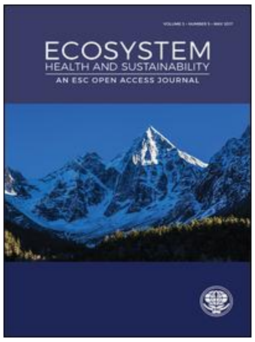

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ABSTRACT
Industrial development has brought China both opportunities and challenges since the reform and opening up in 1978. Spatial and temporal analysis showed that rapid industrialization has made eastern China under a more serious pollution stress. The most serious effects of industrial pollution were reflected in aquatic and soil ecosystem degradation, and damage can be observed from species, population, and community to ecosystem level. Public consciousness about contaminated sites rose from 2004 leading to greater efforts in ecological remediation, monitoring, and risk governance. Considerable efforts are still needed in expanding the extent and breadth of monitoring to explore where the greatest ecological risks lie and how to control them. Ecology of industrial pollution has become a popular discipline in China and will be further developed to help achieve the Sustainable Development Goals. Future research for a better ecological risk management should be focused on multi-media transfer and effects of mixed pollutants, mechanisms for clean energy and material flow, and integration of ecological risk with human health risk.

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Industrial development and pollution in China over forty years

China has achieved a remarkable progress in industrial development over the last 40 years' reform and opening up since 1978. Industrial-added value increased from 162 billion yuan (23 billion USD) in 1978 to 30,516 billion yuan (4,303 billion USD) in 2018 (NBSPRC 2018b) (Figure 1). In terms of the industrial output for 220 industrial products, such as steel, cement, automobiles, air conditioners, personal computers, cell phones, and ships, etc., China ranks first in the world.

Industrial development began mostly in the eastern coastal regions in the initial reform period. Although China accelerated industrial development in inland regions to coordinate regional economic development in the middle 1990s, the eastern coastal regions still dominated. Contribution rate of eastern coastal regions to the national industrial added value was 52% in 2015, while the rate of central and western regions was 21% and 19%, respectively (NBSPRC 2018a).

The rapid industrial development has brought with it an increase in pollutants discharge. According to the *China Environmental Statistics Annual Report 2015*, industrial solid waste from the top four industries, i.e. manufacture of raw chemical materials and chemical products, manufacture of paper and paper products, manufacture of textile, and mining and washing of coal, reached 3.11 billion tons, which accounted for 95.1% of the total. Industrial discharge quantities for wastewater, waste gas, and solid waste from different regions in China were collected from 1986 to 2015 (Figure 2). Industrial waste gas emission and solid waste production showed a close to exponential increase up to 2011, before reaching a plateau. The Central Yellow River and North Coast regions produced the most industrial waste gas and solid waste. Among all the provinces, Hebei and Jiangsu produced the most industrial waste gas and meanwhile Hebei and Liaoning produced the most solid waste, both were in the coastal regions associated with rapid industrial development. Industrial wastewater discharge has followed a different pattern to gas and solid waste. The peak values for industrial wastewater discharge appeared in 1991 and 1994. The Central Yangtze River, East Coast, and North Coast regions showed a larger amount of industrial wastewater discharge, with Jiangsu as the largest discharge province, which was also located in the higher industrial development region.

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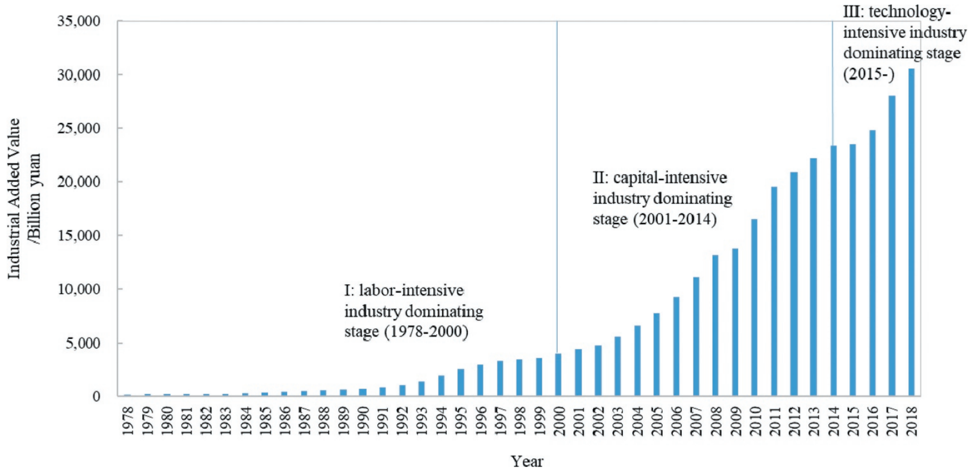

Figure 1. Industrial-added value from 1978 to 2018 in China.

