J. Geogr. Sci. 2020, 30(3): 355-377
DOI: https://doi.org/10.1007/s11442-020-1732-9

Coupled Human and Natural Cube:
A novel framework for analyzing the multiple interactions between humans and nature

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Abstract: Understanding the interactions between humans and nature in the Anthropocene is central to the quest for both human wellbeing and global sustainability. However, the time-space compression, long range interactions, and reconstruction of socio-economic structures at the global scale all pose great challenges to the traditional analytical frameworks of human-nature systems. In this paper, we extend the connotation of coupled human and natural systems (CHANS) and their four dimensions—space, time, appearance, and organization, and propose a novel framework: "Coupled Human and Natural Cube" (CHNC) to explain the coupling mechanism between humans and the natural environment. Our proposition is inspired by theories based on the human-earth areal system, telecoupling framework, planetary urbanization, and perspectives from complexity science. We systematically introduce the concept, connotation, evolution rules, and analytical dimensions of the CHNC. Notably there exist various "coupling lines" in the CHNC, connecting different systems and elements at multiple scales and forming a large, nested, interconnected, organic system. The rotation of the CHNC represents spatiotemporal nonlinear fluctuations in CHANS in different regions. As a system continually exchanges energy with the environment, a critical phase transition occurs when fluctuations reach a certain threshold, leading to emergent behavior of the system. The CHNC has four dimensions—pericoupling and telecoupling, syncoupling and lagcoupling, apparent coupling and hidden coupling, and intra-organization coupling and inter-organizational coupling. We mainly focus on the theoretical connotation, research methods, and typical cases of telecoupling, lagcoupling, hidden coupling, and inter-organizational coupling, and put forward a human-nature coupling matrix to integrate multiple dimensions. In summary, the CHNC provides a more comprehensive and systematic research paradigm for understanding the evolution and coupling mechanism of the human-nature system, which expands the analytical dimension of CHANS. The CHNC also provides a theoretical support for formulating regional, sustainable development policies for human wellbeing.

Received: 2019-06-18 **Accepted:** 2019-10-12
Foundation: Program of the National Natural Science Foundation of China, No.41590842, No.41801164; China Postdoctoral Science Foundation, No.2018M630196
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Keywords: Coupled Human and Natural Cube; human-environment systems; social-ecological systems; pericoupling and telecoupling; climate change; urbanization; human activity; complexity science; sustainability science

1 Introduction

Since the 20th century, interactions between humans and nature have become unprecedentedly intensified. The acceleration of industrialization, urbanization and informatization have led to increasingly serious environmental problems, including shortages of clean water, degradation of ecosystems, increased soil erosion, loss of biodiversity, air pollution, declining fisheries yields, global climate change, and more; the earth has entered the Anthropocene (Bai *et al.*, 2016; Goudie, 2013; Malhi, 2017; Steffen *et al.*, 2016). Understanding human-nature interaction is central to the quest for both human wellbeing and global sustainability. Coordinated development between humans and nature is the basis for achieving the UN 2030 sustainable development goals (Fu, 2019). Therefore, this issue has become the core content of many disciplines, including geography, ecology, environmental science, earth system science, and sustainability science (Alberti, 2008; Glaser *et al.*, 2012; Wu *et al.*, 2014; Nagendra *et al.*, 2018). In recent years, many global research initiatives and projects have been devoted to exploring the coupling mechanism between humans and nature in the process of urbanization and economic development. These initiatives and projects include Future Earth, Intergovernmental Panel on Climate Change (IPCC), Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), The Economics of Ecosystems and Biodiversity (TEEB), Resilience Alliance (Holling, 2001), and the International Network of Research on Coupled Human and Natural Systems (CHANS). In line with these, the International Geographical Union has set up a commission on Geography for Future Earth: Coupled Human-Earth Systems for Sustainability (IGU-GFE), and the international cooperation funding for Towards a Sustainable Earth: Human and Environment Interaction and Sustainable Development (TaSE) has been jointly established by several countries.

The interactive coupling between humans and nature is a large, open and complex system involving society, economy, culture, and nature, which contains complex coupling mechanisms. To understand the interactions, geographers, ecologists, economists, environmental scientists and other scholars from different disciplines have put forward many research theories and frameworks, including principally: Human-earth Areal System (Wu, 1991), Social-Economic-Natural Complex Ecosystem (Wang *et al.*, 2011), Coupled Human and Natural Systems (Liu *et al.*, 2007b), Social-ecological Systems (SESs) (Ostrom, 2009), Human-earth Coupling Loop (Fang *et al.*, 2016b), Footprint Family (Fang *et al.*, 2014), Planetary Boundaries (Steffen *et al.*, 2015), Telecoupling Framework (Liu *et al.*, 2013), Water-Energy-Food Nexus (Liu *et al.*, 2018b), DPSIR Framework (Tscherning *et al.*, 2012), STIRPAT Framework (York *et al.*, 2003), Emergy Analysis (Hau and Bakshi, 2004), Sustainable Livelihoods Framework (Sherbinin *et al.*, 2008), Population-Development-Environment Model (PDE) (Dietz, 2017; Hummel *et al.*, 2013). Moreover, Gunderson and Holling (2001) proposed the famous adaptive cycles model to analyze ecosystems and social-ecological systems across scales; Dietz *et al.* (2003) elaborated the strategies and general principles for adaptive governance of environmental resources; Folke (2006) discussed the resilience perspective for social-ecological systems analysis; Liu (2017) further proposed a metacoupling framework based on telecoupling.

Through a literature review, we found that the traditional study of the human-nature interaction framework tended to focus on a particular areal system in the spatial dimension, the study of the synchronization of system evolution in the time dimension, and on the linear or direct causal relationships. However, due to socioeconomic transformation, improvements in rapid transportation systems, economic globalization, and the information and intelligence revolution, new phenomena at the global scale, such as time-space compression, long range interactions, and social organization reconstruction, have exerted a profound influence on human and natural systems (Liu *et al.*, 2017a; Wang *et al.*, 2018; Warf, 2008). New coupling issues between humans and nature increasingly appear, such as remote influence, dislocation or lag feedback in time, indirectness and concealment of driving forces, and diversity of agents. Thus, traditional research frameworks are unable to cope with complex coupling in the new era, and current theories and paradigms are in urgent need of adaptive innovation and reform.

Based on previous theoretical research, this paper first analyzes the scientific connotation of CHANS. Inspired by theories based on the human-earth areal system, telecoupling framework, planetary urbanization, and perspectives from complexity science (Batty, 2013; Li *et al.*, 2017a), from the four dimensions of space, time, representation, and organization, we create a research framework to explain the coupling mechanism between humans and nature: the “Coupled Human and Natural Cube” (CHNC). Additionally, we propose the concepts of lagcoupling, hidden coupling, and inter-organizational coupling within the CHNC. This framework is expected to promote the development of human-earth system theory in the new era, provide theoretical support for multi-dimensional interaction analysis between humans and nature in the Anthropocene, and to help formulate regional sustainability policy.

