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Global river economic belts can become more sustainable by considering economic and ecological processes

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Abstract

High-quality regional development requires coupling of socioeconomic and natural domains, but it remains unclear how to integrate effectively regional economies with river basin ecosystems. Here we establish a developmental perspective of 65 river economic belts, formed through history along the main stems of the world's great rivers, covering initial, developing, and developed stages. We find that river economic belts characterized by basin-based regional integration can substantially upgrade their eco-efficiency through the harmonization of enhanced regional economic growth and efficient utilization of basin resources, once key prerequisites (e.g., gross domestic product per capita, de-industrialization status) are met for river economic belts entering the developed stage. Importantly, primary concerns such as resource stress, environmental pollution, and biodiversity loss are also inherently addressed. Under representative scenarios of regional development planning and climate change (2015–2050), the basin-based regional integration strategy would provide river economic belts with new opportunities and pathways towards sustainability in emerging regions worldwide.

Keywords: river economic belt, basin-based regional integration, eco-efficiency, industrial upgrading, sustainable development

Maintext

Introduction

Throughout history, human civilizations have flourished along the world's great rivers[1,2]. Taking advantage of abundant water resource, ideal waterways, and environmental and ecological capacity, most large rivers have become the main veins of river economic belts (REBs) emerging from a background of regional integration[2,3]. By connecting material fluxes, cultures, and trades[4–6], REBs act as important conveyors supporting intra-regional and international collaborations[3,7]. Moreover, REBs provide a natural setting for exploring pathways to accelerate economic growth while reducing ecological footprints.

Over millenia, REBs have witnessed the evolution of human civilization, in which dynamic and complex human-nature relations are embedded[8]. In ancient times, our predecessors created settlements, conducted riverine agricultural activities, and developed the first river civilizations, most notably along the Yellow, Indus, Nile, Tigris, and Euphrates rivers[1]. During the initial stage of agricultural civilization, human beings exert very limited impact on river ecosystems. In the developing industrial stage, REBs undergo substantial development as technology advances. Settlements established along REBs grow into towns and cities, accompanied by accelerating urbanization and industrialization[9]. As bonds of economic development, REBs occupy a crucial position in the global supply chain, addressing transport need[5,10]. So far, approximately 50% of the world's large rivers serve as 'Golden Inland Waterways' with great carrying capacity and growth in transportation demand[5]. During this stage, excessive resource consumption and waste emission can be perilous through resource and energy depletion[11], environmental pollution[12,13], greenhouse gas emission[14], and ecosystem degradation[15,16]. In recent decades, modernization has been attained by several large REBs in developed regions such as Europe and North America, which exhibit the core spirit of sustainability by achieving nature-human harmonization alongside increasing resource productivity over their full life-cycles[17,18]. On the path from industrial to modernized stages, REBs face great challenges in the transition[19] because it involves a synthesis of economic, educational, political, and other societal reforms. To date, many indicators have been proposed to quantify the degree of regional development in terms of economic achievement[20], social foundation and human well-being[21], natural capital[22], and their combination[17,18]. Among them, eco-efficiency (E^2E) has been regarded as a key indicator to measure resource productivity that integrates economic and ecological considerations at different scales[23]. Given their heterogenity during the developmental stage[2,21], global REBs then have diverse choices of novel strategies (e.g. industrial structure adjustment, renewable energy investment, and transboundary cooperation)[3,24,25] to support the transition towards sustainability. Due to decoupling of regional economy and basin-based ecosystems, the virtuous cycle of social economic development could hardly be realized through reasonable allocation of shared natural resources in river basins, which in turn obstruct the sustainable development of global REBs.

To trace universal underlying principles that could support the sustainability of global REBs, we establish a conceptual framework for identifying development stages of 65 REBs in the world's great rivers (each with catchment area greater than 100,000 km^2). We find that the co-occurrence of economic and resource gradients in river basins provides a solid foundation for basin-based regional integration along the main veins of large rivers. Once the transition from developing to developed stage is essentially completed in the REBs, the E^2E would be greatly enhanced, and primary concerns on water resource stress, energy consumption, environmental pollution, biodiversity loss, and greenhouse gas emission would be spontaneously addressed. This provides new opportunities and alternative pathways to sustainable development in emerging regions worldwide.

Results and Discussion

Conceptual framework for global REBs at varying development stage

Figure 1 proposes a conceptual framework for describing the characteristics of REBs at different development stages, whose evolution (Fig. 1a) is closely related to industrialization process and human development. According to Chenery et al.'s theory[26], REBs could be regarded as passing through six industrialization phases in terms of gross domestic product (GDP) per capita and industrial structure, i.e., pre-industrialization, early industrialization, middle industrialization, late industrialization, post-industrialization, and modernized phases. This is further simplified into three stages of initial, developing, and developed, based on a human development index (HDI) with embedded human-nature relations.

Driven by regional development, REBs prosper by virtue of their abundant natural resources. Due to unbalanced development, the 65 REBs (each with catchment area exceeding 100,000 km^2) now correspond to different development stages (Fig. 1b). These REBs are representative because in total they occupy 45% of the world's land area, 63% runoff to ocean, 53% bio-capacity (BC, as defined in Methods), 42% population, and > 90% navigational capacity (Supplementary Fig. 1). Noting that REBs exhibit spatial diversity in socio-economic context, cultural environment, and ecological status, we describe the characteristics of REBs at different stages by the following key indices (Supplementary Figs. 2–4): GDP per capita, life satisfaction index (LSI, range 0–10, with 0 for least satisfied, and 10 for most satisfied), cultural realm, and ecological deficit index (EDI, measuring the balance between natural resources consumed and available throughout the REBs, where EDI > 1 for ecological deficit; more details see Methods).

REBs at the initial stage are all located in Africa, and present low labor productivity with very small GDP per capita (1063–7802 US$). In such cases, human poverty and low wellbeing reduce life satisfaction (LSI =3.8–4.2). Cultural traits of these REBs primarily coincide with the cultural realm of Sub-Saharan Africa. Characterized by agricultural and handicraft industries, such REBs place lower demand on natural resources and thus display negligible ecological deficit (median EDI =1.0), suggesting a much greater bio-capacity than is needed to accommodate the ecological footprint.

