts of human society and economic system on the environmental system and relevant uncertainty analysis from a systematic perspective. It particularly concerns socioeconomic processes and transitions driving resource uses, environmental emissions, and environmental impacts. Moreover, this review identifies the problems in existing studies that need to be addressed in the future and proposes possible solutions.

Existing studies have identified critical regions and sectors driving resource uses and environmental emissions from multiple perspectives (e.g., production-based, income-based, consumption-based, and betweenness-based perspectives). They also revealed the supply chain transmission processes of resource uses and environmental emissions and identified critical transmission paths. In addition, existing studies have quantified the contributions of various socioeconomic factors to changes in resource uses and environmental emissions over a time period. Recent studies began to uncover the effects of socioeconomic transitions on the nexus of elements (e.g., energy-water, food-water, food-energy-water, and energy-water-carbon nexus). Recent studies have also extended the influences of socioeconomic processes from resource uses and environmental emissions to environmental impacts (e.g., ecosystem quality and human health). They have identified critical emission sources and consumption drivers of environmental impacts. Moreover, with the focus of policy design gradually developing from end-of-pipe control to source mitigation, recent studies are devoted to evaluating the effects of socioeconomic intervention measures on environmental impacts.

Uncertainty analysis has also been incorporated in most studies. They quantified the uncertainties related to socioeconomic and environmental processes, which were mainly caused by the uncertainties in survey statistics, environmental monitoring sampling, and simulation models. In addition, some studies have proposed possible measures to reduce the uncertainties. Future studies should make more efforts on improving the data quality and understanding the specific mechanisms in socioeconomic and environmental processes to reduce the uncertainties for simulation studies.

This review proposed four prospects and recommended possible solutions. First, future research should loop the dynamic material cycle in the coupled human-natural system modeling, especially the feedback effects of the natural system on the human system. Second, future studies should pay attention to evaluating the effects of socioeconomic structural transitions on various environmental impacts. Third, future work should explore the transboundary environmental impacts of socioeconomic transitions and reveal their source-receptor relationships. Fourth, modelers need to develop multi-system near-real-time decision models to help propose effective interregional cooperation mechanisms and develop synergistic emission control programs.

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