2 Concept of coupled human and natural systems

Human activity on earth’s surface includes a series of complex evolutionary and transformational processes, such as farming, fishing, grazing, trading, urbanization, expansion of residential land, population migration, industrial agglomeration, energy and mineral consumption, and engineering construction (Steffen *et al.*, 2006). Nature is the basis for human survival and reproduction, comprising many elements, such as water, soil, gas, biology, energy, and minerals. It is the sum total of various environmental factors and ecological relations that living organisms rely on for survival, development, reproduction, and evolution (Daily, 1997). Many scholars analyze the interactions between human systems and natural systems using different appellations, including human and natural systems (Liu *et al.*, 2007b), human-environment systems (Turner *et al.*, 2003), human-earth systems (Chapin *et al.*, 2011), social-ecological systems (Ostrom, 2009), ecological-economic systems (Costanza *et al.*, 1993), or population–environment systems. We use “human and natural systems” in this paper, and we analyze multiple interactions between the two systems. Coupling, with a profound connotation, is generally used to explain the complex mutual dependence, interaction, influence, and adaptation processes between humans and nature (Morzillo *et al.*, 2014; Qi *et al.*, 2012). These couplings include positive and negative effects: As a result of population growth, economic development, energy consumption, technological progress, urban management, and expansion of human settlements, human activity has had a coercive or promotional effect on eco-environment systems (Alberti, 2015); in turn, nature exerts constraining or bearing force on human development through resource carrying, ecosystem service, environmental fairness, and policy intervention (Boumans *et al.*, 2015; Cui *et al.*, 2019). Thus, the two systems have a dialectic relationship of coopetition and the unity of opposites.

To better understand coupled human and natural systems visually, we use a conceptual illustration as in Figure 1. Humans and nature are two large, complex, open systems, similar to two buildings. The human system includes subsystems of population, economy, society, and information, while the natural system includes subsystems of water, land, atmosphere, biodiversity, and energy. There are many elements inside each subsystem, some of which are key (called order parameters in Synergetics) and some of which are general. Key elements are represented by the large dots in Figure 1, while small dots represent general elements. In Figure 1, the elements inside a subsystem interact with each other through horizontal lines, and the subsystems interact and connect with each other through vertical lines. There are more lines with interactive coupling effects between human and natural systems. In this paper, these complex lines are collectively referred to as “coupling lines” and represent the positive and negative feedback effects between systems and elements, among which there are promotion and restriction, opposition and unity. The coupling mechanism behind each coupling line is different, and so too is the coupling strength. These complex interactive coupling forces exert influences on the whole CHANS in spatial and temporal dynamic evolution. Self-organization of the underlying elements and the emergence of the system as a whole occur at the same time, resulting in fluctuations of the whole system, which jointly determine the evolutionary direction of the whole coupling system.

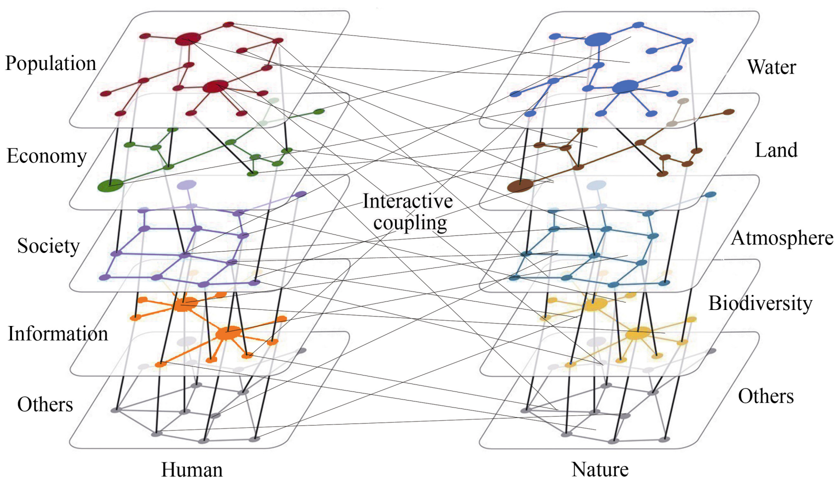


Figure 1 Conceptual illustration of coupled human and natural systems

Overall, the two subsystems in the CHANS not only have their own evolutionary rules and restriction factors but also form a complex large coupling system of mutual connection, support, and restriction through continuous material circulation, energy flow, and information transmission. The evolution of coupling system is a self-organizing fluctuation process from a chaotic to an ordered state within a certain range of time and space, through interaction with the external environment and subsystems (Bak, 2013). The pattern and process of this evolution are multi-layered and interrelated, and there are multiple coupling and feedback mechanisms between processes; moreover, the scales of action of different processes are different (Mchale *et al.*, 2015; Werner and Mcnamara, 2007). According to complexity theory, the CHANS have the characteristics of opening, self-organization, fluctuating, nonlinearity, vulnerability, robustness, feedback, fluctuation, phase change, multiple feedback, and scale nesting (Liu *et al.*, 2007b; Liu *et al.*, 2016a).

3 Theoretical foundation and connotation of CHNC

3.1 Theoretical foundation

The CHNC framework in this paper builds on a long tradition of scholarship on human–nature interactions. Furthermore, it is an innovative development of existing relevant theories, mainly drawing inspiration from the theories of the human-earth areal system, telecoupling, and planetary urbanization.

3.1.1 Human-earth areal system

Wu (1991) proposed that the human-earth areal system is a dissipative unstable structure, nonlinear, and far from an equilibrium state. He believed that researching human-earth interactions must pay attention to the relationship between time and space changes, specifically considering spatial scale, location, and time attributes: the past, present, and future. Our research objective is to explore the interactions between various elements in a system and its overall behavior, and to elucidate the optimization, comprehensive balance, and effective regulation mechanisms of the human-earth areal system at different scales, from the perspectives of spatial structure, time processes, organizational change, overall effect, coordination, and complementarity. People interact with resources and environment using intermediate products, the most basic being food. Input-output is the most basic two-way process in the human-earth areal system. Based on Wu's theory, other scholars have made progress in human-earth system structure, human-earth coupling theory, human-earth system evolution, human-water areal systems, and other aspects (Fan *et al.*, 2017; Li *et al.*, 2017b; Fang, 2006; Liu *et al.*, 2014a).