30 REBs at the developing stage are mainly dispersed across Asia, South America, and Eastern Europe, exhibiting vast cultural diversity. Specifically, REBs in Asia correspond to East Asia, Southeast Asia, and Indic cultural realms; REBs in South America correspond to the Latin American cultural realm; REBs in Eastern Europe correspond to the Continental European cultural realm. In the developing stage, REBs experience substantial increase in labor productivity; notably, median GDP per capital (2015) rises to 27,835 US$ in Asia, 12,191 US$ in South America, and 20,165 US$ in Eastern Europe. Rapid technological advances cause industrial contributions to national income and employment to increase substantially. Meanwhile, human well-being (LSI =4.3–7) greatly improves alongside progress in education, public health, living standards, and the labor market. Increasing human demand on natural capital for rapid

socioeconomic development leads to substantial expansion of the ecological footprint from the early to the late industrial phase for all REBs. At the developing stage, ecological deficit occurs in 63% of the 30 REBs, less so in most of South America (median EDI= 0.4), but more so in Eastern Europe (median EDI =3.1) and Asia (median EDI =1.8), due to different natural endowments and developmental modes.

REBs at the developed stage (related to modernized and post-industrial periods) mainly occur in Western Europe, North America, and Oceania, corresponding to Western European, Anglo-American, and Australian cultural realms. REBs exhibit continuous improvements in economic wealth (median GDP per capita = 44,463 US$), quality of life (LSI =5.5–7.3), along with simultaneous alleviation of ecological deficit. In particular, the percentage of REBs suffering ecological deficit reduces to 46%, mainly in REBs of Western Europe (median EDI =2.3), but less so in REBs of North America (median EDI =0.8), and Oceania (median EDI =0.2). This suggests that REBs benefit considerably from the information revolution, knowledge exchange, improved social outcomes, and growth of technological industries.

From the developmental perspective of 65 river economic belts under the conceptual framework, crucial prerequisites and constraints could be further identified for the transition from a developing to a developed stage, with a full connection of regional economic and ecological processes in river basins.

Basin-based regional integration for resource productivity enhancement

Regional integration is an inevitable tendency along with the upgrading level of socio-economic development. Given that the connotation of regional integration as efficient flow of natural assets, production factors, technology, and talent, regional integration is usually measured according to multiple dimensions such as trade and investment, finance, regional value chains, infrastructure and connectivity, free movement of people, and institutional and social integration[27]. High-quality regional integration requires coupling of socioeconomic and natural domains, and so the co-occurrence of economic and resource gradients in river basins provides a foundation for regional integration in large REBs (Fig. 2a). River basins often serve as naturally established carriers for cross-regional economic systems[28], which facilitate optimal allocation of resources, human capital, and wealth. Here, we measure the degree of basin-based regional integration by introducing a regional integration index (RI), which is a composite quantification based on scores of natural river density, estuarine streamflow, intra-regional transport network density, trade flow strength, logistics performance index, and net migration rate (more details see Methods). RI provides a measure of the economic links both in a REB and between different REBs (Supplementary Fig. 5). Supplementary Fig. 6 illustrates the relationship between RI and GDP per capita for 65 REBs. Positive feedback between RI and increased GDP per capita is observed, which indicates increasing need for regional integration with upgrading of the developmental level. By promoting two or more regions/countries in a large basin to take over economic sovereignty, employ common economic policies, and form economic groups, basin-based regional integration enables entities to unify and provide REBs with tremendous opportunities to enhance resource productivity.

On the way from initial, developing, to developed stages of global REBs, two transition points separate the three development stages. The first transition from initial to developing stage is mainly associated with substantial promotion of labor productivity, whereas the second transition from developing to developed stage implies substantial improvements in societal ideology and resource productivity. To determine the transition thresholds between development stages, we introduce a comprehensive index E^2E, defined as the ratio of GDP to ecological footprint index (EF) (see Methods), to measure the resource productivity of REBs.

In general, E^2E increases alongside the development path of REBs from the pre-industrial phase to the modernized phase and experiences a stagnation period near the end of the developing stage (Fig. 2b). Once REBs enter into the post-industrial and modernized phases, E^2E improves greatly (> 5000 US$ per gha) in 75–87% of REBs. Alternatively, E^2E variation in specific REBs could be interpreted in terms of proportions of economic output from the primary, secondary, and tertiary industries with respect to total GDP. For example, E^2E decreases with increasing proportion (A) of primary industrial output but increases with increasing proportion (S) of tertiary industrial output in total GDP (Supplementary Fig. 7).

E^2E starts to rise when GDP per capita (2015) exceeds 2000 US$[26] in REBs (Fig. 2b). This could be regarded as quantifying the threshold at the first transition point (turning point T-I) between initial and developing stages. Furthermore, E^2E accelerates as GDP per capita (2015) reaches 20,000 US$ and DI is about 1.6 (Fig. 2b), suggesting a paired threshold at the second transition point (turning point T-II) during the post-industrial phase. Threshold values for the second transition are derived from the human development index[21] (HDI, measure of development levels of economics, education, and healthcare) and ecological pressure index[29] (measure of ecosystem health impacted by human activities). Here, we determine the critical values based on 15 REBs that have a very high degree of human development (HDI > 0.8) but low-to-moderate threat exposure to the river ecosystem (ecological pressure index < 0.75) (Supplementary Fig. 8), which suggests a status decoupled from negative environmental consequences that raises eco-technological efficiency, reduces poverty, and increases social inclusion.

Throughout the initial stage, REBs present very low E^2E because of restricted economic growth (Fig. 2b). During the early to late industrial phases of the developing stage, REBs exhibit a wide range of E^2E values (652–7593 US$ per gha). REBs in West Africa and Southeast Asia have E^2E values below 3000 US$ per gha. REBs in Central and East Asia, South America, Africa, and occasionally in Europe have medium E^2E values in the range 3000–5000 US$ per gha. Higher E^2E values (> 4500 US$ per gha) are more common in South Asia (Fig. 2b). Within a given REB, greater GDP per capita and E^2E usually occur in delta regions due to local advantages regarding water resources, transportation, and trade[9]. At the developed stage, all 28 REBs exhibit higher resource productivity with E^2E values in the range of 4500–12,153 US$ per gha. The enhancement of E^2E in REBs at the developed stage implies an advanced socioeconomic development level with substantial increase in GDP per capita characterized by successful upgrading of industrial structures. As a transformation process with the sequential replacement and growth of primary, secondary, and tertiary industries, the upgrading of industrial structures promotes production factors that flow from low-productivity sectors to high-productivity sectors and facilitate rapid economic growth. The resulting 'structural dividend' can enhance the whole social productivity level[30]. During the process of upgrading industrial structures, new financial investment, new markets, new technology, and new talents are required to establish new industrial chains. Basin-based regional integration is one the most cost-effective pathways to optimize the layout of the new industrial chains, and to materialize sustainable economic benefits. As illustrated in Fig. 2b, E^2E also exhibits a significant positive correlation with RI, which fairly reveals that basin-based regional integration is effective at promoting resource productivity in REBs.