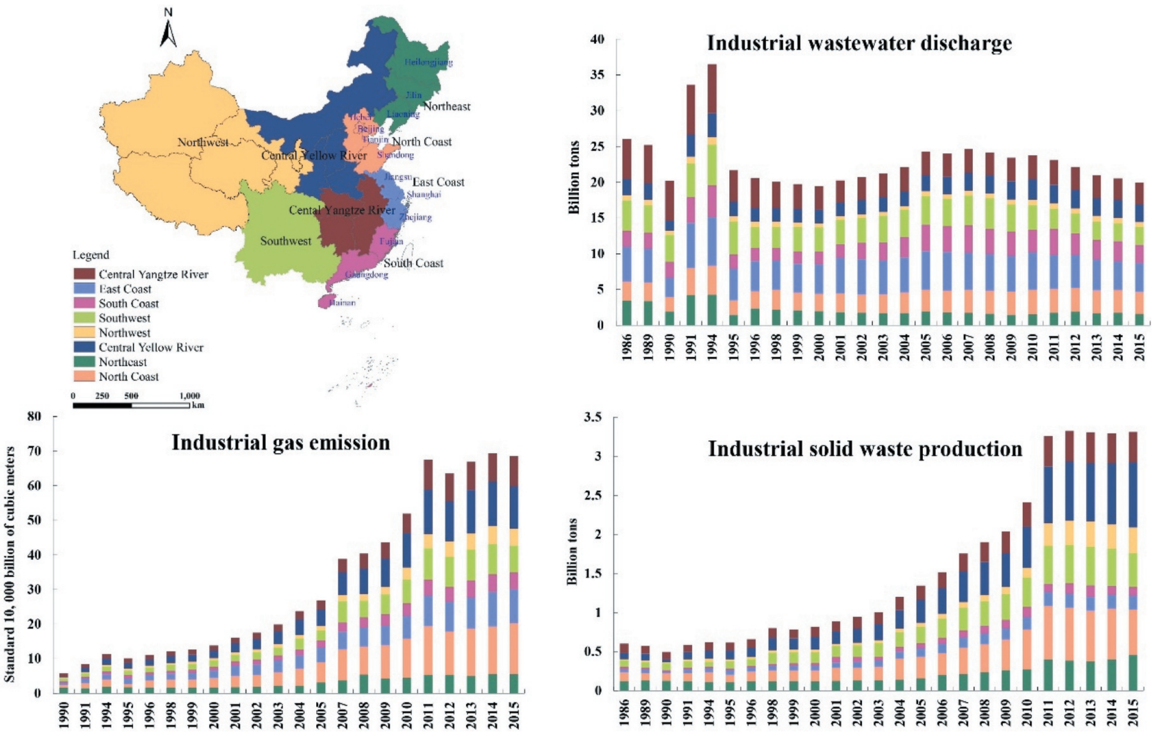

Figure 2. Industrial discharge from different regions in China from 1986 to 2015.

All these three waste emissions (gaseous, wastewater, and solids) can be integrated into a single value called pollution index. In this case, the pollution index was calculated based on the discharge data of waste gas, wastewater, and solid waste from 1995 to 2015 using the Coupling Degree method. From the distribution of pollution index associated with industrial development in different provinces and regions from 1995 to 2015, we can see that coastal regions with higher industrial-added value were accompanied with a higher pollution index (Figure 3). A notable change in the temporal trend occurred after 2013, due to the implementation of national "Ecological Civilization" strategy proposed in 2012, and the strictest ever revised Environmental Protection Law (He et al. 2013; Lu et al. 2019).

Data sources: China Statistical Yearbook (1996, 2001, 2006, 2011, and 2016). Some data of wastewater, waste gas, and solid waste were not available in Beijing, Hebei, Liaoning, Chongqing, Guizhou, and Tibet in 1995, pollution index values in these regions were non-applicable. Gray indicates no data.

Environmental pollution generated by industrial development has inevitably had an impact on soil and aquatic ecosystems. According to the first National Soil Pollution Survey Bulletin published in 2014, 16.1% investigated sites have exceeded the soil background value in China (MEEPRC and MNRPRC 2014). Groundwater quality of more than 60% monitoring sites has been classified as poor or extremely poor category for many years (MEEPRC 2017). Some of the key industrial pollutants, such as $PM_{2.5}$ and SO_2, greenhouse gas, heavy metals, persistent

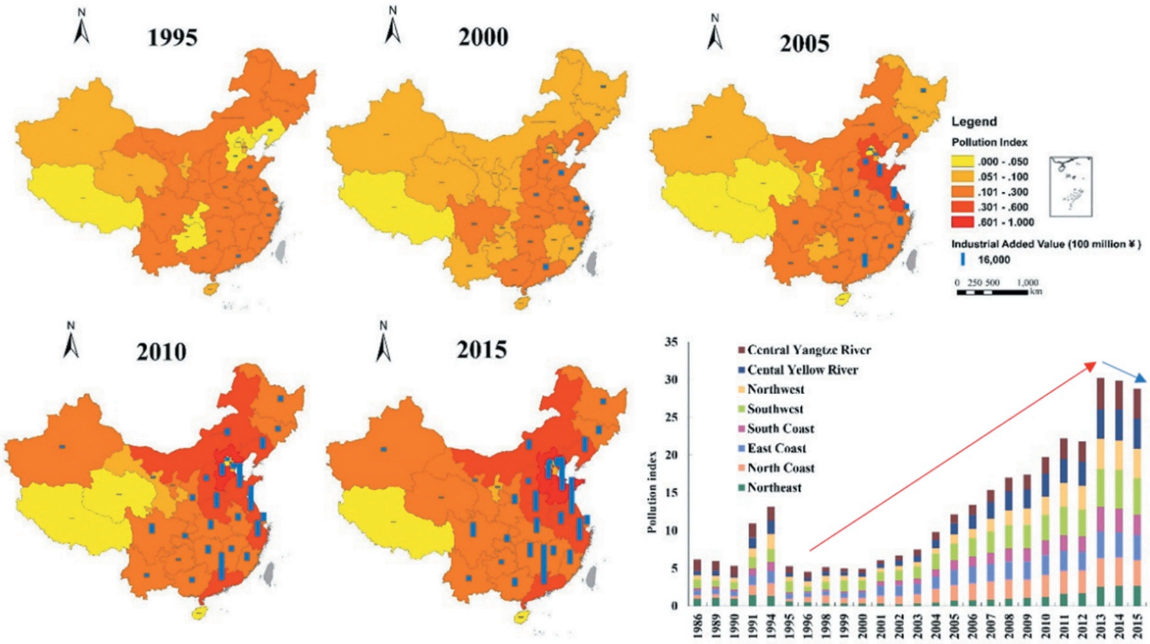

Figure 3. Variation of pollution index and industrial-added value in China from1995 to 2015.

