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Toward sustainable climate change adaptation

Yi Yang[1,2] | Beibei Liu[3,4] | Peng Wang[1,5] | Wei-Qiang Chen[1,5,6] | Timothy M. Smith[2]

[1]Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen, P. R. China

[2]Department of Bioproducts and Biosystems Engineering, University of Minnesota, St Paul, Minnesota

[3]State Key Laboratory of Pollution Control & Resource Reuse, School of Environment, Nanjing University, Nanjing, P. R. China

[4]The Johns Hopkins University-Nanjing University Center for Chinese and American Studies, Nanjing, P. R. China

[5]Xiamen Key Lab of Urban Metabolism, Xiamen, Fujian, P. R. China

[6]University of Chinese Academy of Sciences, Beijing, P. R. China

Correspondence
Wei-Qiang Chen, Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, P. R. China.
Email: wqchen@iue.ac.cn

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Abstract

Industrial ecology (IE) has made great contributions to climate change mitigation research, in terms of its systems thinking and solid methodologies such as life cycle assessment, material flow analysis, and environmentally extended input–output analysis. However, its potential contribution to climate change adaptation is unclear. Adaptation has become increasingly urgent in a continuously changing climate, especially in developing countries, which are projected to bear the brunt of climate-change-related damages. On the basis of a brief review of climate change impacts and adaptation literature, we suggest that IE can play an important role in the following two aspects. First, with the emphasis on a systems perspective, IE can help us determine how climate change interacts with our socio-economic system and how the interactions may aggravate (or moderate) its direct impacts or whether they may shift burden to other environmental impacts. Second, IE methodologies can help us quantify the direct and indirect environmental impacts of adaptation activities, identify mitigation opportunities, and achieve sustainable adaptation. Further, we find that substantial investment is needed to increase the resilience of infrastructure (e.g., transport, energy, and water supply) and agriculture in developing countries. Because these sectors are also the main drivers of environmental degradation, how to achieve sustainable climate-resilient infrastructure and agriculture in developing countries deserves special attention in future IE studies. Overall, IE thinking and methodologies have great potential to contribute to climate change adaptation research and policy questions, and exploring this growing field will, in turn, inspire IE development.

KEYWORDS
climate change adaptation, climate resilience, climate-smart agriculture, life cycle assessment (LCA), low-carbon infrastructure, material flow analysis

1 | INTRODUCTION

The urgency of climate change adaptation is being increasingly recognized (de Coninck et al., 2018). The speed at which some of the most costly effects of climate change are approaching has been generally underestimated (Melillo, Richmond, & Yohe, 2014). Compared with previous estimates, oceans are warming at much faster rates (Cheng, Abraham, Hausfather, & Trenberth, 2019) and yields of staple crops will likely decline sooner (Challinor et al., 2014). For example, heatwaves in Australia from 2000 to 2009 reached a level projected for 2030 (Steffen, Hughes, & Perkins, 2014), and coral reefs in Florida, USA, have already started dissolving (Muehllehner, Langdon, Venti, & Kadko, 2016). In addition, the progress on climate change mitigation so far has been discouraging, and so are future trajectories. Global CO_2 emissions have continued to grow by 2018 (Jackson et al., 2018), and for reasons such as the carbon lock-in effect of existing infrastructure, we are unlikely to achieve the target of limiting global warming to 2 or 1.5°C (Brown, Alexander, Arneth, Holman, & Rounsevell, 2019; Davis, Caldeira, & Matthews, 2010; Raftery, Zimmer, Frierson, Startz, & Liu, 2017). A changing climate, together with the likelihood of global greenhouse gas (GHG) emissions continuing to rise in the medium to long term, calls for immediate adaptation efforts. In response, a series of global initiatives have been launched, including the recent Global Commission on Adaptation, to accelerate adaptation actions around the world by facilitating international cooperation and providing guidance and support for concrete solutions.

Industrial ecology (IE) is a young field that aims to improve the environmental sustainability of socioeconomic systems by mimicking the workings of ecosystems (e.g., efficient recycling of resources) (Frosch & Gallopoulos, 1989). IE sees socioeconomic activities through their interactions with the environment, applies systems perspectives in modeling, focuses on product design for problem-solving, and emphasizes the importance of businesses in technology innovation (Lifset & Graedel, 2002). Under the framework of IE are several distinctive methodologies, including industrial symbiosis (e.g., eco-industrial parks), life cycle assessment (LCA), environmentally extended input–output analysis (EEIO), and material flow analysis (MFA). Over the past few decades, these methodologies have grown to become major approaches in the broad field of sustainability science, playing an increasingly important role in environmental, and to more limited extent social, sustainability analysis, and decision support across different scales. For example, LCA is widely used to promote eco-friendlier materials, products, technologies, and farming practices (Mitrano, Motellier, Clavaguera, & Nowack, 2015; Notter, Kouravelou, Karachalios, Daletou, & Haberland, 2015; Yang, Tilman, Lehman, & Trost, 2018). MFA is widely used to determine patterns of material utilization, recycling, and losses (Brunner & Rechberger, 2016), notable examples including estimates of metal requirements of modern society (Graedel, Harper, Nassar, & Reck, 2015) and of plastics waste entering the ocean (Jambeck et al., 2015).