3.1.2 Telecoupling

Interactions between distant places are increasingly widespread and influential. Liu *et al.* (2007a) proposed that CHANS exhibit nonlinear dynamics with thresholds, reciprocal feedback loops, time lags, resilience, heterogeneity, and surprises. Furthermore, past couplings have legacy effects on present conditions and future possibilities. The implications of telecoupling were then discussed as an umbrella concept that refers to socioeconomic and environmental interactions over distances, and the international research network of CHANS was created (Liu *et al.*, 2013). The telecoupling framework contains five major interrelated components, i.e., coupled human and natural systems, flows, agents, causes, and effects. Population migration, tourism, trade, species diffusion, technology transfer, and investment are important telecoupling processes (Liu *et al.*, 2013; Liu *et al.*, 2015). In recent years, using this theoretical framework, scholars have conducted extensive discussions on land use change (Liu *et al.*, 2014b), water resource management and virtual water (Deines *et al.*, 2016), ecosystem services (Liu *et al.*, 2016b), energy (Fang *et al.*, 2016a), fishery management (Carlson *et al.*, 2017), the Belt and Road Initiative (Yang *et al.*, 2016), and other fields.

3.1.3 Planetary urbanization

Planetary urbanization theory was proposed in 2011 (Brenner and Schmid, 2011), globally arousing scholars' attention (Buckley and Strauss, 2016). The theory highlights that the city is not a closed unit, but a process of change, and the traditional boundaries between urban and rural areas tend to be blurred. Urbanization is a global, multi-scale historical process that extends to every corner of the earth. Planetary urbanization means that even spaces that lie well beyond the traditional city cores and suburban peripheries—from transoceanic shipping lanes, transcontinental highway networks, and worldwide communications infrastructures, to alpine and coastal tourist enclaves, "nature" parks, offshore financial centers, and even the world's oceans, deserts, jungles, mountain ranges, and atmosphere—have become integral parts of the worldwide urban fabric (Brenner, 2013; Brenner and Schmid, 2011). Urbanization contains two dialectically intertwined moments—implosion (concentration, agglomeration) and explosion (extension of the urban fabric, intensification of interspatial connectivity across places, territories, and scales). Many places have changed into extended regional urbanization, and the research paradigm should go beyond "urban centrism" and turn to "planetary urbanization" (Brenner and Schmid, 2014).

3.2 The connotation of CHNC

Absorbing the core ideas of the above theories, we expand the four analytical dimensions of space, time, representation and organization of CHANS, as well as deconstructing the complex system based on spatial distance, time span, causal relationship, and organizational connection. The four dimensions constitute a panoramic and dynamic analytical framework to explain the coupling mechanism between humans and nature, and the four dimensions, as a whole, nest with each other, having mutual contact. For understanding and memory, the novel analytical framework is expressed in the form of a Rubik's cube (CHNC).

As shown in Figure 2, the coupled human-nature system in any particular region can be regarded as a small cube (CHNC-c) in the Rubik's cube. Zooming in on the little cube, its interior contains numerous eco-environment and socioeconomic elements, represented by small balls of different sizes (1, 2, 3, ..., i). Among them, the larger ones have a much stronger influence on the system (the order parameters) than the smaller ones. Positive and negative feedback effects occur between the balls through the "coupling line." The system is open: the arrows of inputting and outputting cubes represent the inflow and outflow of people, goods, energy, and information. Each cube represents a coupled human-nature system in a particular region.

Each cube has four interrelated dimensions: time, space, organization, and representation. As shown in Figure 2, the X-axis represents the time dimension, and the axis inside the small cube belongs to the short-term coupling effect between humans and nature, while the axis outside belongs to the long-term coupling effect. The Y-axis represents the organizational dimension, and the axis inside the small cube belongs to the intra-organization coupling effect between humans and nature; the axis outside belongs to the inter-organizational coupling effect. The Z-axis represents the spatial dimension, and the axis inside the small

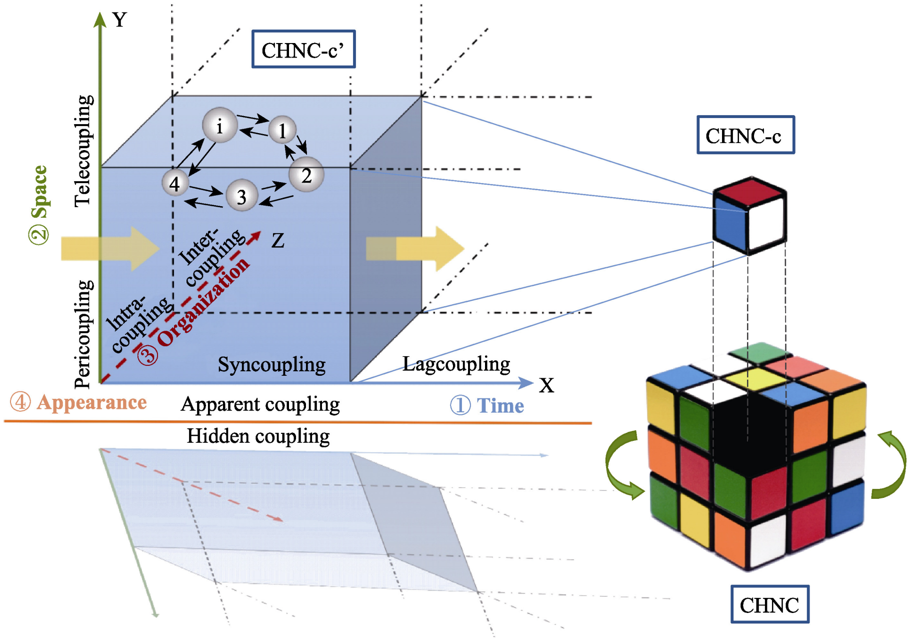


Figure 2 The conceptual illustration of Coupled Human and Natural Cube

cube belongs to the short-distance coupling effect between humans and nature, while the axis outside belongs to the remote coupling effect. In addition, from the perspective of whether causality is direct, there is not only an explicit interactive coupling between humans and nature but there is also an implicit, indirect interaction that cannot be seen on the surface or through the third party; this effect is called "hidden coupling." Therefore, there are pericoupling, syncoupling, apparent coupling, and intra-organization coupling between humans and nature inside the cube. On the outside of the cube, there are also four dynamic mechanisms of telecoupling, lagcoupling, hidden coupling, and inter-organizational coupling. These will be discussed in section 4.

3.3 Evolution rules of CHNC

There are many colorful small cubes in the large Rubik's cube CHNC (Figure 2), each of which represents a particular human-nature system. These small cubes are interrelated and interact with each other through the complex axes and chains inside the Rubik's cube, which are the "coupling lines" mentioned above. According to the theory of telecoupling and planetary urbanization, there are numerous large or small cubes with different properties on earth, which all have tight or loose relations. The coupling system between humans and nature at the global scale is a super-large Rubik's cube, while the coupling system at the national or regional scale is a relatively small Rubik's cube. Certain fractal rules or scale nesting exist among them, as in Figure 3c (Jiang and Ma, 2018). Figure 3 also shows the evolution rules of CHNC. The color of each surface of a small cube represents the subsystem of CHNC, such as water, land, air, economy, population, and energy, and the Rubik's cube drives itself to rotate through axes and chains; this rotation process involves the collision of different cubes and different colored surfaces. The axes and chains represent the transfer of people, things, and information between different regions, while the rotation of the Rubik's cube represents the nonlinear coupling effect in space and time of the CNHC between different regions with constant fluctuations of the system.