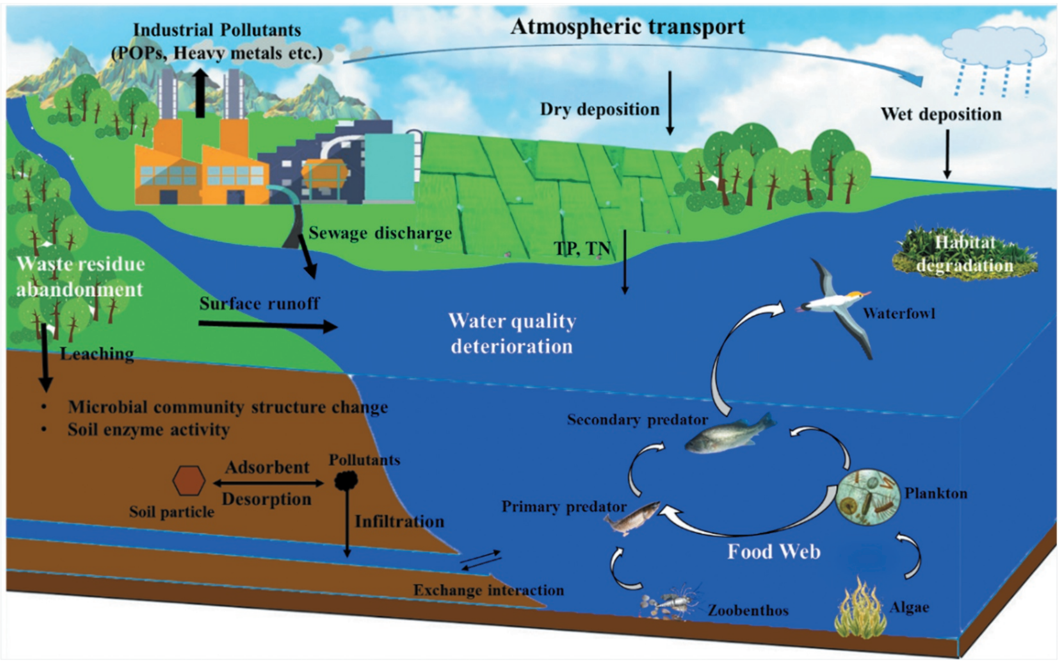

Figure 4. Schematic of industrial pollution on the aquatic and soil ecosystems.

organic pollutants (POPs), and emerging pollutants, have raised more and more public concerns (Ji et al. 2011; Li et al. 2016; Liu and Bae 2018; Wang et al. 2012b, 2016).

Impacts of industrial effluents on aquatic ecosystems

Research about impacts of industrial effluents on the aquatic ecosystems started in the 1970s in China, with focuses on detection methods (Wang 1994; Xu et al. 2008), distribution (Su, Liu, and Li 2006; Sun et al. 2018b; Wo et al. 2007), risk of ecological effects (Shao et al. 2010), and water pollution control (Chen et al. 2007; Kong 2009; Molinari et al. 2001; Zhang, Chen, and Wen 2012). Records in China's Environmental Status Bulletin (1989–2018) for chemical pollutants from industrial wastewater have focused on total nitrogen (TN), total phosphorus (TP), petroleum, oxygen-consuming organic matter, and heavy metals. There are also studies focused on emerging pollutants (ECs) (de Alda et al. 2003; Jiao et al. 2013; Meng et al. 2015). Chemical pollutants from industrial sewage discharge can lead to the deterioration of water quality and degradation of habitats (Figure 4). Damage to the

Table 2. Effects of different pollutants on the elements of aquatic ecosystem.

	Targets and Effects			
Pollutants	Species	Population	Community	Ecosystem
Organic pollutants	Polycyclic Aromatic Hydrocarbons (PAHs), harmful to central nervous system, liver, brain and muscle of Zebrafish (1) Organochlorine pesticides (OCPs), carcinogenic, mutagenic and teratogenic to aquatic organisms (2)	Decline of individual quality, population quantity and density (3)	Affect microbial community structure and the predation or competition relationship among aquatic organisms (4), (5)	Life cycle change of organisms, effects on the structure and function of ecosystem, safety threat to the aquatic ecosystem (6)
TN,TP	Low concentration is beneficial to algae growth; high concentration can inhibit algae growth (7)	Number of planktonic algae increases, species with poor tolerance decrease or even disappear (8)	Replacement of dominant species of phytoplankton; reduction of benthic species and biomass (9)	Stimulate or enhance the development, maintenance and proliferation of primary producers; decline of species diversity, loss of self-purification ability and ecological function of ecosystem (10)
Heavy metals	Hg, inhibit respiratory movement of fish (11) Cd, damage to the metabolic capacity of wild yellow perch (12) Pb, affect the normal physiological and reproductive function of organisms (13)	Reduce the number and density of biological population, affect its distribution and sex ratio, extinction of some species (14)	Affect the composition and structure, total abundance reduction, replacement of dominant species in the aquatic community (15)	Transport and enrichment along the food chain, inhibit functions of producers, consumers and decomposers, affect stability of the entire ecosystem (16)
ECs	Perfluorinated compounds (PFCs), toxicity to the nervous, metabolic and reproductive system of fish (17) Pharmaceutical and personal care products (PPCPs), inhibit photosynthesis and normal growth of algae; Cause different degrees of damage to tissues and organs of fish (18)	Affecting the distribution and density of aquatic plants, and the number, birth rate, mortality and sex ratio of aquatic animals (19)	Affecting the structure and distribution of sensitive aquatic communities (20)	Enrichment and amplification effects along the food chain, and potential threats to aquatic ecosystems (21), (22)

References: (1) (Kazeto, Place, and Trant 2004) (2) (Fleming, Clark, and Henny 1983) (3) (Menzie, Potocki, and Santodonato 1992) (4) (Menasveta and Cheevaparanapiwat 1981) (5) (Langworthy et al. 1998) (6) (Wu et al. 2014) (7) (Downing and McCauley 1992) (8) (Li et al. 2014) (9) (Li et al. 2014) (10) (Camargo and Alonso 2006) (11) (Ahmad et al. 2010) (12) (Couture and Rajotte 2003) (13) (Ahmad et al. 2010) (14) (Mance 1987) (15) (Clements et al. 2000) (16) (Klerks and Levinton 1989) (17) (Suja, Pramanik, and Zain 2009) (18) (Harada et al. 2008) (19) (Di Poi et al. 2018) (20) (Allyson Q and Abessa 2019) (21) (Rosal et al. 2010) (22) (Peng et al. 2018b)

freshwater aquatic environment can be observed from species, population, and community to the ecosystem level (Table 2).

Pollutants such as organic pollutants, heavy metals, and ECs are toxic and can affect physiological and biochemical processes and gene expression of the aquatic species (Ahmad et al. 2010; Deblonde, Cossu-Leguille, and Hartemann 2011; Kar et al. 2008; Liu et al. 2012; Rai 2008). Physiological function of liver, kidney, and reproductive system of the aquatic animals can be affected through direct contact. Physicochemical property change of the aquatic environment can affect the activity and diversity of aquatic plants, zooplankton, and bacteria (Barbosa et al. 2016; Gogoi et al. 2018; Sousa et al. 2018). It has been reported that about 10,000 ng/L of PAHs will reach the half lethal dose for aquatic organisms, and long-term exposure of low concentration PAHs can induce the sub-acute, chronic, and even molecular genotoxicity of organisms (Barron et al. 1999). There has been a decline for zooplankton, benthic species, and fish due to organic pollutants in Taihu Lake since 1980 (Chen et al. 2016b). Excessive nutrients such as TP and TN can bring overgrowth of algae and aquatic organisms, which will result in the death of fish and other organisms due to hypoxia (Camargo and Alonso 2006; Skei et al. 2000). The coverage of aquatic plants will be almost zero when the concentration of TN and TP reached 0.1 mg/L and 2 mg/L, respectively (Wang et al. 2017b). Excessive inputs of nitrogen and phosphorus have caused serious eutrophication in Chaohu Lake, Taihu Lake, and Dianchi Lake in China (Le et al. 2010; Liu and Qiu 2007; Shang and Shang 2007).