IE methodologies have been applied primarily in the context of climate change mitigation rather than adaptation. Specifically, LCA has been the main approach to identifying, for example, low-carbon electricity technologies (Weisser, 2007), low-carbon biofuels (Larson, 2006), low-carbon building materials (Cabeza et al., 2013), and low-carbon diets (Tilman & Clark, 2014). In fact, life cycle thinking underpins a number of national renewable fuel policies with explicit GHG reduction targets, such as the Renewable Fuel Standard in the United States (USEPA, 2010) and the Clean Fuel Standard in Canada (ECCC, 2018). Other IE methodologies such as MFA and industrial symbiosis are also commonly applied in mitigation research. For example, Bajželj et al. (2014) demonstrated the importance of dietary change and reducing food waste in mitigating food-related GHG emissions, based on a suite of models including an MFA model. Zhang et al. (2018) employed a dynamic MFA model to explore energy conservation and carbon mitigation potential of China's iron and steel industry by 2015. And many researchers have studied the climate mitigation potential of eco-industrial parks (Al-Mohannadi & Linke, 2016; Jung, An, Dodbiba, & Fujita, 2012; Liu, Zhang, Bi, Wei, & He, 2012).

However, how IE methodologies may contribute to climate change adaptation research is unclear, a question we hope to explore in this paper. Through a review of climate change impacts and adaptation studies, we identify two major areas to which IE can contribute. First, the systems perspective—which IE emphasizes and from which IE methodologies like LCA and MFA were developed—can help us better determine the social, economic, and environmental impacts of climate change. Only when we gain a better understanding of what may happen can we be more prepared to adapt. Second, whereas adaptation actions and efforts are crucial to reducing the risks of being affected by climate variability and change, they have their own environmental costs (Fezzi, Harwood, Lovett, & Bateman, 2015). How to reduce or minimize the costs is a question to which IE is especially relevant and can contribute directly.

In the following sections, we expand on these two points. We begin with a brief review of the literature on potential impacts of climate change and associated adaptation strategies, followed by a discussion of IE methodologies' instrumental role to improving understanding. In the review, we focus on developing countries, as they are more susceptible to climate change but at the same time less capable of coping and adapting because of economic constraints (IMF, 2017).

2 | CLIMATE CHANGE IMPACTS AND ADAPTATION IN DEVELOPING COUNTRIES

2.1 | Major climate change impacts

Impacts of climate change are global in scale, but evidence abounds that poor countries will bear the brunt (Dell, Jones, & Olken, 2012; King & Harrington, 2018). Poor countries are located in hotter regions and are projected to experience a greater increase in temperature variability (Bathiany, Dakos, Scheffer, & Lenton, 2018) and a greater shift in local climate (King & Harrington, 2018). A 1°C increase in temperature is estimated to reduce 0.9% of per capita GDP (gross domestic product) growth in emerging economies and 1.2% in low-income developing economies (IMF, 2017). If climate change were unmitigated by the end of this century, most low-income countries would encounter significant economic losses, that is, ~9% reduction in per capita GDP (IMF, 2017). In fact, rising temperature over the last few decades has already significantly reduced economic output in poor countries and fueled their political instability (Dell et al., 2012), contributing to global economic inequality (Diffenbaugh & Burke, 2019).

The most direct impacts of climate change are increases in the frequency and intensity of extreme weather events (or natural disasters), such as heatwaves, droughts, wildfire, storms, and sea-level rise (Field, Barros, Stocker, & Dahe, 2012). Projected frequency of extreme heat waves at

1.5 or 2°C of warming is drastically higher for Africa, Latin America, Middle East, and some Southeast Asian countries than for other parts of the world (Russo et al., 2019). In particular, heatwaves in Africa have accelerated in the last few decades and are projected to occur regularly by 2040 if the current trend of emissions continues (Russo, Marchese, Sillmann, & Immé, 2016). Occurrence of drought has also been projected to worsen over Latin America, southern and central Africa, and southeast Asia (Dai, 2013). Global wildfires were primarily associated with precipitation before the Industrial Revolution but have shifted to being driven by climate change, and future warming will likely intensify wildfires across much of the globe, including south and central Asia and South Africa (Pechony & Shindell, 2010).

Climate change has wide-ranging socio-economic effects (Carleton & Hsiang, 2016), but some sectors are more severely affected than others (Melillo et al., 2014). There is a broad consensus that crop yields will be negatively affected by climate change in most tropical and subtropical areas (Wheeler & von Braun, 2013). Future climate change could reduce grain production in China by 20% (Piao et al., 2010), rice output in Vietnam by 18% (Le, 2016), wheat yield in India by 20% (Lobell, Sibley, & Ivan Ortiz-Monasterio, 2012), and crop production in Africa by 8–22% (Schlenker & Lobell, 2010). Impacts of climate change on water resources are intertwined with population growth: some developing regions may become less water-stressed (e.g., south and east Asia) while others more (e.g., south and east Africa and South America) (Arnell, 2004). Driven partly by climate change, major coastal cities around the world may encounter substantial flood losses by 2050, and most of the top 20 cities with the highest losses are located in developing countries like China and India (Hallegatte, Green, Nicholls, & Corfee-Morlot, 2013). Climate change impacts human health in various ways, from extreme weather-related mortality and morbidity (O'Neill et al., 2009), deteriorated air quality (Bell et al., 2007), to the increasing prevalence of infectious diseases (Patz, 1996). Populations in low-income countries are likely at a much higher risk of these adverse effects than those in high-income countries (Haines, Kovats, Campbell-Lendrum, & Corvalan, 2006). Climate change can also affect electricity generation, especially hydropower. A significant decrease in hydropower output is projected for many developing regions, including parts of South America, southeast China, Central America, and northern Africa, while a large increase is projected for central Asia (Turner, Ng, & Galelli, 2017).