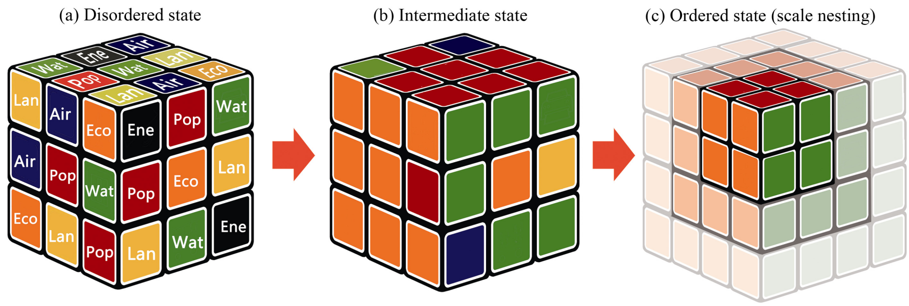


Figure 3 Evolution and nested-scaling of Coupled Human and Natural Cube

We propose that when the color of each side of the Rubik's cube becomes the same, it represents the coordinated development of all subsystems between different regions (but not to the same extent). This process requires work done by an external force, that is, the system is constantly absorbing negative entropy, and when the system reaches a certain threshold, a critical phase transition and emergence occur. Now, a coupled human and natural system at a certain spatial scale achieves coordination and order, and the Rubik's cube "game" is successful. Internal or external disturbances in the coupled system can be in the form of a sudden event, such as a natural disaster or financial crisis, or in the form of a slow precipitation effect similar to Boiling Frog. Considering the vulnerability and elasticity of the system, along with the input of energy, once the threshold is exceeded, the system will collapse (phase transition) and order will be broken again; the system will then enter a new round of evolution.

However, it is impossible to achieve complete coordination between human and natural subsystems, and regional development will also not be absolutely coordinated, that is, evolution of the Rubik's cube is difficult to achieve uniform in color for every sides. In reality, the system constantly dynamically fluctuates and is always in an intermediate state between order and disorder, steady state and unsteady state; this is also the general law of evolution of most complex systems in nature (Figure 3). To make the human and natural system as orderly as possible, the order parameters which have the greatest influence on the overall evolution of the system should be selected for regulation. For example, water, reflected by green in the Rubik's cube in Figure 3, is the order parameter in the arid area; thus, the green side should be adjusted preferentially.

4 Four dimensional framework of CHNC

4.1 Spatial dimension: Pericoupling and telecoupling between humans and nature

From the perspective of the areal space dimension, the coupling between humans and nature can be divided into two categories: pericoupling and telecoupling. Most current research refers to pericoupling, which mainly focuses on the coupling mechanism between subsystems, as well as the elements within a particular areal system. Pericoupling includes different linear and nonlinear coupling mechanisms, and many papers and books have been written in this field (Fang *et al.*, 2016b; Glaser *et al.*, 2012; Marzluff *et al.*, 2008).

Telecoupling refers to the interactions between humans and nature in different remote areal systems, or at different spatial scales. Compared with pericoupling, the telecoupling is lack of systemic research, and its coupling mechanism is more difficult. However, in the last ten years, many scholars have paid considerable attention to this field. Telecoupling is different from teleconnection in simple natural systems (Liu *et al.*, 2013), such as the teleconnections about monsoon rainfall variations over South and East Asia (Kripalani and Kulkarni, 2001). Telecoupling is also different from economic globalization, such as the impact on American employment from the Indian IT services outsourcing industry (Friedman, 2005). Telecoupling for humans and nature in this paper emphasizes the remote bidirectional feedback between the natural and socioeconomic systems, and it includes the impact of the local eco-environment on inhabitants far away, as well as the impact of local human activities on the remote eco-environment. Unlike Liu's definition, we divide telecoupling into two categories: multi-regional telecoupling (MRTC) and multi-scale telecoupling (MSTC).

4.1.1 Multi-regional telecoupling

MRTC refers to the long-distance interaction and promotion between human and natural systems in different areal systems through various flows, including people, materials, energy, and information. For example, fruit, vegetables, meat, eggs and other foods in big cities come from other small and medium-sized cities, or even other countries. This has a long-distance impact on land use, water security, carbon emissions, and the ecosystem health (Fang and Ren, 2017; Zhao *et al.*, 2015), and even on environments of food importing country (Sun *et al*., 2018). The energy consumption of heavy industry in Hebei Province in China has a significant impact on air quality in Beijing, even in Korea and Japan (Lee *et al.*, 2013; Liu *et al.*, 2017b). Water diversion has resulted in telecoupling between water supply areas and demand areas in aspects of agriculture, urbanization, and groundwater (Liu and Yang, 2013). Since the Belt and Road Initiative was put forward, the trade volume between China and related countries has increased sharply. China's rapid economic growth means that more energy and minerals are needed, which will impact the ecological security of exporting countries (Liu *et al.*, 2018a).

4.1.2 Multi-scale telecoupling

MSTC refers to the interaction coupling between human and nature systems at different scales, which can be divided into two paths: top-down and bottom-up (Figure 4). In general, the coupling between systems with similar scales is more frequent and intense, such as that between the urban agglomeration and urban scales. The occurrence rate of coupling between systems with very different scales is relatively small, such as at the national and block scales. In analysis of the multi-scale interaction telecoupling mechanism, attention should be paid to the scale effect of coupling. There are great differences in forms of expression and measurement indicators for humans and nature at different scales. In addition, as shown in Figure 4, urban agglomerations and cities are mesoscale areas between national macro-strategy and micro-implementation subjects (Li, 2016). Regional synergy of industries and regional linkage of environmental governance should be completed at the mesoscale, which is the

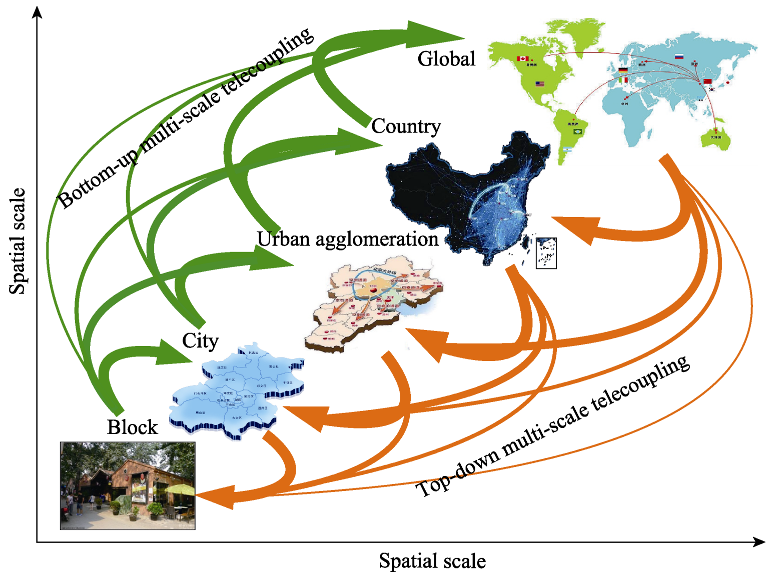


Figure 4 Cross-scale telecoupling

node of scale transformation and multi-scale coupling, having its own special scale attributes in politics and economy (Brenner, 2000). Generally, top-down multi-scale coupling is more common. For example, the impact of global climate change on local urban development and pollution control is a typical case of global scale affecting local scale (Adachi *et al.*, 2013; Liu *et al.*, 2017b). Bottom-up multi-scale coupling is also widespread, such as the disordered urban expansion in central Inner Mongolia, which will aggravate land desertification and affect the ecological security of the whole of Northeast Asia (Xiao *et al.*, 2017).