Industrial pollutants can result in a reduction of certain aquatic species and an imbalance in sex ratio at the population level (Liu et al. 2018). Studies have shown that very low dose (1 ng·L^{-1}) of synthetic estrogen in water will interfere with the endocrine function and lead to the feminization of fish (Sun et al. 2010). Industrial pollutants can promote the population differentiation and generation of meta-population. Previous studies have indicated that offspring of long-term interference

Table 3. Soil pollution status in different industrial block types.

Block type	Ratio of over standard sites	Major pollutants	Industry type
Heavily polluting industrial land	36.3%	Heavy metals and PAHs	paper, petroleum, coal, chemical, metal products, electric power, etc.
Abandoned industrial land	34.9%	Zn, Hg, Pb, Cr, As and PAHs	chemical, mining, metallurgy, etc.
Industrial park	29.4%	Cd, Pb, Cu, As, Zn and PAHs	metal smelting, chemical industry
Solid waste disposal land	21.3%	Inorganic and organic pollutants	Refuse disposal station
Oil recovery land	23.6%	PHCs and PAHs	Oil recovery industry
Mining land	33.4%	Cd, Pb, As and PAHs	Mining industry
Sewage irrigation land	26.4%	Cd, As and PAHs	

Data source: National Soil Pollution Survey Bulletin (MEEPRC & MNRPRC, 2014)

by cadmium will evolve into populations of resistance to cadmium (Shirley and Sibly 2001). Investigations of benthic community in Beijiang River in the 1980s and 2017 showed that there was a decline of species richness due to water quality deterioration but an increase in the proportion of pollution-tolerant species (Cao et al. 2017; Su and Li 1985). Pollution-tolerant species can replace sensitive or widespread species and become the dominant organisms, which will simplify the community structure (Hong and Chen 2002; Karaouzas et al. 2018).

Due to impacts on the species, population, and community in the aquatic ecosystem, industrial pollution also causes the relationship change among producers, consumers, and decomposers, which will consequently affect the composition, structure, and function of the ecosystem and cause an alteration of the ecosystem productivity (Connell 1991). Because of the high concentration of nitrogen due to the discharge of industrial and domestic sewage, net primary productivity of the Pearl River Delta was only one-fifth of the Haihe River in 2017 (Zou et al. 2017). The destruction of ecosystem structure and the decline of primary productivity will result in a loss of ecosystem service function. Because of water pollution in Dianchi Lake, the value of climate regulation and pollution purification decreased by 87% and 32%, respectively, from 2010 to 2013 (Hu 2015). Both metals and ECs showed the accumulation and amplification potentials along the food chain (Gan 2010; Islam et al. 2015; Peng et al. 2018b; Zhang et al. 2018). A study on the sediment of Dongjiang Port in Tianjin showed that the enrichment factor of arsenic was the highest, with a maximum value of 1.59 (Guo et al. 2010).

Impacts of industrial pollution on soil ecosystem

According to the National Soil Pollution Survey Bulletin, which was based on the first national soil pollution survey conducted from 2005 to 2013 in China, the soil environment has been seriously polluted during the past 40 years. Soil pollution was most serious in the Yangtze River Delta, Pearl River Delta, and the old industrial base in Northeast China, where exhibit a relatively higher industrial-added value (MEEPRC and MNRPRC 2014) (Figure 3). Industrial activities can produce a large number of toxic and harmful substances, such as soot, sulfur dioxide, heavy metals, and POPs (Shi et al. 2005; Chen et al. 2015; Cheng 2003; Wang et al. 2012c). Sites with heavy metal pollution above the regulatory standard are mainly located in the southwest and central south China due to concentrated industrial activities in these regions (Yang et al. 2018). Concentrations of Cd in the industrial areas were 100 times higher than the rural areas without industries (Cheng 2003). In urban industrial areas, 36.40% of soil heavy metal pollution was caused by industrial emissions (Li and Feng 2010). Table 3 shows the soil pollution status in different industrial block types (MEEPRC and MNRPRC 2014). Industrial pollutants can be discharged into the soil through exhaust gas deposition, wastewater discharge, and waste residue dumping (Guan et al. 2018; Jia, Li, and Wang 2018). Soil ecosystem health was threatened in the form of physicochemical property change, biodiversity loss, microbial community structure change, soil enzyme activity, and soil structure change (Lu et al. 2015b; Wang et al. 2017a; Zhu et al. 2019b) (Figure 4).

Industrial pollutants like metals and POPs can affect soil ecosystem health by damage to the soil physicochemical property, which is a key factor for the maintenance of soil ecosystem stability. Industrial pollutants may alter the content of soil organic matter which will affect the plant productivity. The higher the organic carbon content in polluted soils, the lower the efficiency of microbial populations in mineralization of organic matters (Kozdr and Elsas 2001). Normally, microbial biomass carbon and nitrogen in industrial-polluted sites were only 31.6% and 64.4% of the background value (Hu et al. 2014). On the other hand, metals may inhibit the soil respiration and enzyme activity. For example, metabolism activity will cease once the concentration of Cr reaches 100 mg/kg in the soil. Catalase activity will decrease by 25% when the concentration of As reaches 5 mg/kg. Wastewater was used for irrigation due to surface water scarcity in some regions of China, which will destroy the soil environment and bring agricultural land and food pollution (Lu et al. 2015a).