2.2 | Critical areas of adaptation in developing countries

According to the Intergovernmental Panel on Climate Change (IPCC), adaptation is defined as "adjustments in human and natural systems, in response to actual or expected climate stimuli or their effects, that moderate harm or exploit beneficial opportunities." Climate change adaptation measures are commonly characterized as soft and hard measures (Hallegatte, 2009; IMF, 2017; Sovacool, 2011). Soft measures leverage technical, informational, institutional, and financial tools and make relatively small and reversible changes to existing systems. Examples include long-term land and water use planning, early-warning and evacuation systems, and strengthened insurance schemes for weather shocks (Hallegatte, 2009; IMF, 2017). In contrast, hard measures are at larger scales and irreversible and may involve costly investment in infrastructure, such as building seawalls and dams and using permeable paving surfaces (Mullan, 2018). Both types of adaptive measures are important and being widely proposed (Karanth & Archer, 2014).

As shown above, developing countries will be affected by climate change in various ways, and to adapt to climate change may require considerable investment in infrastructure. In Asia, for example, ~40 billion US dollars a year may be required for investment in climate-resilient infrastructure from 2016 to 2030, mainly in transportation and power systems, as estimated by the Asian Development Bank (ADB, 2017). Areas of improvement may include elevation of roads and road embankments, strengthening drainage systems, and relocation of water intake and treatment works (ADB, 2017). Asia's cities, many of which are among the most densely populated in the world and are continuing to expand, are particularly prone to both weather shocks and long-term stresses of climate change (Dulal, 2019; Hallegatte et al., 2013). Recognizing the major challenges facing these cities, the Asian Climate Change Resilience Network (ACCCRN) was launched in 2008 by the Rockefeller Foundation to help strengthen their adaptive capacity. The network now involves more than 40 cities in six climate-vulnerable countries: Vietnam, India, Indonesia, Thailand, Bangladesh, and the Philippines. For example, in Surat, the ninth-largest city in India, a number of soft measures have been implemented through ACCCRN, to strengthen monitoring systems for floods and climate-related diseases and to promote cool roofs and ventilations (Karanth & Archer, 2014).

A similar scale of infrastructure investment (~40 billion US dollars per year) is needed to address climate change-related development issues in Africa, as estimated by the African Development Bank (Chinowsky, Schweikert, Strzepek, & Strzepek, 2015). Integrating climate change in the planning and design of road, power, and water infrastructure is likely to bring substantial benefits (Cervigni et al., 2015; Chinowsky et al., 2015). For example, investment in roads may reduce climate change costs by ~70 million US dollars a year in South Africa (Chinowsky, Schweikert, Strzepek, & Strzepek, 2012). Though the importance of infrastructure investment in Africa cannot be overstated, especially considering its existing gaps with other regions (Calderon, 2009), building a more climate-resilient Africa will also benefit from soft adaptation interventions, such as crisis insurance and relocation initiatives (Doczi & Ross, 2014).

In developing countries, agriculture has been one of the main reported adaptation initiatives because climate change is projected to take a heavy toll on crop yields (Ford et al., 2015). It has also received broad support from the United Nations. For example, the Integrating Agriculture in National Adaptation Plans (NAP-Ag) program has been established, under United Nation Development Programme (UNDP) and Food and Agriculture Organization (FAO), to facilitate integration of adaption measures into national planning and budgeting toward agricultural sectors in developing countries. Countries currently supported include Kenya, Thailand, Nepal, Uganda, and Columbia. Overall, a wide range of technological and managerial solutions have been put forward that can increase the resilience of agricultural systems, including the use of water-saving technologies