4.2 Time dimension: Syncoupling and lagcoupling between humans and nature

From the time dimension, the coupling between humans and nature can be divided into syncoupling and lagcoupling. Current research mainly focuses on the interaction between humans and nature in similar time sections. In quantitative analysis, it is customary to compare natural and human variables in the same time section, and then to analyze the causal relationship between them. In this paper, an interaction effect occurring in a similar time section is called "syncoupling." This kind of analytical path has been a classical research paradigm for a long time.

However, because social and economic development have a long dynamic process, and nature has its own evolutionary direction, the development of the two systems is path-dependent. Many forces are time lagged. Sometimes the input of new materials, energy, and information may immediately break the original equilibrium structure; but at other times, due to system resilience, it takes a long time for forces to accumulate before showing themselves to be effective. Therefore, the current state of CHANS may be the result of fluctuations in a subsystem or variable many years ago. Similarly, the current social and economic development of humans may have a lagging impact on the local or larger regional eco-environment in the future (Mcdonald *et al.*, 2008); current natural changes will also affect human survival in the coming years (Zhang *et al.*, 2007). Therefore, we call the interaction and feedback between the human and nature systems in different time periods "lagcoupling," in which the causal chain has relatively long time intervals.

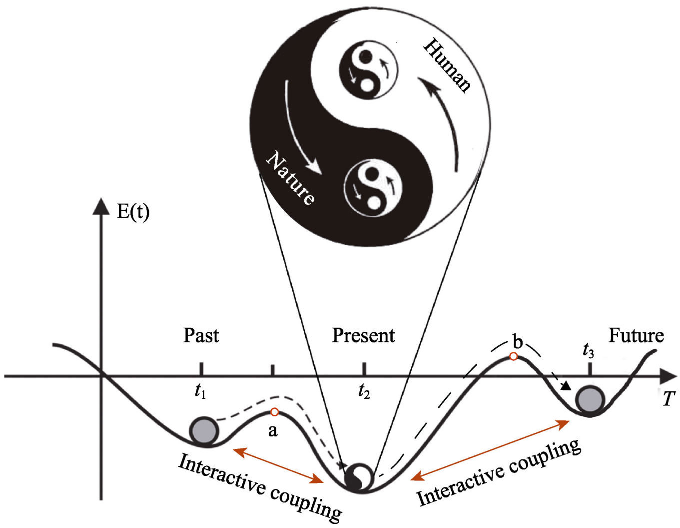


Figure 5 Syncoupling and lagcoupling of human-nature systems

Figure 5 shows a conceptual map of syncoupling and lagcoupling between humans and nature. The coupling system is represented by a nested Taiji Diagram, which reflects the multi-scale of the CHANS and the interaction between the two subsystems. In the coordinate system, T is the time axis; $E(t)$ entropy value; t_1, t_2 and t_3 the three stable states of the coupled system, which represent the past, present and future of the CHANS, respectively. There are many long-term human-nature interactions between the three time periods. In addition, the system is more stable in t_2 than in t_1 or t_3. When the fluctuations (driven by factors such as human activities, climate change, and natural disasters) are strong enough, the CHANS can cross the barriers (a, b) and tend to a new stable state, generating emergence.

Lagcoupling is a common phenomenon in nature, and is of great significance for examining the real causal relationship between human activity and environmental change. Because of the irreversibility of time, most lagcoupling phenomenon is the influence of the past on the present or the present on the future. For example, land use change in Asia over the last 200 years has resulted in substantial negative ecological consequences, including increased anthropogenic CO_2 emissions, deteriorated air and water quality, alteration of regional climate, an increase in disease, and a reduction in biodiversity (Zhao *et al.*, 2006); Cocoa farming has been a major driver of deforestation in West Africa, contributing to an ever-increasing drying of the climate in a positive feedback cycle–a hotter, drier future climate would likely continue to push cocoa farmers into the wetter southwest of the sub-continent (Ruf *et al.*, 2015); the current upgrading of China's industrial structure and energy structure will have a positive impact on air quality years later (Fang *et al.*, 2015; Zheng *et al.*, 2015). However, there are also some influences of future events on the current system. For example, at the Paris Climate Conference, China promised to peak carbon emissions around 2030, which has promoted China's current industrial transformation and green growth (Mi *et al.*, 2017).

4.3 Appearance dimension: Apparent coupling and hidden coupling between humans and nature

From the perspective of appearance, we divide the coupling mechanism between humans and nature into apparent coupling and hidden coupling. Apparent coupling refers to the direct interaction between subsystems, elements within the CHANS. The causal chain is expressed as A→B, and the external forms can be directly perceived. For example, with the advancement of urbanization in developing countries, urban expansion has directly led to the occupancy of woodland and farmland, and the weakening of ecosystem services (Long *et al.*, 2014); the increase in the number of environmental refugees in the last half century has been directly caused by climate change and environmental pollution (Warner, 2010).