Soil biodiversity is important for the maintenance of soil ecosystem functioning. Industrial pollution may lead to the selective change of species abundance in soil. A lot of research has shown that industrial pollutants can induce the change of soil communities and related biota, such as plants (Zvereva and Kozlov 2011), soil microbes (Li et al. 2017b; Liu et al. 2009; Luo et al. 2018; Zheng et al. 2015) and soil invertebrates (Chen et al. 2009a; Edwards and Pimentel 2008). Industrial pollutants can kill soil organisms through direct acute toxicity. There are also indirect effects on the soil organisms due to the soil physicochemical property change or contamination of food supply (Edwards 2002; Morgado, Loureiro, and González-Alcaraz 2018).

Among all of the soil biota, microbes play a significant role in nutrients utilization and decomposition of organic matter, minerals, or pollutants. They are more sensitive to environmental stresses than macroorganisms in the soil ecosystem and will be more likely to be affected by industrial pollutants (Chu 2018). Such industrial activities as mining can affect the soil microbial community structure (Beattie et al. 2018). Based on the analysis of soil microbial phospholipid fatty acids (PLFA), abundance of the community composition and activities of fungal and bacteria fell 5–35% and 8–32%, respectively, under the influence of heavy metals, which consequently had an adverse impact on the soil microbial carbon immobilization (Xu et al. 2019).

Considering their activities such as burrowing, soil macroinvertebrates are helpful for the maintenance of ecosystem structure and habitats (Morgado, Loureiro, and González-Alcaraz 2018). Industrial pollutants, such as metals and PAHs, can affect soil invertebrate communities and then have a strong effect on soil structure. A number of studies have shown that the total biomass and species diversity of nematodes decreased significantly with an increasing concentration of heavy metals. However, the number of nematodes increased first and then decreased with an increasing concentration of PAHs (Chen et al. 2009a). Exposure of earthworms to Hexabromocyclododecane (HBCD) showed that HBCD can induce high levels of anaerobic respiration and osmotic pressure change, which indicated a damage to the membrane structure (Shi et al. 2018).

Ecological monitoring and assessment of pollution in watersheds

A wide range of environmental quality degradation caused by industrial pollution has facilitated the forming of environmental monitoring system in China since the 1970s. A comprehensive management of watershed pollution was triggered by the industrial pollution event in Guanting Reservoir in 1972 (Liu and Sun 2009; Xu 2015). The first environmental regulation in China was then published in 1973 to control the industrial emission, and environmental monitoring stations were firstly established in 20 major cities. Several environmental monitoring and ecological observation networks were then gradually established in the Yangtze River and Three Gorges, Huaihe River Basin, and Taihu Lake Basin, which had covered the major watersheds in China (Huang 2004; Jahiel 1998). Monitoring indices required for water quality and industrial discharges at the early stage mainly included physical-chemical characteristics of contaminants and highly toxic pollutants, such as temperature, pH, dissolved oxygen, chemical oxygen demand (COD), sulfide, fluoride, lead and mercury. The content and amount of environmental monitoring indices were then largely extended during the 1980s.

Uncontrolled discharge from industrial sources was suggested to be the major reason for watershed pollution and was the focus of monitoring activities from 1980 to 2005. A series of environmental standards and regulations were implemented at that time, which facilitated the development of environmental monitoring in China. Because of the water pollution event in Songhua River in 2005, which had a tremendous social impact with millions of residents being affected, the State Environmental Protection Administration (SEPA) of China urged the local environmental protection agencies to improve the monitoring systems for environmental emergency response. Comprehensive monitoring and assessment of environmental quality have been the core of monitoring activities since then. During that period, baseline data on surface/groundwater, soil, sediment, aquatic community, and pollutants distribution were collected, monitoring technologies for traditional and emerging pollutants were developed and applied, and several integrated monitoring index systems were established and assessed (Chen et al. 2004, 2009b; Sha et al. 2007; Wang et al. 2015). Besides that, studies on watershed environmental problems and comprehensive control schemes were carried out in several major aquatic systems, such as Taihu Lake, Yellow River, and Haihe River (He et al. 2003; Li et al. 2013; Liu and Xia 2004; Long et al. 2018; Shen et al. 2001; Wang et al. 2007; Zhang and Zhang 2006).

Since ecological civilization was officially taken as a national strategy in 2012, environmental monitoring has been required to provide a solid science-based support for the ecosystem conservation (Deng et al. 2016). The monitoring and assessment of watershed pollution have transformed from dose–response analysis based on single sensitive/resistant species to the evaluation of ecosystem structure and function change (Jones et al. 2010; Pinel-Alloul et al. 1996; Siddig et al. 2016). Increasing attention has been paid to the development of methods for monitoring ecosystem physiochemical or biological elements. Fish, invertebrate, and microorganism are used as ecosystem health indicators (Conti and Cecchetti 2001; Czerniawska-Kusza 2005; Lu et al. 2015b; Peng et al. 2018a; Shi et al. 2016; Zhou et al. 2008). Biological indices, such as