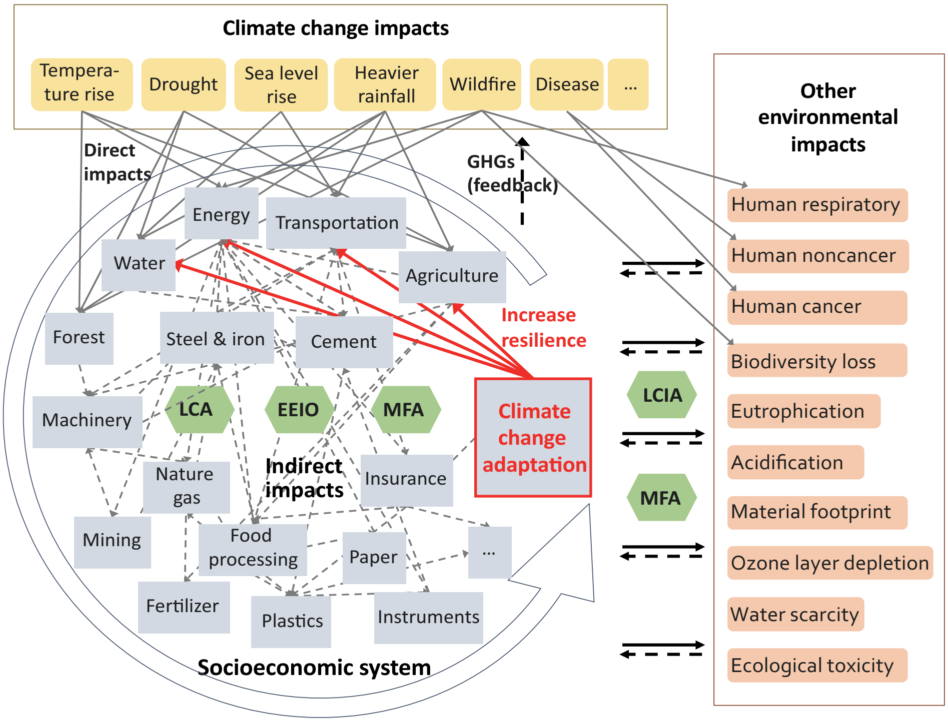

FIGURE 1 A conceptual framework for integrating climate change adaptation into industrial ecology (IE). Climate change, directly and indirectly, impacts our socioeconomic system, driving us to adjust and adapt, especially to increase the resilience of those sectors significantly affected. All these responses have potential environmental and social implications (including GHGs as climate change feedback), which can be estimated by MFA and life-cycle impact assessment (LCIA) models. And LCA, EEIO, and MFA can be useful for modeling the direct and indirect impacts of climate change within the socioeconomic system. Climate change can also directly affect human and ecological health, which in turn affects the socioeconomic system

like micro-irrigation, planting of climate-resistant crop cultivars, and restoration of degraded soils and waters (Jat et al., 2016). In China, adaptation efforts are being made at different levels, with governments focused on new technology development and institutional capacity improvement (Wang, Huang, & Yang, 2014). To cope with drought in Thailand, farmers' strategies include crop diversification, change of land use patterns, and building farm ponds in paddy fields (Polthanee, Promkhumbut, & Bamrungrai, 2014). A survey of thousands of smallholder farmers in three regions of South Asia found that changing cropping patterns and adopting resilient crop varieties may be the most widely adopted practices (Bhatta & Aggarwal, 2016). In Kenya, many households were able to make small changes to their farming practices but yet to adopt more costly investments like installing irrigation systems (Bryan et al., 2013). In West Africa, there have been recent efforts from policymakers at both national and regional levels to promote climate-smart agriculture (Zougmoré et al., 2016).

3 | TOWARD A BETTER UNDERSTANDING OF CLIMATE CHANGE IMPACTS

3.1 | IE models to estimate climate change impacts

The current studies of the socioeconomic impacts of climate change tend to focus on high-level aggregate indicators such as GDP (Burke, Hsiang, & Miguel, 2015; Mann, Tolbert, & Cushman, 2002; Nordhaus & Moffat, 2017), or on individual sectors (see discussion in (O'Brien, Eriksen, Sygna, & Naess, 2006)). While GDP may indicate the overall magnitude of climate change impacts, it falls short of providing insights into the actual impacts being felt "on the ground". Similarly, sectoral studies are informative but can miss important indirect impacts that occur across sectors through intersectoral linkages (O'Brien et al., 2006). There has been a growing body of research taking more integrated approaches to examine the impacts of climate change beyond the direct (Calvin & Fisher-Vanden, 2017; Herrera-Estrada, Diffenbaugh, Wagner, Craft, & Sheffield, 2018; Nicholls & Kebede, 2012; Nkhonjera & Dinka, 2017; Smithers & Blicharska, 2016). But substantial knowledge gaps remain (Melillo et al., 2014).

Climate change not only directly impacts certain sectors of our socioeconomic system, but it interacts with the system in ways that can (a) aggravate (or moderate) the direct damages of climate change (e.g., air pollution), (b) shift burden to (or alleviate) other problems not directly related to climate change (e.g., ecological toxicity), or (c) amplify (or lessen) future climate change via releasing (or sequestering) GHG emissions which would not have occurred otherwise (Figure 1). To capture these complicated interactions requires systems approaches and cross-disciplinary collaborations. Major systems models to examine the socioeconomic impacts of climate change across economies have employed computable general equilibrium (CGE) approaches, and their derivatives (e.g., dynamic CGE) (Dixon & Jorgenson, 2012). CGE models, however, are highly aggregated (at typically ~30 sectors), assume optimized behavior, and include only a small number of pollutants (Rose, 1995; Yang & Heijungs, 2018). These limitations make CGE models inadequate in capturing (a) the actual interactions between economic agents, especially those that occur via detailed intersectoral dependences, and (b) linkages among different environmental issues (Figure 1).