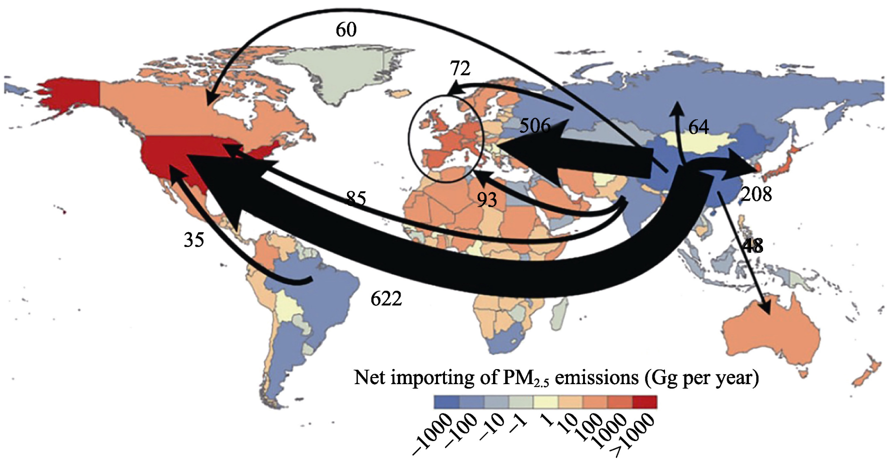


Figure 6 A case of hidden telecouplings: Tele-connecting local primary $PM_{2.5}$ emissions to global consumption

Hidden coupling is the interaction between elements or systems which is indirect, working indirectly through a mediator or through an implied system or element. There are two main forms: One has the causal chain A→C→B, in which C is a mediator. For example, the impact of urbanization (A) on air pollution (B) is mediated by coal combustion (C_1), car emissions (C_2), building dust (C_3), and other mediators; the impact of CO_2 (A) on humans (B) is mainly mediated by climate warming (C_1), and plant photosynthesis (C_2). Another form of hidden coupling can be expressed as A (C)→B. It first seems that there is a direct causal relationship between A and B; however, a real coupling effect occurs between C and B. For example, the pollutants, carbon emissions, and virtual water hidden in regional trade are typical hidden coupling cases (Dalin *et al.*, 2014; Fang *et al.*, 2014). Another example is $PM_{2.5}$ whose emissions and distribution will be affected by consumption in other regions through global production supply chains. About 30% of global industrial production emissions are caused by the production of export products (Meng *et al.*, 2016). These emissions are mainly reflected in exports from developing countries such as China, India and Brazil to developed countries such as the United States and Western Europe (Figure 6).

Moreover, most of the coupling mechanisms between humans and nature involve both apparent and hidden relationships. Like an iceberg in the ocean, such a mechanism consists of two parts: the surface part and the underwater part. Additionally, direct causality at the current cognitive level may well also imply indirect causality due to various mediators. There are also some chain reactions such as A→C→D→···→B, which are similar to the "butterfly effect." Therefore, apparent coupling and hidden coupling based on the causal chain are unities of opposites.

4.4 Organization dimension: Intra-organizational coupling and inter-organizational coupling between humans and nature

The type of organization discussed in this paper is a group with similar values formed by people's self-organizing cooperation and competition, in order to achieve certain goals in the process of human development. The values here mainly refer to the trade-off between social economic development and the eco-environment. Governments, NGOs, academics, media, companies, and local community organizations make up different interest groups. Some organizations can also be further subdivided; for example, most governments have departments such as economic development, ecological environment, natural resources, urban construction, water conservancy, energy, and other functional departments, which constitute different political ecologies (Adger *et al.*, 2001; Zimmerer and Bassett, 2003). The cultural, institutional and living environments of each organization are different, leading to different levels of attention and types of decision-making from individuals within different organizations. As a result, different organizations have different values and behaviors, and hence, different coordination mechanisms within the context of the human-nature relationship (Agyeman *et al.*, 2002; Dietz *et al.*, 2003). Organizational behavior will affect the related eco-environment, meanwhile, the eco-environment will in turn affect organizational behavior and human activities.

From the organization dimension, this paper divides the coupling between humans and nature into two categories: intra-organizational coupling and inter-organizational coupling. Intra-organizational coupling refers to the interaction between humans and nature in a particular organization. For example, when dealing with the relationship between economic development and the ecological protection, the department of finance would probably rate GDP as of first importance, while the environmental protection department would highly prioritize environmental protection and governance. The media will mainly focus on prominent contradictions in human-nature relationships (such as Amazon rainforest deforestation[①], and the cancer village[②]) to enhance news viewership and readership as much as possible. The enterprise will focus on maximizing its own economic benefits. Because in intra-organizational coupling the members are mainly in the same interest group, the conflict is relatively small. Therefore, the research objects and goals are clear, and it is easy to grasp the core issues for analysis.

Inter-organizational coupling refers to the complex interest game strategy to tradeoff economic development and environmental protection between different organizations and stakeholders. Figure 7 is a schematic diagram of inter-organizational coupling. The CHANS

① https://www.bbc.com/news/world-latin-america-46327634
② https://www.theguardian.com/world/2013/jun/04/china-villages-cancer-deaths

is still represented by an open and continuously rotating sphere, which contains different organizations, such as the public, government, media, enterprise, scholars, and NGOs. Most of the eco-environmental issues involve multiple stakeholders playing a complex dynamic evolutionary game (Bäckstrand, 2003; Wu *et al.*, 2017). Compared with intra-organization coupling, the factors in CHANS driven by different organizations are more complex. How to achieve equity and sustainability between different organizations is a complex interactive question (Leach *et al.*, 2018). The direction and speed of the coupling sphere are determined by the joint efforts of the public, government, media, enterprise and other organizations. Self-organization and other-organization driving forces exist simultaneously. In the evolution process of the coupling sphere, the number of organizations involved, and the forces of different organizations will change accordingly. For example, in the early stages of industrialization of Europe, environmental governance was not given enough attention, and NGOs did not emerge. In the middle and late stages of industrialization, the power of environmental protection organizations gradually increased. Inter-organizational coupling between humans and nature affects the formulation and implementation of climate and environmental governance decisions and further affects overall social development and human wellbeing (Newig and Fritsch, 2009).

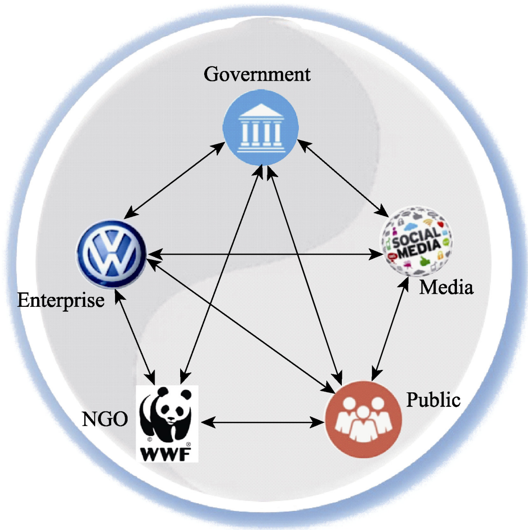


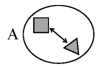
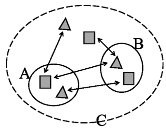
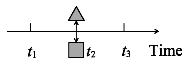
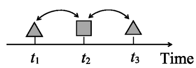
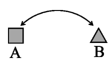
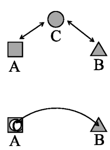
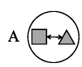
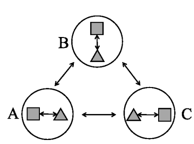
Figure 7 Inter-organizational couplings of human-nature systems

There are many examples of inter-organizational coupling, for example, the attention and participation of citizens to the eco-environment for different stakeholders has a significant impact on the local environmental governance (Fu and Liu, 2017; Xu *et al.*, 2006). Stakeholders such as government, farmers, media, NGOs, and scholars have different roles and behavioral responses in the mechanism of ecological compensation (Liu *et al.*, 2008). With the gradual change in the environmental management paradigm, from management and participatory management to governance, the collaborative environmental governance model, with multiple social agents, has been strengthened (Armitage *et al.*, 2009; Bodin, 2017).