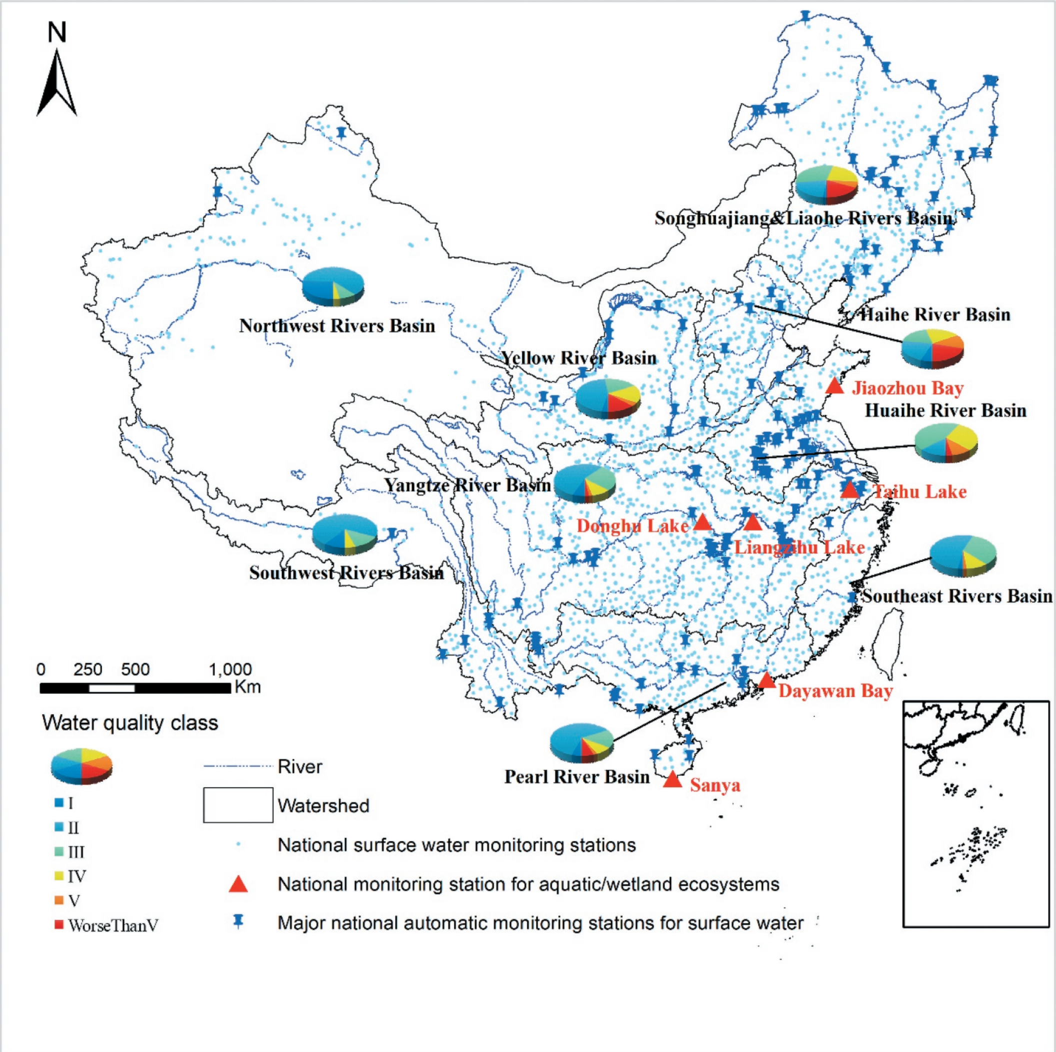

Figure 5. Distribution of watershed monitoring stations and water quality conditions of the major watersheds (MEEPRC 2018).

Table 4. Major industries and pollutants in different types of industrial-contaminated sites in China.

Contaminated site type	Industry type	Major pollutants
Heavy metal contaminated site	Steel, iron and smelting Mining Chemical solid waste piling	Arsenic Lead Cadmium Mercury Chrome
POPs contaminated site	Chemical Pesticides production Capacitor dismantling and burial	DDT HCB Chlordane Mirex Polychlorinated biphenyls Dioxin Polybrominated diphenyl ether
Organic pollution contaminated site	Petrochemical Coking	Benzene Hydrocarbons Heavy metals
Electronic waste contaminated site	Electronic waste disposal	Heavy metals Bromination flame retardants Dioxin

biotic integrity and biological diversity, have been proposed to reflect the ecological conditions (Siqueira et al. 2012; Yoccoz, Nichols, and Boulinier 2001; Zhu et al. 2019a). Besides that, with the development of remote sensing technology, geospatial analysis has been applied to assess the water quality, land use/land cover change, landscape characteristics of watershed, and identification of potential pollution sources (Singh, Kumar, and Kanga 2017; Wang, Hong, and Du 2008; Yan et al. 2015).

After more than 40 years of efforts, environmental monitoring technology has been developed from physiochemical methods to integrated methods using biological, ecological, and remote sensing technologies in China.

Although technical methods and investment in monitoring systems have improved, great challenges still remain in ecological monitoring systems for watershed pollution. Firstly, monitoring efficiency needs to be improved to meet the more stringent requirements for watershed management. A total of 2050 national surface water quality automatic monitoring stations have been established until now, which has covered ten major watersheds in China (MEEPRC 2018). Although large investment has been made in automatic monitoring equipment (Shao et al. 2018; Xia et al. 2011), there is still a long way to achieve a full coverage of online real-time monitoring. Major automatic monitoring stations were mainly established in the eastern-urbanized regions, which covered the most seriously contaminated basins. However, further construction of monitoring systems is also needed in the regions with rapid industrial development, such as the Southwest and Central Yellow River regions (Figure 3). Secondly, pollutant emission control is still the core of the current watershed environmental management in China, while developed countries have focused more on watershed ecological conditions in recent years (Beyer 2006; He et al. 2012). The Chinese Ecological Research Network (CERN), with a similar mission and structure as the U.S. Long-Term Ecological Research network (LTER) was established in 1988 to systematically monitor the biophysical environment changes. However, there are only three stations for freshwater ecosystem monitoring in CERN (i.e., East Lake, Liangzihu Lake, and Taihu Lake; Figure 5), which is not enough for the watershed ecological reservation (Chang et al. 2009). Besides, CERN is independent of the national environmental monitoring system. More cooperation and integration are needed for the monitoring of industrial emission, water, soil, atmosphere, and ecosystem. Thirdly, the current environmental monitoring indicators mainly include basic physical-chemical parameters and traditional pollutants, such as pH, oxygen-consuming organic pollutants, nutrients, and heavy metals, which cannot meet the requirements for watershed ecosystem restoration. The environment is affected by many other pollutants, especially emerging pollutants without any explicit environmental criteria at the moment. Environmental thresholds for the pollutants were set without considering their long-term and potential effects on the ecosystems, and relevant indicators for the assessment of ecosystem health are still lacking. Additionally, regulatory and supervision mechanisms for environmental monitoring and public participation need to be improved. The Ministry of Ecology and Environment of China (MEEPRC) is trying to achieve a unified supervision through the construction of a national automatic monitoring network, which separates the supervision from local environmental monitoring departments to a certain extent. Therefore, cooperation and participation of all the stakeholders, from data monitoring to final decision-making, is necessary. The establishment of eco-environmental criteria and regulations should consider not only the scientific research but also the social-economic factors.

Ecological remediation of contaminated sites

Contaminated sites (also referred to brownfield) are sites with pollution hazards beyond acceptable risk levels for human or ecosystem health (Lu et al. 2015b; MEEPRC 2014). According to conservative estimates, over 200,000 contaminated sites were formed in China during the rapid urbanization and industrialization, and 320 of them were identified as seriously polluted with a coverage of more than 5 million hectares (Li et al. 2017a). However, due to lack of relevant laws and regulations, some contaminated sites were directly redeveloped and utilized without effective risk assessment and remediation (Li et al. 2018). The poisoning event in Beijing Songjiazhuang Subway Station in 2004 alerted the government and the public to take the remediation of contaminated sites seriously (Huang, Zhang, and Deng 2012a; Wang et al. 2011).