In contrast, advances in process-based LCA and EEIO over the past two decades have yielded a comprehensive data infrastructure with sectoral specificity and covering a wide range of stressors contributing to various environmental issues (Figure 1). A large number of national EEIO models, commonly at 100–500 sector levels, have been developed around the world and applied to study a diversity of questions from GHG emissions, water stress, biodiversity loss, to waste and material management (Bogra, Bakshi, & Mathur, 2016; Carvalho, Antunes, Freire, & Henriques, 2015; Liang et al., 2017; Marques, Verones, Kok, Huijbregts, & Pereira, 2017; Yang, Ingwersen, Hawkins, Srocka, & Meyer, 2017). There have also been efforts to expand EEIO models toward global scales for transboundary analysis, on one hand, or subnational scales for regional analysis, on the other (Caron, Metcalf, & Reilly, 2017; Lenzen et al., 2017; Moran & Wood, 2014; Zhang & Anadon, 2014).

Similarly, process-based LCA databases have experienced a significant expansion. More databases have been built with different focuses, such as LCA commons, Agri-footprint, and ARVI (GreenDelta, 2019). And existing databases, such as ecoinvent, have continued to grow both in product coverage and in modeling sophistication (Wernet et al., 2016). The most comprehensive LCA and EEIO models (Liang et al., 2017; Wernet et al., 2016; Yang et al., 2017) cover several hundreds to over 1,000 different stressors (e.g., emissions and resource use) linked to various environmental areas (Figure 1) and at increased spatial resolution (Smith et al., 2017). Application of EEIO and LCA models has substantially improved our knowledge of how production and consumption activities impact the environment.

3.2 | Research challenges and needs

While EEIO and LCA models provide a comprehensive data infrastructure, several areas need improvement to better estimate the impacts of climate change within our socioeconomic system and on the environment (Figure 1).

First, EEIO and LCA modeling itself need to be refined and broadened. EEIO and LCA models are mostly retrospective, based on historical data like input–output tables, but most climate change impacts will happen in the future and over a long timeframe. Also, EEIO and LCA models focus narrowly on product supply chain (Yang & Heijungs, 2018). Although the supply chain is important, it is incomplete and other market mechanisms should also be accounted for, such as the rebound effect, feedback, and competition between sectors for resources (Berkhout, Muskens, & Velthuijsen, 2000; Rajagopal, 2014; Sandén & Karlström, 2007). Recent efforts to integrate other models (e.g., partial equilibrium, system dynamics, and agent-based modeling) into LCA to make the framework more dynamic, prospective, and predictive for better policy support (Chaplin-Kramer et al., 2017; Rajagopal, 2014; Stasinopoulos, Compston, Newell, & Jones, 2012; Yang, 2016) offers insight into how similar work can be done to strengthen the modeling for climate change.

Second, EEIO and LCA models need to be "climate calibrated." Conventionally, these models have been used to study how our economic activities contribute to climate change via GHG emissions, not the other way around. Some climate change impacts can be readily translated to production and consumption (e.g., repairing and reconstructing a road after being damaged by a storm). But others are more complicated and require cross-disciplinary research and detailed modeling to reveal the full impacts. For example, a prolonged drought can cause significant GHG and other emissions via killing vegetation, reducing hydropower output, and increasing irrigation use (Figure 2). And climate change-induced changes in streamflow, humidity, air density, and air and water temperature can reduce thermoelectric generation in the long run (Bartos & Chester, 2015). In other words, EEIO and LCA models need to be expanded or incorporate other models to better understand the interface between climate change variables and economic activities.

Third, we need to better understand how climate change interacts with other environmental impacts, particularly human health, and how the interactions feedback to our socioeconomic system (Figure 1). Climate change can cause illness and injuries via, for example, diseases and extreme weather events like storms and thus reduce employee attendance and productivity, how does this affect sectoral output? In LCA and EEIO modeling, environmental impacts (ecosphere) are basically exogenous to the socioeconomic system (technosphere), but climate change raises new questions and the need for modeling of feedback from the ecosphere to the technosphere.

4 | TOWARD SUSTAINABLE CLIMATE CHANGE ADAPTATION

4.1 | Environmental impacts of climate change adaptation

Despite the anecdotal efforts and support from foundations and the United Nations, planning, implementation, and governance of climate change adaptation in developing countries are at an early stage as revealed by systematic reviews (Araos et al., 2016; Dulal, 2019). But even less attention from either policymakers or scholars has been paid to the environmental impacts of adaptation measures themselves (Fezzi et al., 2015). Whereas adaptation efforts can help moderate climate change-related damages, they may lead to adverse environmental consequences (Figure 1). For example, Adger, Arnell, and Tompkins (2005) indicated that overacting to extreme weather events may not be sustainable in the long run, as in