REBs entering the developed stage may exhibit different modes of industrial structures (de-industrialization index DI, Methods) which are closely related to regional economy status, population density, and ecological environment (Fig. 2c, Supplementary Fig. 9). Mode I involves industry convergence driven by technological innovation[31], and REBs corresponding to very high DI (3.6–4.1) are mostly distributed in populated regions usually associated with ecological deficit in their developmental processes such as in the US and Western Europe (Fig. 2c, Supplementary Fig. 9) except the Rhine flowing through the Ruhr Industrial Base. Mode I is associated with the majority of economic output (about 80% of total GDP) from tertiary industry dominated by knowledge services and the remainder (about 20%) from secondary industry. Technological innovation enhances the industrial structure and promotes emerging industries (e.g., artificial intelligence, biomedicine, and advanced materials). Labor-intensive industry and its environmental pollution cost are increasingly outsourced. Economic outputs from traditional industries such as agriculture, mining, and construction tend to stabilize. Progress in bio- and information technology improves agricultural production. Benefiting considerably from the information revolution, knowledge exchange, improved social outcomes, and growth of technological industries, REBs exhibit higher levels of economic wealth, transport infrastructure, and trade flow. Meanwhile, REBs under Mode I experience greater EF per capita in the US than in Western Europe (Fig. 2c) due to their different energy consumption patterns. With abundant indigenous energy resources, the US has high material and energy consumption levels. European countries depend on the international market for material and energy supply, and tend to rely on resource saving, material cycle, and renewable energy strategies.

Mode II presents an industrial structure (DI of about 2.4–2.5) characterized by abundant natural resources and lower population, and the corresponding REBs are more common in Canada and Australia[32,33] where agriculture provides 1.5 % and 2.1% of total GDP. Secondary industry contributes about 28% to total GDP, dominated by the manufacturing, mining, hydrocarbon exploitation, and construction sectors. Tertiary industry accounts for 69–70% of total GDP. In Canada, natural resources and related industries contribute about 40% to total exports and 20% to total GDP. In Australia, export-related economic output mainly comprises mineral products (62.4% in 2019). Under Mode II, REBs in Canada and Australia all present higher EF per capita given their reliance on natural resources (Fig. 2c). However, due to rich natural capital, most REBs still exhibit ecological surplus rather than deficit (Supplementary Fig. 9).

Mode III presents an industrial structure (DI in the range 1.7–1.8) characterized by tourism, agriculture, advanced manufacturing, pharmaceutical industries, and relatively low GDP per capita, with many industrial headquarters located in REBs of Central Europe[34] (Fig. 2c, Supplementary Fig. 9). REBs under Mode III present lower EF per capita, with priority given to ecological conservation and imported resources as shown in Fig. 2c.

These representative modes could also provide references for REBs in Asia and Africa currently still at initial and developing stages. For the foreseeable future, REBs in Asia are likely to follow Mode I given their resource and population pressures, REBs in South America and Africa might be more appropriate for Mode II given their rich natural resource endowment and sparse population. However, other modes could be derived as different countries develop due to their varying social and cultural contexts. Within a globalized, collaborative industrial world, the economic links and trade between REBs would also have an impact on different industrial modes. As is illustrated in Fig. 2c, REBs of Mode I exhibit greater level of RI compared to REBs of Mode II and Mode III. No matter which of the three modes are chosen after completion of transition from developing to developed stage, the upgradation of industrial structures will provide a pathway towards increased resource and energy productivity.

Resource, environmental, and ecological consequences

Human demand on biophysical resources often exceeds the earth's biological rate of regeneration, thus accelerating resource and energy consumption, environmental pollution, ecological deterioration, and greenhouse gas emission. Noting commonly used approaches[17,18,35–37], we estimate human pressure on the environment by means of a modified planetary boundary framework, which incorporates 12 indicators (more details see Methods). These indicators are further categorized into three major issues (resource stress, environmental pollution, and biodiversity loss), which are subject to change with increasing GDP per capita in 65 REBs under different developmental stages. As a result, our study strongly suggests that promotion of E^2E as REBs attain developed stage would ultimately address the foregoing concerns.

In Fig. 3, almost all indicators except fish biodiversity display inverted U-shaped curves with increased GDP per capita, known as Environmental Kuznets Curves (EKC)[38]. During the initial and developing stages, REBs are mostly located along the rising EKCs, whereas REBs in the developed stage appear near the falling EKCs. From a global perspective, the turning point from intensive to relieved resource stress, environment pollution, and ecological deterioration occurs at GDP per capita of 8000–13,000 US$ during the late industrial period, whilst shifts in different REBs may occur under varying natural, social, and political conditions (Supplementary Fig. 10). Among the key indicators, fish biodiversity shows a pattern (Fig. 3c(i)) that differs from the

EKCs because damaged freshwater species are unable to recover sufficiently quickly[39]. REBs in Europe, United States, Canada, and Australia continue to suffer severe biodiversity threats, despite huge mitigation efforts[29].

At different development stages, REBs can experience variations in geo-compositions of resource and energy consumption, and pollution emission[40]. REBs close to the developed stage mostly rely on outsourcing resources, materials, and energy use through intra-regional and international trade[40]. Strict regulations in developed economies tend to displace pollution-intensive industries to developing countries that have lax environmental standards, low-cost resources, and cheap labor[16]. This leads to virtual resource flows (water, land, energy, and materials) embedded in trade commodities[20,41] bringing additional benefits to richer REBs[42], and creates a new problem of inequity among REBs whose solution will require long-term effort by all stakeholders.

Path choice for eco-efficiency upgradation of REBs

REBs are strongly coupled economic-ecological systems controlled by interactions between biophysical and social processes, stepping forward with human socio-economic development under varying regional development planning and climate change scenarios. To forecast the development degree and the potential for eco-efficiency enhancement of the world's large REBs from 2015 to 2050, we consider three scenarios (A, B, C) based on a combination of regional development planning and climate change hypotheses (expressed by shared socioeconomic pathways (SSPs) and representative concentration pathways (RCPs)). Typical scenarios (A: SSP1-RCP2.6; B: SSP4-RCP6.0; and C: SSP5-RCP8.5) are generated to represent sustainable, unequal, and highly fossil-fueled global situations, corresponding to low, moderate, and high levels of climate change (more details see Methods).