4.5 Comparison of four-dimensional coupling types in CHNC

Based on the above analysis of the four dimensions of CHNC, we further summarize the basic meanings, conceptual sketches, quantitative methods, and typical cases of eight coupling types, including pericoupling and telecoupling, syncoupling and lagcoupling, apparent coupling and hidden coupling, and intra-organizational coupling and inter-organizational coupling. As shown in the conceptual sketches in Table 1, the square represents humans, the triangle nature, the ellipse the areal system, the circle the organization group, and the double-sided arrow represents interaction and coupling. The quantitative analysis methods listed

Table 1 Comparison of different coupling types in the Coupled Human and Natural Cube

Conceptual framework	Analysis dimensions	Coupling type	Concept	Diagram	Research methods	Typical cases
"CHNC"	Space	Intracoupling	Interaction between subsystems, as well as the elements within the particular areal system.		Statistics, coupling degree, coupling coordination degree, etc.	Omitted
		Telecoupling	Interaction between humans and nature in different remote areal systems, or in different spatial scales. Two categories: Multi- regional telecoupling (MRTC) and multi-scale telecoupling (MSTC).		Multi-region input-output model, spatial Durbin model, hierarchical spatial autoregressive model, network analysis, material flow analysis, energy flow analysis, etc.	MRTC: Water diversion, industry transfer, tourism, international trade, technology transfer, investment; MSTC: Local responses to climate change, global diffusion of local pollution
	Time	Syncoupling	Interaction effect between humans and nature occurring in a similar time section.		Statistics, coupling degree, coupling coordination degree, time series analysis, etc.	Omitted
		Lagcoupling	Interaction and feedback between humans and nature in different time periods; the causal chain has relative long time intervals.		Time-delay model, dynamic general equilibrium model, multi-level temporal autoregressive modeling, etc.	The time lag effect of environmental investment on local eco-environment; the 1.5 C global warming target in the Paris Agreement has important effect for current policy.
	Appearance	Apparent coupling	Direct interaction between subsystems; elements within the CHANS and causal chain are A→B		Correlations analysis, linear regression analysis, coupling degree, coupling coordination degree, etc.	Omitted
		Hidden coupling	Interaction between elements or systems is not direct, but works indirectly through a mediator or through an implied system or element, and the causal chain is A→C→B or A(C)→B.		Mediating effects model, multi-region input-output model, environmental footprint, life cycle assessment, etc.	A→C→B: Urbanization has indirect effects on carbon emissions by influencing the structure and intensity of energy consumption; A(C)→B: Pollutants, carbon emissions, virtual water hidden in international trade.
	Organization	Intra-organizational coupling	Interaction between humans and nature in a particular organization.		Statistics, game theory, etc.	Omitted
		Inter-organizational coupling	Complex interest game to tradeoff human development and environment between different organizations and stakeholders.		Game theory, multi-agent modeling, complex adaptive systems theory, multicenter self-organization theory, complex networks, big data analysis, etc.	Stakeholders such as government, farmers, medias and NGOs have different roles and behavioral responses in ecological compensation.

in the table can solve some issues in a particular dimension, which can be used for empirical research (Carlson *et al.*, 2018). For example, telecoupling can be simulated using methods such as spatial metrology, the multi-regional input-output model and the hierarchical spatial autoregressive model (Dong and Harris, 2015). Lagcoupling calculations can refer to a time-delay model or dynamic general equilibrium model, for example. Hidden coupling can be simulated using the mediating effects model (Preacher and Kelley, 2011) and various environmental footprint methods. Multi-agent modeling, complex networks and big data analysis can be used to study inter-organizational coupling (An *et al.*, 2014). Relevant cases within a traditional research framework are omitted, and only typical cases of telecoupling, lagcoupling, hidden coupling and inter-coupling are listed in Table 1.

It should be noted that the eight coupling types of CHNC are relative and dialectical. The length in the space dimension is mainly talked in a particular spatial scale. The length in the time dimension is mostly measured in years in the specific study. The appearance dimension is largely based on a current cognitive level. For the organization dimension, inter-organizational coupling and intra-organizational coupling change with people's values. Therefore, four-dimensional analysis of the CHNC framework should be conducted in a specific application, and the system thinking and dialectical thinking of unity and opposites should be established.

5 Discussion

5.1 Human-nature coupling matrix based on Coupled Human and Natural Cube

Using complexity science and metaphorical analogy, this paper constructs a multi-scale hierarchical nested complex system of the Coupled Human and Natural Cube by making the four dimensions of time, space, organization, and appearance in the analytical framework. This framework is an effective way to analyze the dynamic evolution mechanism of CHANS.

Any CHANS inevitably exists in time and space in the real world, most of which belong to an organization, and have some hidden sides. Therefore, most of the CHANS have the interaction coupling effect of multiple dimensions simultaneously. The four dimensions of the CHNC also exist simultaneously and are dialectically unified. As shown in Table 2, based on practical human wellbeing orientation, the coupling effect of any two dimensions can be expressed by a two-dimensional matrix, which we call the "coupling matrix." For example, the issue of virtual water in cross-regional trade mentioned above is mainly the integration of telecoupling and hidden coupling. The Qinghai-Tibet Plateau, often termed the Third Pole, saw its number of tourists reach 61 million in 2018. Local government, enterprise, Buddhists and tourists place different values on the fragile ecological environment. Meanwhile, the impact of global tourists on the ecology of the Third Pole is becoming increasingly significant. This is an integration of inter-organizational coupling and telecoupling.

In theory, a more complex combined matrix of three-dimensional or four-dimensional coupling effects can also be produced. For example, China's imports of soybeans from the US have increased in recent years, affecting farmers in rival Brazil; meanwhile, environmental groups and scholars are concerned about China's decision to replace soybeans with wheat, corn and other crops, and to apply more nitrogen fertilizer, as well as increase non-point source pollution over time. This example involves multiple interweaved dimensions of telecoupling, lagcoupling, hidden coupling, and inter-organizational coupling. When we deal with similar practical issues, beginning from a system perspective is a good choice. First, we can conduct a macroscopic qualitative analysis of the issue from the dimensions of time, space, appearance, and organization. Then, we can choose one or two dimensions, according to the degree of importance, to solve the most prominent contradictions in the system; that is, to adopt the idea of "systematic thinking, first heavy then light, break through one by one." Therefore, the Coupled Human and Natural Cube provides a relatively clear analytical framework for us to analyze the complex human-nature relationship.