There are mainly four types of contaminated sites in China, including heavy metal-contaminated sites, persistent organic pollutant (POPs) contaminated sites, organic pollution sites (such as petroleum, chemical engineering, and coking), and electronic waste contaminated sites (Jian and Li 2011). The related pollutants of the four different types of contaminated sites are listed in Table 4, which can be found in almost all of the environmental media, even the deep soil, and groundwater within a contaminated site. In the Songjiazhuang poisoning incident, three workers collapsed underground about five meters due to the high concentration of mixed volatile toxic substance residues from a former pesticide plant located in the 1970s.

In addition to direct pollution, industrial activities like mining can cause indirect geological problems, including land subsidence, hills of gangue and fly ash, ground cracks, landslide, mud-rock flow, and decline of groundwater tables (Chang et al. 2009). The cumulative land occupied or destroyed by mining was 28,100 km^2 in 2012 in China (Hajabbasi, Jalalian, and Karimzadeh 1997; Zheng et al. 2015; Zolfaghari et al. 2016). These geological problems exacerbate the pollution situation by bringing serious deterioration of the original ecosystem, which can cause a reduction of ecosystem services such as biomass production, biodiversity maintenance, carbon storage, and soil and water conservation (Fan et al. 2003).

Bioremediation technology is the most commonly used method for the ecological restoration of industrially contaminated sites (Adams, Raman, and Hodgkins 2013; Song et al. 2019). Bioremediation agents mainly include

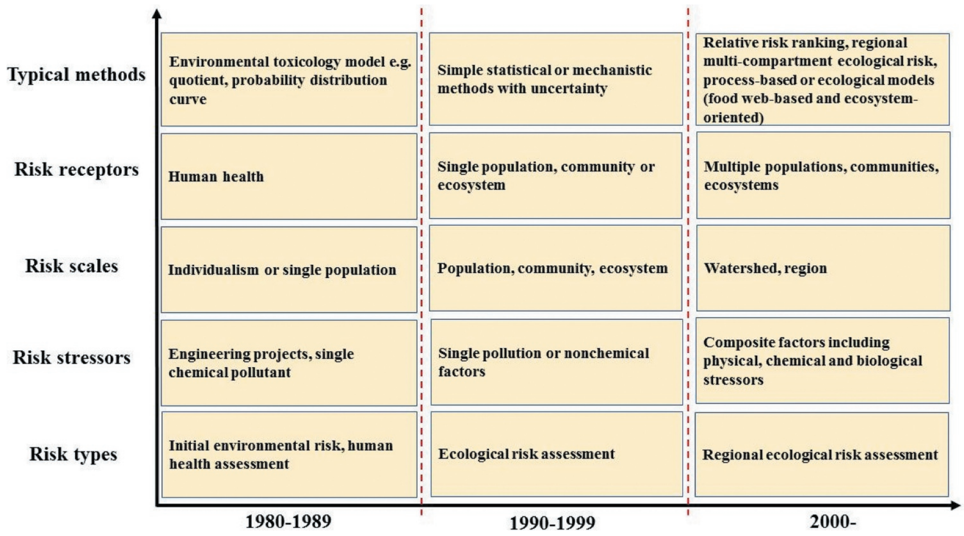

Figure 6. Framework for the development of ecological risk assessment.

plants, microorganisms (bacteria, fungi, and algae), enzymes, and protozoa (Quintella, Mata, and Lima 2019). Phytoremediation is the most effective bioremediation technology for heavy metal pollution (Wang et al. 2019), which includes phytostabilization, phytostimulation, phytotransformation, phytofiltration, and phytoextraction (Ashraf et al. 2019). Because microorganisms can convert organic pollutants into inorganic matters, nutrients, and cell biomass, they are widely used for organic pollution treatment (Yang et al. 2014). Some hyperaccumulators were discovered for the removal of arsenic and heavy metals (Chen et al. 2002; Wei, Zhou, and Wang 2005; Xue et al. 2003; Yang, Long, and Ni 2002), and lots of high effective strains have been screened out for organic pollutants like PCB and PAHs in China (Jiang et al. 2015; Liu et al. 2017; Shuai et al. 2016). Molecular biological technology is becoming an important tool to clarify the bioremediation mechanism in recent years. Although the advances in phytoremediation and microremediation, bioremediation technology is still in the test and demonstration stage, especially the in-situ methods (Daniel, Jegathambal, and Bevers 2019; Jugnia et al. 2018; Saiyari et al. 2018).

Landscape design has been increasingly applied for regions with topographical change caused by mining activities to reduce the ecosystem service loss since 1990s (Fu et al. 2016; Zhu 2017). There are many typical cases of landscape design for mining wasteland in China. Plants with vigorous roots were chosen to enhance the soil slope stability for the reclamation of Haikou phosphate deposit in Kunming (Yang et al. 2014). For mining areas with land subsidence, ecological reconstruction based on the changed topographical condition was more preferable. Pan'anhu and Jiulihu Wetland Parks in Xuzhou were successful cases for restoring the ecological functioning of mining subsidence areas (Chang et al. 2009; Zhang et al. 2017a; Zhu, Song, and Li 2009). After the transformation from farmland to wetland with fishing and tourism functions, ecosystem service value in the coal mining area of Huaibei City was almost doubled (Li et al. 2015).

Nowadays, great attention has been paid to contaminated sites in China due to their deteriorating environmental effects. The national key research and development program of China "Pollution and Treatment Technology for Contaminated Land" was launched by the Ministry of Science and Technology in 2018, with a total funding of 608 Million Chinese Yuan. Pollution source identification, monitoring and risk governance, remediation of mining and petroleum contaminated sites, risk control of urban contamination sites and remediation technology for groundwater, were identified as the priority areas within a four-year project duration.