Compared with the development degree of global REBs in 2015 (Fig. 4a), a greater number of REBs (54 and 42) would enter the developed stage under Scenarios A and B by 2050, whereas a smaller number (13) of REBs would enter the developed stage under Scenario C (Figs. 4b–d), based on predicted GDP per capita, DI, and HDI. Meanwhile, more REBs associated with an increase in $E^2E > 50\%$ would occur under Scenario A (57) than under Scenarios B (39) and C (9).

Scenario A (Fig. 4b) is expected to provide an ideal opportunity for E^2E increase in REBs in Africa (Congo, Volta, Senegal, Zambezi, Niger, and Nile), Southern Asia (Godavari, Krishna, Mahanadi, Ganges, Indus) that could benefit greatly from rapid economic growth, and also in REBs in Central Europe (Dnieper, Don, Wisla) due to significant decline in EF (Supplementary Fig. 11). For REBs in South America and Oceania, the enhancement in E^2E results from a combination of GDP growth and EF decrease (Supplementary Fig. 11). The foregoing would benefit considerably from continuous upgradation of industrial structures and deep transformation as global integration progresses.

Under Scenario B (Fig. 4c), significant improvement of E^2E is observed for REBs in Western and Central Europe (Loire, Oder, Wisla, Dnieper, and Don), Oceania (Burdekin, Fitzroy, Flinders, and Murray-Darling), and North America (Mississippi, Brazos, Fraser, and Mackenzie), primarily induced by EF reduction (Supplementary Fig. 12). The E^2E enhancement for REBs associated with lower income regions such as Africa and South Asia is slowed down (Supplementary Fig. 13), implying negative consequences from inequalities in economic opportunity, political power, and investment in human capital.

Despite conditions of rapid economic growth, E^2E would be much lower under Scenario C (Fig. 4d, Supplementary Fig. 14), characterized by high-level climate change and energy-intensive development pathways, particularly for REBs whose natural asset base is more sensitive to extreme hydrological events. Examples include REBs in Eastern Asia (Amur), South-Eastern Asia (Salween, Irrawaddy, Mekong), and South America (Orinoco, Parnaiba, and Sao Francisco).

Implications for management

The framework for global REBs proposed by this study can identify the economic growth, industrial structure, integration degree, environment and ecological status, and resource productivity of REBs in socio-economic and cultural contexts at different stages of development, and so is helpful for policy makers concerned with promoting high-quality development within and across basins.

As focal lines of riverine civilization, large REBs can take advantage of key strategic resources such as water, energy, and food in riparian regions or countries[7]. Full integration of multiple sub-regions within a large river basin would also benefit from strong river connectivity and watershed integrity. Regional development drives productivity growth by accelerating active collaboration and mutual assistance in the economic, social, cultural, technological, and administrative spheres, while integrated watershed management facilitates efficient resource utilization through reasonable allocation of shared natural resources in river basins. In fact, certain European and North American REBs (e.g. Rhine, Danube, and Mississippi)[43,44] have achieved concerted development throughout the whole river basin by effective coordination among riparian countries/regions of an integrated regional development policy. Nonetheless, economic integration in Asia seems more challenging because of administrative and socio-cultural differences within each basin, varying landscape, water-use competition, and difficulty in law enforcement[45]. For example, there is a pressing need for regional integration in the Mekong river basin because of its booming population, hydro-energy exploitation, increasing industrial demand, and transportation need[46]. To enhance sustainable development throughout the basin, the Mekong River Commission and the Greater Mekong Sub-region Program have been established to harmonize the intersected interests of different stakeholders[46]. Similar trends in regional integration are emerging along other large rivers[3], demonstrating that socioeconomic development depends heavily on tailor-made water management strategies for transboundary rivers. In China, the REB along the Yangtze[47] also encounters problems arising from uneven regional development. To achieve enhanced natural resource productivity in this REB, stakeholder provinces and cities from upstream to downstream should strengthen cooperation, and effective coordination mechanisms be implemented at national level.

Nowadays, cooperation between REBs on economic and ecological dimensions is also necessary to optimize resource allocation, which further facilitates smooth economic circulation and promotes coordinated regional development[20]. For instance, international trade provides a vital link connecting REB with different levels of development, whereby commodities are often traded and consumed outside the regions they are produced[48] . In this regard, the accounting and management of virtual resources embedded in trade are essential for achieving and balancing sustainable development for all REBs[20]. Another example concerns inter-basin water transfer projects, which offer an easy remedy for the imbalance between supply and demand of water resources among different REBs, but can have large consequences for water supplies, hydrologic, environment and ecological conditions in both donor and receiving basins[49]. Herein, the interconnections among REBs primarily focus on transportation, trade, and human migration. In the future, new dimensions of shared interests and common values among global REBs need to be explored following the perspective of 'community with a shared future for mankind'. For regions and countries that possess multiple REBs, a comprehensive regional framework based on the natural endowment and socio-economic development stage of each REB is required. More specifically, it is essential to formulate basin-specific sustainable development strategies and design high-level pathways to facilitate the systematic advancement of major REBs and their tributaries.

The foregoing trends could be disrupted by unexpected events such as natural disasters, pandemics, and regional conflicts[50]. However, there is a general move towards regional and international integration across large REBs as human civilization evolves. Although different socio-economic and historical backgrounds, resource utilization levels, and cultural and political institutions lead to the spatial diversity of REBs, those REBs characterized by basin-based regional integration should provide promising pathways to accelerate economic growth while reducing ecological footprint. With successful completion of the transition from developing to developed stage in REBs, E^2E should be substantially enhanced through improved resource and energy efficiencies, and by spontaneously addressing primary concerns such as water resource stress, energy consumption, environmental pollution, biodiversity loss, and greenhouse gas emission. In the long run, large REBs would then act as ideal conveyors that realize the virtuous cycle of social economic development leading towards sustainability.

Methods

Extraction of global REBs

Basin boundaries and mainstreams of 65 REBs each of catchment area ≥100,000 km^2

were extracted from the HYDROSHEDS (http://www.hydrosheds.org/) and PKU river network databases.