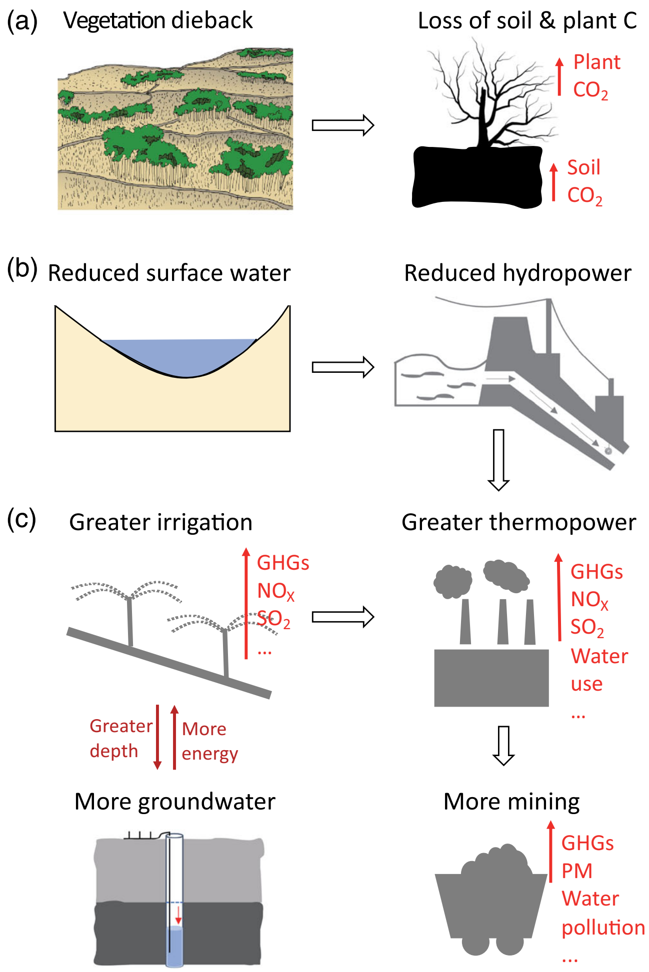

FIGURE 2 Main impacts of drought on the natural and socioeconomic systems. (a) Vegetation dieback, leading to loss of plant and soil carbon. Although new vegetation will grow back, it may take decades before reaching the original level of plant and soil C stock (Yang, Tilman, Furey, & Lehman, 2019). The initial loss of carbon and gradual sequestration back is equivalent to carbon emissions in dynamic climate modeling (Levasseur, Lesage, Margni, Deschenes, & Samson, 2010). (b) Reduced surface water and hydropower, leading to greater thermopower and fossil fuel mining with various environmental impacts (Gleick, 2016). (c) Greater irrigation use, leading to (1) various emissions on-site and/or greater thermopower, and (2) a greater reliance on groundwater, which may lower water table and in turn increase irrigation energy intensity (Haacker, Cotterman, Smidt, Kendall, & Hyndman, 2019; Zhang, Lin, Rogers, & Lamm, 2015)

the case of installing air conditioning after a rare heatwave. Recently, Fezzi et al. (2015) estimated that adaptation in the farming sector in the UK may deteriorate river water quality, directly conflicting with policies aimed at protecting freshwater ecosystems. In a critical review, Enríquez-de-Salamanca, Díaz-Sierra, Martín-Aranda, and Santos (2017) discussed that the reasons for the lack of attention to adaptation-related environmental impacts may include, among others, our inclination to see adaptation as intrinsically good and our greater interest in climate change impacts. And they suggested including strategical environmental assessment (SEA) or environmental impact assessment (EIA) in adaptation planning and design to better assist decision making. Thus, how to quantify and reduce the environmental impacts induced by climate change adaptation efforts merits more and wider attention.

4.2 | Sustainable climate change adaptation

IE can help achieve sustainable climate change adaptation (Figure 3). In fact, the primary goal of IE methodologies—including LCA, EEIO, and MFA—is to inform decision making towards sustainable production and consumption (Guinée & Heijungs, 2017; Hendriks et al., 2000).

In particular, LCA is widely used to identify alternative materials, products, technologies, energy sources, and services that are more eco-friendly. For example, Van den Heede and De Belie (2017) applied LCA to quantify the benefits of industrial by-products like fly ash and blast-furnace slag in lieu of cement. Using an LCA model, Pallas, Vijver, Peijnenburg, and Guinée (2019) explored the environmental performance of two lab-scale routes for producing nanowire-based solar cells. Yang et al. (2018) estimated the carbon footprint of several management practices in search of sustainable intensification in grassland biomass production. Employing LCA hotspot assessment and procurement portfolio optimization, Pelton, Li, Smith, and Lyon (2016) examined alternative industrial purchasing strategies. Combining LCA and green chemistry, Tabone, Cregg, Beckman, and Landis (2010) evaluated the sustainability of petrol- and bio-based polymers. And Ng (2018) coupled LCA with ant colony optimization (ACO) to design assembly sequences with a lower environmental burden.