Table 2 Human-nature coupling matrix

Analysis dimension	Space	Time	Appearance	Organization
Space	Intracoupling or telecoupling	Intracoupling or telecoupling + syncoupling or lagcoupling	Intracoupling or telecoupling + apparent or hidden coupling	Intracoupling or telecoupling + intra-organizational or inter-organizational coupling
Time	Syncoupling or lagcoupling + intracoupling or telecoupling	Syncoupling or lagcoupling	Syncoupling or lagcoupling + apparent or hidden coupling	Syncoupling or lagcoupling + intra-organizational or inter-organizational coupling
Appearance	Apparent or hidden coupling + intracoupling or telecoupling	Apparent or hidden coupling + syncoupling or lagcoupling	Apparent or hidden coupling	Apparent or hidden coupling + intra-organizational or inter-organizational coupling
Organization	Intra-organizational or inter-organizational coupling + intracoupling or telecoupling	Intra-organizational or inter-organizational coupling + syncoupling or lagcoupling	Intra-organizational or inter-organizational coupling + apparent or hidden coupling	Intra-organizational or inter-organizational coupling

5.2 Implications of the Coupled Human and Natural Cube

The framework of CHNC is a logical extension of research on coupled human and natural systems from the perspectives of time, space, appearance and organization. It is the development and deepening of human-earth areal system theory in the new era, which makes up for deficiencies in the traditional framework and it has a general significance for studying CHANS. Different from the human-earth areal system, telecoupling, and planetary urbanization, the main contribution of this framework is providing a considerably comprehensive and interdisciplinary conceptual framework to recognize the evolution and coupling mechanism of the human-nature system. This framework can enrich sustainability science (Kates *et al.*, 2001; Clark, 2016), enhance the paradigm of comprehensive geographic research, and help to better assess the evolution mechanism of the complex human-nature system against the background of global climate change and frequent disasters. It provides a new analytical framework for the regulation and optimization of the human-nature system within the context of ecological civilization and sustainable development; it also helps to enhance the effectiveness and sustainability of regional policy formulation.

The CHNC helps form a comprehensive, steric and multi-dimensional system view to cognize the world. It emphasizes that humans and nature are unity of opposites, like two sides of a coin, and they are an organic whole that interacts, depending on and containing each other, constituting our world. This view accords with the concept of strong sustainability, which assumes that man-made and natural capital are basically complements, not substitutes (Wu, 2013).

This framework focuses more on positive and negative feedback, spatial spillover, mediating, time lag, stakeholder effects, and so on. When exploring the coupling mechanism of the human-earth system, it helps us to have a holistic view. A comprehensive analysis, involving the analysis of the hidden interactions, "the submerged part of the iceberg," such as telecoupling, lagcoupling, hidden coupling, and inter-organizational coupling is crucial when regulating the relationship between humans and nature; merely assessing the surface interactions provides a grossly incomplete picture of this relationship. In governmental decision-making, emphasis should be placed on evaluating and balancing the intracoupling and telecoupling, syncoupling and lagcoupling, apparent coupling and hidden coupling, and intra-organizational coupling and inter-organizational coupling effects between the social economy and eco-environment.

The CHNC inspires us to rethink the first law of geography of Tobler in the information age (Tobler, 2004). In many cases, two systems that are far apart may be closely related; conversely, some systems are close, but their connections are weak because they exist in different organizations. In the new era, telecoupling and hidden coupling may have posed certain challenges to Tobler's first law. How to reappraise the first law of geography and develop it, with the possible introduction of new rules, is worth further consideration.

5.3 Quantitative research on the Coupled Human and Natural Cube

This paper has proposed a preliminary conceptual framework. How to measure and simulate the CHNC using specific quantitative models is also an important issue. For each dimension, quantitative analysis methods are found in Table 1. For the evaluation of the overall evolution of the CHNC, the law of thermodynamics and the concept of information entropy may be used. With the development of complexity science, system dynamics, big data, and artificial intelligence, quantitative models of different dimensions should be integrated within the framework of CHNC to gradually form a set of useful methods including description, simulation, prediction, and evaluation (Li *et al.*, 2018). In the future, the analytical framework and quantitative methods of the CHNC will be used in typical practices to further perfect the theory, and to render it more applicable in the field (Xiang, 2016).

6 Conclusions

(1) The conflict and disharmony between humans and nature are the root causes of global ecological and environmental problems. The socio-economic system and natural system have their own evolution laws and constraints. Through continuous material circulation, energy flow and information transmission, humans and nature form a giant, complex, coupled system, comprised of interrelated elements supported and constrained by each other. Through interactions with the external environment and subsystems in a certain time and space dimension, the evolution of the coupled system is based on a self-organizing fluctuation process from chaotic state to orderly structure. Normally, the system is in a mid-state between order and disorder

(2) Inspired by theories, including the human-earth areal system, telecoupling framework

and planetary urbanization, we extend the connotation of the coupled human and natural systems (CHANS) and its four dimensions—space, time, appearance, and organization, and a novel framework, “Coupled Human and Natural Cube (CHNC),” is proposed to explain the coupling mechanism between human and natural environments. There exist various “coupling lines” in the CHNC, which connect different systems and elements at multiple scales, forming a larger, nested, interconnected, organic system. The rotation of the Rubik's cube represents the spatiotemporal nonlinear fluctuation of the CHANS. When the color of each surface is the same, all subsystems are developing synergistically in different regions. As the system continually exchanges energy with the environment, a critical phase transition occurs when fluctuation reaches a certain threshold, leading to emergent behaviors of the system. The system can now become more orderly or collapse into the next cycle.

(3) The CHNC is interrelated and dialectically unified in the four dimensions of time, space, organization, and appearance, and includes eight types of coupling: intracoupling, telecoupling, syncoupling, lagcoupling, apparent coupling, hidden coupling, intra-organizational coupling, and inter-organizational coupling. Telecoupling refers to the interactions between humans and nature in different remote areal systems, or at different spatial scales. Lagcoupling refers to the interaction and feedback between human and nature systems in different time periods, in which the causal chain has relatively long time intervals. Hidden coupling is the process of interaction and influence between elements or systems that is not direct but works indirectly through a mediator or through an implied system or element. Inter-organizational coupling refers to the complex interest game strategy to trade-off economic development and environmental protection between different organizations and stakeholders. This paper also summarizes research methods and typical cases of different coupling types. Finally, based on the CHNC, we put forward a general analysis framework of the human-nature coupling matrix to integrate multiple dimensions. Facing the complex human-nature system, we should follow the analytical paths of “systematic thinking, first heavy then light, break through one by one.”

Acknowledgments

The authors thank Danian Ye, Dadao Lu, Hanying Mao, Jianguo “Jack” Liu, Yi Liu, Changqing Song, Jianguo Wu, Yuming Shen, Pengjun Zhao, Shenghe Liu, Shaoqiang Wang, Yu Yang, Ruiqi Li, Bingbing Zhou, Yanxu Liu, Yueyue Du for their significant suggestions and comments.

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