Preliminary division of development stages of REBs

The human development path of REBs was initially divided into three stages based on six industrialization phases and a human development index (HDI). The stages comprise an initial stage corresponding to the pre-industrialization phase with HDI < 0.55; a developing stage corresponding to early, middle, and late industrialization phases with HDI ≥ 0.55; and a developed stage corresponding approximately to post-industrialization and modernization phases with HDI ≥ 0.8. Transition from the developing to the developed stage likely occurs at some point during the post-industrialization phase. The six industrialization phases were identified in terms of GDP per capita and industrial structure based on Chenery et al.'s theory[26]. HDI is a composite index measuring average achievement in dimensions of human health, education, and standard of living, assessed according to life expectancy at birth, years of schooling for adults aged 25+ years and expected years of schooling for children of school entry age, and gross national income per capita[21]. HDI > 0.8, 0.55–0.8, and < 0.55 correspond to high, medium, and low degrees of human development. Gross Domestic Product (GDP) per capita (US$) was determined from the ratio of GDP to population. Data on basin-scale GDP per capita (US$) and population (persons) in 2015 were extracted from the following global gridded datasets, https://datadryad.org/stash/dataset/doi:10.5061/dryad.dk1j0, and https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-count-rev11. Characteristics of industrial structures were measured as proportions of primary (*A*, %), secondary (*I*, %), and tertiary (*S*, %) outputs in total GDP. The industrial structure characteristics of REBs could also be quantified by a combination of A, I, and S, e.g., the industrialization index (DI) defined as the ratio of (S−A) to I was used in the present study. Basin-scale information on A, I, and S was obtained from country-scale data (http://data.un.org/) using a partition coefficient matrix.

Characterization of stage-specific distinctiveness of REBs

The characteristics of REBs at different stages were quantified in terms of economic wealth, cultural characteristics, human welfare, and ecological consequences (Supplementary Figs. 2–4). Economic wealth was measured using GDP per capita. Cultural characteristics were described by the cultural realms to which REBs belong. Human welfare was measured by means of a life satisfaction index (LSI) that described the overall perception of individual well-being, ranging from 0 (least satisfied) to 10 (most satisfied)[21].

Ecological consequence was represented by the ecological deficit index (EDI). EDI is defined as the ratio of ecological footprint (EF, in global hectares, gha) to bio-capacity (BC, in global hectares, gha), which measures the balance between the demand placed on natural resources and the resources available throughout the REBs. EF is a measure of how much area of biologically productive land and water is required for an individual, population, or activity to produce all the resources it consumes and to absorb the waste it generates, using prevailing technology and resource management practices[51]. Here the term biologically productive land and water area refers to the area of land and water (both marine and inland) that supports photosynthetic activity and the accumulation of biomass used by humans. As a land-based flow indicator, EF has six components based on specific land types, i.e., cropland footprint, grazing land footprint, fishing grounds footprint, forest products footprint, CO_2 footprint, and built-up land footprint[51]. Herein, fishing grounds footprint represents the demands of fisheries on aquatic ecosystems as the equivalent surface marine and inland water areas required to sustainably support a country's catch. Moreover, carbon footprint is included in the ecological footprint, and is represented by the area of forest land required to sequester anthropogenic carbon dioxide emissions amounting from domestic fossil fuel combustion and electricity use, embodied carbon in traded items and electricity, a country's share of global international transport emissions, and non-fossil-fuel sources[51]. BC is the amount of biologically productive land and water area available to provide the resources consumed by the population and to absorb its waste, given present technology and management practices[51]. An ecological deficit occurs when EDI >1, in which case human demand on an ecosystem exceeds the ecosystem's capacity to regenerate the resources it consumes and absorb its waste; hence, the region is either usually importing biocapacity through trade or liquidating regional ecological assets, or else emitting waste into the global commons. Conversely, an ecological reserve exists for EDI < 1. In the present work, we transformed the country-scale BC into basin-scale BC for each REB, using a partition coefficient matrix. Data on the country-scale BC and EF were derived from the Global Footprint Network (https://www.footprintnetwork.org/).

Measurement of basin-based regional integration of REBs

Basin-based regional integration of REBs was measured by a regional integration index (RI) which was a composite quantification based on scores of natural river density (RND, km^{-1}), estuarine streamflow (Q, $m^3 \cdot s^{-1}$), intra-regional transport network density (ITND), trade flow strength (TRAD), logistics performance index (LPI), and net migration rate (NMR), as follows:

$$\mathrm{RI}_w = \left[\frac{\widehat{\mathrm{RND}}_w - \min(\widehat{\mathrm{RND}}_w)}{\max(\widehat{\mathrm{RND}}_w) - \min(\widehat{\mathrm{RND}}_w)} + \frac{\hat{Q}_w - \min(\hat{Q}_w)}{\max(\hat{Q}_w) - \min(\hat{Q}_w)} + \frac{\widehat{\mathrm{ITND}}_w - \min(\widehat{\mathrm{ITND}}_w)}{\max(\widehat{\mathrm{ITND}}_w) - \min(\widehat{\mathrm{ITND}}_w)} + \frac{\widehat{\mathrm{TRAD}}_w - \min(\widehat{\mathrm{TRAD}}_w)}{\max(\widehat{\mathrm{TRAD}}_w) - \min(\widehat{\mathrm{TRAD}}_w)} + \frac{\widehat{\mathrm{LPI}}_w - \min(\widehat{\mathrm{LPI}}_w)}{\max(\widehat{\mathrm{LPI}}_w) - \min(\widehat{\mathrm{LPI}}_w)} + \frac{\widehat{\mathrm{NMR}}_w - \min(\widehat{\mathrm{NMR}}_w)}{\max(\widehat{\mathrm{NMR}}_w) - \min(\widehat{\mathrm{NMR}}_w)}\right]/6 \quad (1)$$

where $\widehat{\mathrm{RND}}_w$, $\hat{Q}_w$, $\widehat{\mathrm{ITND}}_{\mathrm{i},w}$, $\widehat{\mathrm{TRAD}}_w$, $\widehat{\mathrm{LPI}}_w$, and $\widehat{\mathrm{NMR}}_w$ are the ascending rank orders over all waterways of the six indicators, and *w* refers to a certain REB.