MFA has also been increasingly applied to provide detailed and quantitative analysis of resource pathways associated with historical and future service needs (Pauliuk & Müller, 2014; Pauliuk, Arvesen, Stadler, & Hertwich, 2017). One main goal of such analyses is to inform various strategies for sustainable pattern transition, for example, to promote circular material flow economy, advance process and infrastructure design for resource

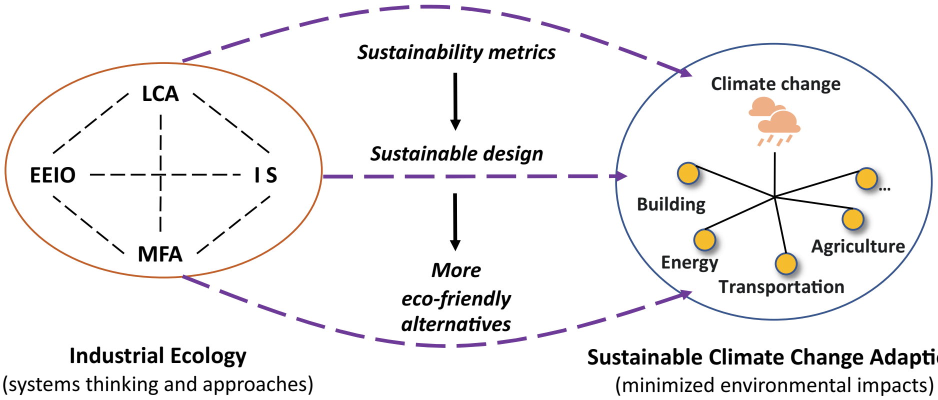

FIGURE 3 The role of industrial ecology in sustainable climate change adaptation. IE methodologies (e.g., LCA, MFA, EEIO, and IS) can help improve the environmental sustainability of climate change adaptation measures across different areas by minimizing their environmental impacts

efficiency, and maximize system material efficiency (Weisz, Suh, & Graedel, 2015). Gao and You (2018), for example, proposed a dynamic MFA-LCA model for sustainable supply chain design in shale gas extraction. Further, EEIO models have been used to determine the impacts of service sectors, which are often not associated with environmental issues (Rosenblum, Horvath, & Hendrickson, 2000). Nansai et al. (2009), for example, found that the direct and indirect material and energy use of service sectors in the United States was a major contributor to the country's rising GHG emissions from 1990 to 2000.

As demonstrated by these examples, IE methodologies can be used to (a) integrate sustainability metrics into climate change adaptation, (b) design sustainable adaptation measures, and (c) compare between different measures to identify the most environmentally friendly one (Figure 3). Below, we illustrate this in more detail in the context of climate change adaptation in developing countries.

4.3 | Research needs for developing countries

As shown before (Section 2.2), substantial investment is needed to improve the climate resilience or smartness of agriculture and infrastructure in developing countries. The two sectors are also the main drivers of environmental degradation. Agriculture occupies the largest area of the world's land surface (~40%) and is the main threat to biodiversity (Foley et al., 2005; Tilman, May, Lehman, & Nowak, 1994). Globally, it also consumes ~70% of freshwater and uses ~85% of synthetic nitrogen, resulting in various reactive species like ammonia and nitrate that contaminate air and water (Campbell et al., 2017). Infrastructure accounts for ~70% of GHG emissions through electricity generation, buildings, and transportation (Meltzer, 2016). In China, infrastructure expansion caused most of the emissions since the early 2000s (Z. Liu et al., 2013), partly because of its high embodied energy and material use. Existing infrastructure can also lock in future emissions for decades to come (Davis et al., 2010).

Given the large impacts of agriculture and infrastructure, if adaptation in these two areas is done without sustainability in mind, it can put further pressure on both domestic and global environments. Unsustainable adaptation can aggravate climate change by causing GHG emissions or shift burden to other environmental issues via causing, for example, air and water pollution and land-use change (Figure 1). Therefore, how to achieve sustainable climate-resilient agriculture (SCRA) and infrastructure (SCRI) in developing countries should be an important area of future research.

4.3.1 | Sustainable climate-resilient agriculture (SCRA) in developing countries

The key question for SCRA analyses is to estimate both the effectiveness of different adaptive strategies and their direct and indirect environmental impacts. Previous studies have identified a wide range of adaptive strategies for agriculture, such as shifting planting times, applying pesticides and fertilizers at greater rates, adopting more resilient varieties, diversifying crop choices, and installing irrigation systems (Howden et al., 2007). But, it is unclear how effective each strategy might be, or whether a particular strategy is even suitable, for a specific location given high regional variability in weather, soil, management practices, and climate. Furthermore, each strategy may have very different environmental impacts, in terms of both the magnitude of the impacts and the major areas affected (e.g., human respiratory or aquatic eutrophication). For example, irrigation mainly leads to air pollution (e.g., GHGs and NO_X), on-site or upstream, depending on the energy source (e.g., diesel or electricity) (Eranki, El-Shikha, Hunsaker, Bronson, & Landis, 2017). Fertilizer and pesticide application leads to both air (e.g., N_2O, NH_3, and particulates) and water pollution (e.g., pesticide and nitrate runoff and leaching) (Hill et al., 2019; Yang, Bae, Kim, & Suh, 2012). Extensive planting mode may reduce GHG emissions but sacrifice the land use efficiency (B. Liu, Wang, Zhang, & Bi, 2013), and excessive straw return-to-field reduces air pollution from seasonal burning but can lead to higher GHG emissions (Liu, Wu, Wang, & Zhang, 2019). Introducing a different crop may have a completely different environmental profile than that of existing crops grown.