Integrated ecological risk assessment at regional scales

At an early stage equipped with single industrial facilities, environmental problems were simple and mainly involved a few types of pollutants such as COD, NH_4^+, metals, and PAHs, etc. Ecological risk assessment (ERA) mainly focused on environmental effects of a single chemical pollutant, including heavy metals (Han et al. 2018; Li et al. 2009; Niu et al. 2009; Wang et al. 2005; Zheng et al. 2007) and POPs (Chen et al. 2016a; Li et al. 2010; Wang et al. 2003, 2011a), in a single environmental medium, i.e. soil, water, sediment, or organism (Sun et al. 2018a; Tang et al. 2015; Yu et al. 2012; Zhang et al. 2017a). The risk receptor was mainly the human body. Evaluation methods were mainly based on the framework of American ecological risk assessment criteria such as risk quotient (RQ) (USEPA 1998).

With the improvement of industrial facilities and the detection of emerging pollutants such as PFCs, brominated flame retardants (BFRs), and PPCPs in the environment, the focus of environmental problems has shifted from single pollutant to multiple pollutants. These pollutants can transfer in a variety of media through biogeochemical cycling at different scales which cover species, population, community, and ecosystem. Previous methods for ERA cannot meet the need for such a complex environmental context. Therefore, integrated ERA approach based on multi-pollutants, multi-media and multi-receptors at the regional scale has been developed, such as weighted assessment method (Yan et al. 2018; Yu et al. 2013), probabilistic ERA (Shi et al. 2016) and relative risk ranking (Johnson et al. 2018; Su et al. 2017; Zhang et al. 2017b, 2017c). These integrated ERA approaches pay attention not only to the chemical pollutants but also to the interaction with physical and biological stressors (Figure 6). For instance, Shi et al. (2016b) established a method to quantify and distinguish the regional multi-compartment ecological risk based on the current pollutant concentration and toxicity data, and applied in the Bohai and Yellow Seas where many industrial parks located. By using this approach, the ecological risk level of pollutants in different media was accurately measured at the regional scale. However, as different receptors showed different sensitivities to the pollutants, like heavy metals, HBCD, and PAHs, the relative risk-ranking approach was established to determine which commonly monitored chemical pollutant poses the greatest threat to the aquatic or terrestrial ecosystem (Johnson et al. 2018; Su et al. 2017; Zhang et al. 2017b, 2017c).

A variety of ecological models have been applied to evaluate and predict the ecological risks at different levels (Chen, Chen, and Fath 2013; Malekmohammadi and Blouchi 2014; Wang et al. 2011b). Currently, the food web-based model and ecosystem-oriented model have been demonstrated to be efficient in evaluating the structural and functional responses within a variety of ecosystems (Chen, Chen, and Fath 2013). The food web-based model was developed for the modeling of cumulative effects of toxic chemicals and other stressors in the environment, which is useful for the determination of ecological risk significance. Ecosystem-oriented model not only focused on the predator–prey relationship between organisms but also the interaction between organism and environmental factors. It mainly included the probability estimation of change in the biomass of multiple populations as a result of toxic effects from the pollutants, regional vulnerability assessment, and communities and habitats assessment. By applying these models, the changing trajectories of risk are explored, and the temporal and spatial evolution process and the cumulative effect of ecological risk are modeled.

ERA is an essential tool for the environmental risk management. Since the connotation of ERA involves multiple pollutants, multiple receptors, multiple systems, and multiple scales, the corresponding risk management should be integrated at the regional scale. ERA can provide scientific evidence for the construction of a risk management system. For example, when there is an emergent pollution incident without any corresponding quality standards as a reference, treatment of chemical pollutants and damage assessment can be carried out according to the result of ERA. In addition, the coupling relationship between regional ecological risk and industrial development can provide a basis for the identification of risk sources and risk receptors, which can help to form a dynamic feedback process of ecological risk assessment and management for the decision-makers.

Conclusion and perspective

Forty years of reform and opening up for industrial development have brought China both opportunities and challenges. The economy has undergone rapid development, whilst industrial pollution has also posed serious threats to the ecosystems. Industrial-added value in China has increased 188 times since 1978. Spatial-temporal analysis of pollution index from 1995 to 2015 showed that in coastal regions of China high pollution index was also correlated with a highly developed industry. Industrial pollution in China is still a serious issue and there has been a sign of pollutant transfer from eastern to western China. Besides that, as most of the developed industries are located along the coast, pollutants produced from the land-based activities have posed a great pressure on the coastal regions.

The most serious effects from industrial pollution were reflected in aquatic and soil ecosystems. Industrial sewage discharge, which includes pollutants like TN, TP, petroleum, oxygen-consuming organic matter, heavy metals, and emerging pollutants, can affect the aquatic ecosystem at different levels from species, population, and community to the whole ecosystems, and leads to the deterioration of water quality and degradation of habitats. Soil ecosystem was affected by the toxic and harmful substances produced by industrial activities through exhaust gas deposition, wastewater discharge, and waste residue disposal, which can lead to physicochemical property change, biodiversity loss, microbial community structure change, soil enzyme activity, and soil structure change. Due to the negative effects induced by industrial pollution, these impacted aquatic and soil ecosystems also had poor service functioning. This situation has been improving since 2012, when "ecological civilization" was taken as the national strategy, and economic growth showed in a decoupling trend for major pollutants since 2015 (Lu et al. 2019). Besides the goods and services delivered by terrestrial ecosystems, an effective management of pollutants in the marine ecosystem has also attracted greater attention. Contaminated sites were another consequence of industrial development, which raised public concern only after 2004. Bioremediation is the mostly used technology for the removal of pollutants from industrial-contaminated land. With the acceleration of industrialization and urbanization, more and more attention should be paid to ecological remediation, monitoring, and risk governance of contaminated sites.

Previous research about the indusial pollution in China mainly focused on the pollution itself, especially concentration of the pollutants. Nowadays, more studies have focused on the source identification, multimedia transportation, ecological effects, and ecological risks of the pollutants. The basic eco-environmental monitoring systems have been established in China, which involves industrial discharge, soil, water, and atmospheric environment. However, it still needs further improvement in terms of the integration of ecological observation and environmental monitoring networks, full coverage of the real-time monitoring infrastructures, real-time monitoring of pollution and effects on the ecosystems, and real-time gathering and inputs of monitoring data.

The following points should be stressed for the future research on the ecology of industrial pollution. First, it is of great significance to simulate the transport pattern and effects on the ecosystem on a large scale considering multiple pollutants and multiple risks. Second, it is important to transfer from single ecological risk to integration with human health risk. Third, it is important to transfer from source emission control to the energy and material flux regulation and to implement the risk prevention and control over pollutants from traditional ecology to industrial metabolism ecology.

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