RND was estimated as the total channel length of river with channel width greater than 30 m per unit area[52]. Mean annual Q data was derived from Li et al[4], ITND was given by the mean densities of golden inland waterways, roads, and railways (Supplementary Table 1). Data on golden inland waterways were obtained from Wang et al[5]. Data on road and railway distributions were obtained from https://www.naturalearthdata.com/. TRAD was expressed as the percentage sum of exports and imports of goods and services in total GDP (Supplementary Table 2), which measured international trade openness and economic integration, obtained from http://www.cepii.fr/. LPI reflected the perception of a region's logistics based on efficiency of customs clearance processes, quality of trade- and transport-related infrastructure, ease of arranging competitively priced shipments, quality of logistics services, ability to track and trace consignments, and frequency with which shipments reach the consignee within the scheduled time (https://lpi.worldbank.org/). Net migration rate (NMR) was the net total of migrants during the period, i.e., the number of immigrants minus the number of emigrants, including both citizens and noncitizens, available from https://data.worldbank.org/indicator/SM.POP.NETM?view=map.

Estimation of resource productivity of REBs

Resource productivity was represented by Eco-efficiency (E^2E, US$ per gha), determined as the ratio of GDP to EF. Greater E^2E implies increased output for human consumption, along with minimized waste disposal, pollution, and natural resource depletion[23].

Evaluation of human pressure on environment

Human pressure on environment was evaluated by a modified planetary boundary framework[37]. We downscaled four planetary boundaries (freshwater use, climate change, biogeochemical flow, land system change, and biosphere integrity) to river basin scale, and selected 8 relevant control variables (e.g. blue water footprint; greenhouse gas emissions; gray water footprint related to anthropogenic nitrogen and phosphorus loads; biodiversity loss of terrestrial species due to agricultural, forest, and pasture land use; and change in biodiversity of freshwater fish fauna impacted by human activities). In addition, we included 4 separate indicators (material footprint, energy use, mercury exports from rivers to oceans, and mismanaged plastic waste mass per river basin which are not part of the planetary boundaries framework but are widely reported measures of environmental pressure in river basins and are closely related to sustaining human well-being. These 12 indicators in our framework were further categorized into three major issues (resource stress, environmental pollution, and biodiversity loss).

For each REB, resource stress was determined from the blue water footprint (Mm^3 per month)[53], material footprint (Mt)[54], energy use (kilogram of oil equivalent, https://data.worldbank.org/indicator/EG.USE.PCAP.KG.OE), and greenhouse gas emissions (Mt, https://ourworldindata.org/greenhouse-gas-emissions). Environmental pollution of a given REB was represented by the gray water footprint related to anthropogenic nitrogen[55] and phosphorus[56] loads, mercury exports from rivers to oceans[12], and mismanaged plastic waste mass per river basin[13]. The biodiversity loss of each REB was measured as the cumulative change in biodiversity of freshwater fish fauna impacted by human activities[15], and biodiversity loss of terrestrial species (10^{-6} global species eq. lost*years)[57] due to agricultural, forest, and pasture land use.

Statistical analysis

Relationships between indicators were identified with Spearman correlation analysis (a value of $p < 0.05$ was considered significant). Dissimilarities of economic links between REBs with different industrial Modes were examined by Wilcoxon rank-sum tests (wilcox.test function in 'stats' package in R).

Scenario analysis

Projections of the development degree and resource productivity for REBs were based on established scenarios that represent possible future socio-economic and climate change conditions. Here, shared socioeconomic pathways (SSPs) provide a comprehensive framework of five scenarios[58] that consider potential pathways and uncertainties of future socio-economic factors. SSP1 is a sustainable pathway that is people-oriented and follows a green approach. SSP2 is a middle pathway lying between SSP1 and SSP3. SSP3 is a regional rivalry pathway that is contrary to global cooperation. SSP4 is a divided pathway in which inequality and stratification are increasing both across and within countries. SSP5 is a fossil-fueled development pathway in which the global economy grows rapidly, but people face severe mitigation challenges. Representative Concentration Pathways (RCPs)[59] describe different climate futures, depending on possible volumes of greenhouse gases emitted in the years to come. The RCPs include a mitigation scenario that leads to a very low forcing level (RCP2.6), two medium stabilization scenarios (RCP4.5, RCP6.0), and a very high baseline emission scenario (RCP8.5). In this study, we carried out scenario simulations of development stage and E^2E for global REBs in 2050, based on three different SSP and RCP combinations, namely Scenario A (SSP1-RCP2.6), Scenario B (SSP4-RCP6.0), and Scenario C (SSP5-RCP8.5) in order to explore the influence of climatic and socioeconomic drivers on resource productivity enhancement of REBs.

Gridded GDP and population data at 0.5 × 0.5 degree resolution for the different SSPs scenarios were derived from Huang et al[60]. Projected DI values for Scenario SSP4 were extracted from the International Futures (IFs) platform[24] produced by the University of Denver, US (https://pardee.du.edu/). DI values in 2030 and 2050 were set to be 20% and 40% greater than the SSP4 results in SSP1, and 20% and 40% lower in Scenario SSP5. For the remaining factors HDI and EF, we undertook linear/exponential extrapolations of historical data; the results are called HDI' and EF'. Scenario-setting was based on the extrapolated results (see Supplementary Tables 3, 4). Historical EF values were derived from https://www.footprintnetwork.org/. Historical HDI values from 1990 to 2015 were obtained from https://datadryad.org/stash/dataset/doi:10.5061/dryad.dk1j0.

Data Availability

Basin-scale data related to REBs reported in this paper are available here: https://doi.org/10.6084/m9.figshare.24632331.v2.

Code Availability

Python codes used to estimate basin-scale parameters from the datasets at country scale are available here: https://doi.org/10.6084/m9.figshare.24619095.v2.

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Author contributions

J.R.N. designed the research. Y.C.W. performed research. Y. C.W., J.R.N., and A.G.L.B. wrote the paper. J.B.W., J.H.X., C.M.Z. contributed new ideas and information. All authors contributed to interpretation of the findings.

Ethics declarations

Competing interests

The authors declare no competing interests.