Advances in LCA, particularly the integration with agricultural systems modeling, have paved the way for such SCRA analyses. Agricultural systems models (e.g., DNDC, DAYCENT, EPIC, and SWAT) simulate biogeochemical processes of agricultural systems considering an array of factors (e.g., soil, weather, and nutrient input) and are widely used to inform farm-level decision making (Jones et al., 2017a). They can determine the effectiveness of different adaptive strategies in increasing and stabilizing crop yield under different climate scenarios (Jones et al., 2017b). LCA then complements these models by estimating the life-cycle environmental implications of the adaptive strategies. The integration between agricultural systems models and LCA (Adler, Grosso, & Parton, 2007; Deng, Paraskevas, & Cao, 2017), with also the aid of agricultural LCA databases, offers great potential to help achieve SCRA. Case studies that apply LCA and agricultural models to examine both resilience and environmental sustainability in developing countries are welcome.

Gaps and challenges, however, remain for such research in developing countries. Most agricultural systems models originated from developed countries, and despite some progress are yet to be widely applied to or adopted by the developing world (Gilhespy et al., 2014; Jiang et al., 2017). The same geographic disparity can be said about LCA research. Both can be attributed to limited data availability and poor research capacity in many developing countries (Jin et al., 2019). Therefore, greater investment in agricultural research and data collection (e.g., survey and satellite remote sensing) is urgently needed in these countries.

4.3.2 | Sustainable climate-resilient infrastructure (SCRI) in developing countries

The key challenge for SCRI analyses is integrating environmental sustainability in the design, building, and operation of climate-resilient infrastructure, which includes (a) new infrastructure to be built with strengthened resilience against the risks of extreme weather events and other climate impacts, (b) new infrastructure (e.g., sea walls) built specifically to reduce the physical impacts of climate change (e.g., rising sea levels), and (c) existing infrastructure to be retrofitted in consideration of future climate risks (Mullan, 2018). Infrastructure is in general resource-intensive and, once built, can lock in future emissions for decades to come (Davis et al., 2010; Zheng, Wang, Wood, Wang, & Hertwich, 2018b). How to reduce the material footprint of infrastructure or use renewable materials instead and how to design it in a way that minimizes emissions during operation are critical to achieve SCRI.

There has been extensive IE research on infrastructure such that climate change adaptation can be readily integrated for SCRI analyses. Among others, there has been a growing body of research on low-carbon infrastructure (Busch, Dawson, & Roelich, 2017; Kennedy, Ibrahim, & Hoornweg, 2014; Zheng et al., 2018a), with some preliminary work considering resilience (Kennedy & Corfee-Morlot, 2013). Recognizing the energy and emission intensities of building and road materials, the search for sustainable alternatives has long been a focus of IE research (Mroueh, Eskola, & Laine-Ylijoki, 2001; Thormark, 2002). There is also recent interest in understanding the various environmental implications, particularly material requirements of large-scale infrastructure deployment (Hertwich et al., 2015; Vidal, Rostom, François, & Giraud, 2017; Wang, Chen, Ge, Cai, & Chen, 2019). For example, Wang et al. (2019) estimated that China's plan to transition toward a renewable-based energy system in 2050 may require substantially more critical materials than its national reserves.

For SCRI research in developing countries, as with SCRA, there is also the need for continuous investment in building life-cycle inventories, especially for infrastructure sectors (e.g., energy, transport, and water). This will help us better understand the environmental impacts of infrastructure and support SCRI analyses. Also, combining IE methodologies with engineering models (e.g., WBM-TP2M (Miara et al., 2017), VIC (van Vliet, Wiberg, Leduc, & Riahi, 2016), and IPSS (Melvin et al., 2017)) or statistics models, can better simulate environmental impacts of infrastructure building and operating with different technologies and also better capture the climate influences on infrastructure. These fusions will complement the merits of IE approaches and other models, and help quantify life-cycle vulnerabilities and select effective adaptive strategies.

5 | CONCLUSIONS

The main goal of this article is to discuss potential contributions IE can make to climate change adaptation in hopes of stimulating more IE research into this growing field, especially with respect to developing countries. As we are increasingly confronted with the gravity of climate change (Hansen et al., 2016), climate change adaptation deserves more attention in the IE community. We believe IE methodologies—such as LCA, EEIO, and MFA, with the integration of other approaches—(a) have the potential to improve our understanding of the socioeconomic and environmental impacts of climate change, and (b) can help achieve sustainable climate change adaptation by minimizing the environmental impacts of adaptation activities. Research into questions of climate change adaptation may in turn help improve IE methodologies and benefit the community.

In addition, developing countries will face much greater challenges than the developed nations. They are under the dual pressures of development—to improve the well-being of a growing population—and adaptation, as they are expected to bear the brunt of climate change-related damages. Consequently, they need substantial investment in agriculture and infrastructure (e.g., power, transport, water supply, and sanitation) to ensure both economic progress and successful climate change adaptation. Therefore, how to achieve sustainable climate-resilient infrastructure and agriculture in develop countries deserves special attention in future IE studies.

CONFLICT OF INTEREST

The authors have no conflict to declare.

ORCID

Yi Yang https://orcid.org/0000-0002-1131-6196
Wei-Qiang Chen https://orcid.org/0000-0002-7686-2331

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