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Figure captions

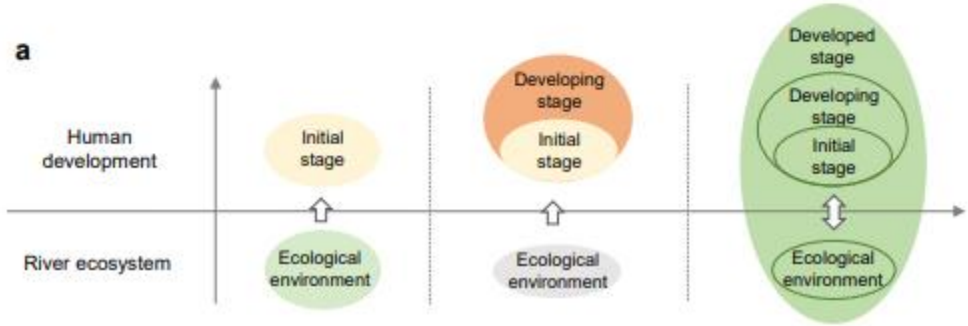
Fig. 1. A conceptual framework for identifying river economic belts (REBs) at varying development stages. a, Concepts and divisions of human development stages. *A*, *I*, and *S* are proportions of economic output value from primary, secondary, and tertiary industries. **b**, Present distribution of global large rivers and REBs at different development stages.

Fig. 2. Basin-based regional integration and enhancement of eco-efficiency (E^2E) **on the path towards sustainability. a,** Route designated for upgradation of E^2E in REBs through basin-based regional integration. **b**, E^2E variation trends with GDP per capita (2015 US$) for the three development stages separated by two turning points (T-I and T-II). The sub-graph in Fig. 2b plots the relationship between regional integration index (RI) and E^2E (** $p < 0.01$; Pearson correlation). **c**, E^2E variation under representative modes of industrial structures (where DI is the de-industrialization index defined as the ratio of (S–A) to I) for REBs at the developed stage. *A*, *I*, and *S* are proportions of economic output values from primary, secondary, and tertiary industries to total GDP. Dots of greater size in **c** represent REBs with larger EF per capita. The box plots in Fig. 2c display the RI of REBs with different industrial Modes (ns $p \geqslant 0.05$; * $p < 0.05$; Wilcoxon rank-sum test).

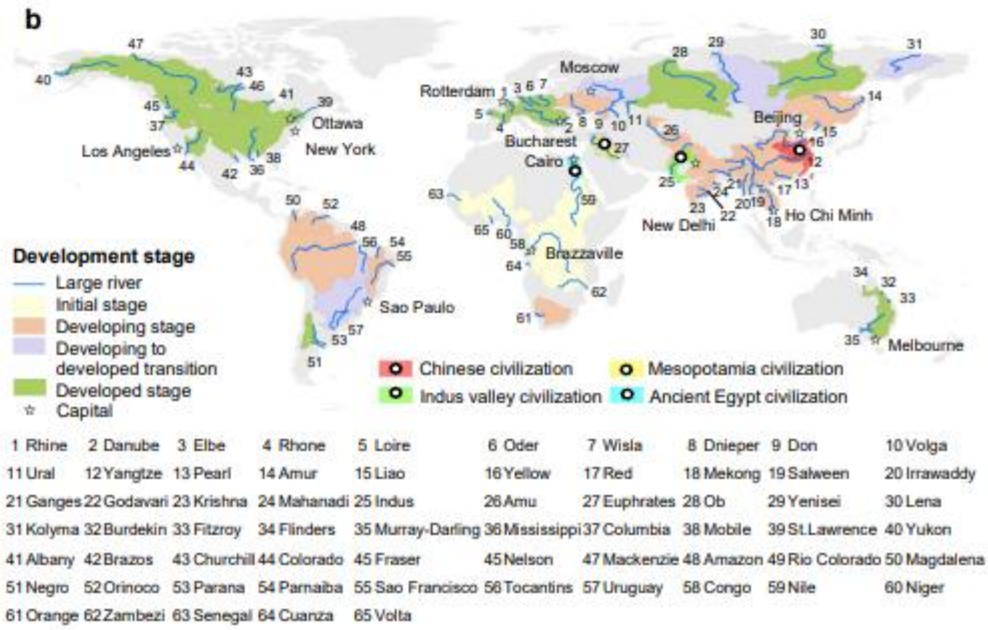
Fig. 3. Representative indicators for resource stress, environmental pollution, and biodiversity loss of global REBs at different development stages (2015). a, Resource stress represented by blue water footprint (i), material footprint (ii), energy use (iii), and greenhouse gas emissions (iv). **b**, Environment pollution represented by gray water footprint related to anthropogenic nitrogen load (i), phosphorus load (ii), mercury exports from rivers to oceans (iii), and mismanaged plastic waste mass per river basin

(iv). **c**, Biodiversity loss measured through cumulative change in biodiversity of freshwater fish fauna impacted by human activities (i), biodiversity loss of terrestrial species due to agricultural land-use (ii), forestation (iii), and pasture land-use (iv). The dotted lines denote schematic Environmental Kuznets Curves (EKCs)

Fig. 4. Eco-efficiency (E^2E) **and its upgradation for global REBs at different development stages. a,** E^2E of global REBs in 2015. **b–d** represent E^2E in 2050 under Scenarios A (SSP1-RCP2.6), B (SSP4-RCP6.0), and C (SSP5-RCP8.5), respectively.



Development stage	Initial stage	Developing stage	Developed stage
Industrialization process	Pre-industrialization phase	Early, middle, and late industrialization phase	Post-industrialization, and modernized phase
GDP per capita (US$)	<1783	<13375	>13375
Human development index	< 0.55	≥ 0.55	≥ 0.8
Industrial structure	*A* > *I*	*A* < *I*, *I* > *S*	*A* <10%, *S* > 50%
Human-Nature relation	Conform to nature	Reform nature	Harmonize with nature



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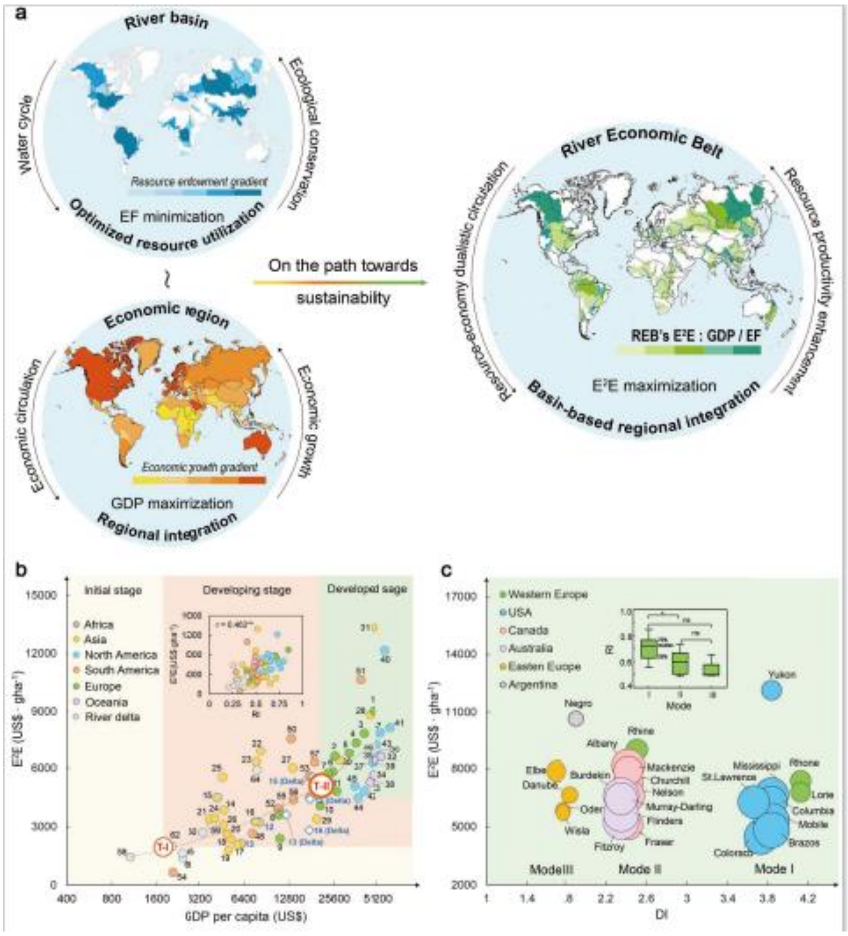

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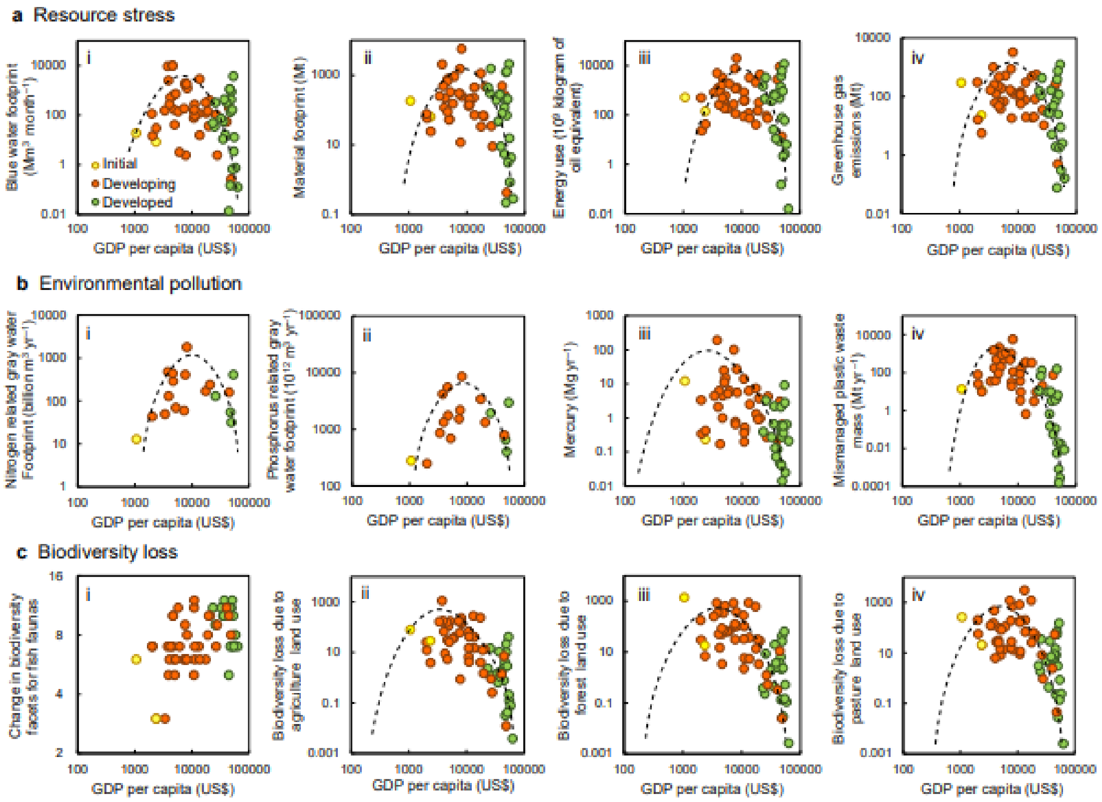

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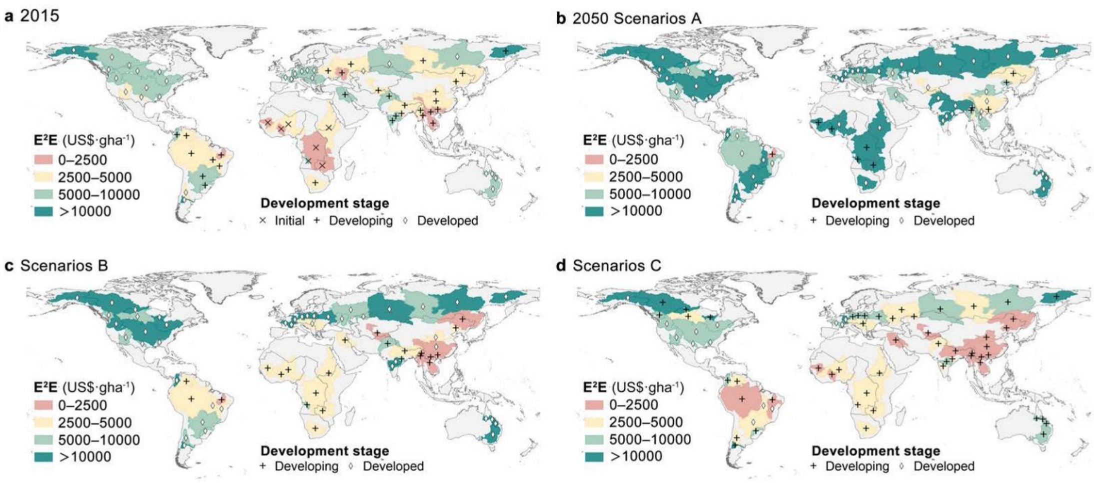

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