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Assessing China's human-environment relationship

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Abstract: China's coupled human-environment system (CHES) is assessed here via a systems schema that emphasizes the complex interactions of components and their attributes. In addition to the human and environment components, we identified two other components to evaluate the relationship. The four components are human activity intensity, resource carrying capacity, ecological constraints and system's openness. Based on their interactions, we derived a cognitive schema for classifying the level of strain or stress of an area. The analysis draws on 11 indicators and 29 sub-indicators including remote sensing data and statistical data that are used to estimate the four components. The findings indicate that human activities are highly intense in a few geographical areas, particularly large urban systems and trade and investment zones on the eastern coastal areas. Nonetheless, these areas are also well-endowed in water resources and fertile soils although urban systems are increasingly stressed from negative pollution externalities. They are also open systems which allow them to bear a higher level of pressure and adjust accordingly. Desertification and soil erosion point to relatively fragile biophysical systems in the west and southwest, but human activities are still relatively less intense compared to their coastal counterparts. As a whole, only 14% of areas may be said to be relatively or highly strained. This however belies another one-third of areas that are currently unstable, and likely to become strained and thereby vulnerable in the near future.

Keywords: coupled human-environment relationship; systems; human activity intensity, resource-carrying capacity; ecological constraint; openness; China

1 Introduction

Studies of the relationship between human activities and the natural environment have gained currency in the past two decades (Yang and Mei, 2001; Turner II *et al*., 2003; Wu,

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2008; Harden, 2012; Galvani *et al*., 2016). As developing countries compete and scramble for resources, uncontrolled global and regional environmental pollution, food insecurity, climate change, urban sprawl, poverty, and unsustainable development have become central concerns in human-environment (H-E) studies (NRCNA, US, 2010; Harden, 2012). Such stresses are expected to rise in developing countries with large populations and that have yet to peak in their industrial transition. More specifically, H-E studies have highlighted issues of regional vulnerability and sustainability as scholars examine issues related to economic and social provisions of humankind that do not threaten nature's support system.

Turner II (2003, 2010) maintains that humans and the environment are necessarily coupled (CHES) as part of subsystems that link environmental services to the economic livelihood of humans. CHES framing suggests that a systems approach to understanding the coupled nature of the subsystems of H-E may be useful in the context of China where the intersection between rapid and sustained economic development, atmospheric pollution and fragile ecosystems is attracting attention (Wang *et al*., 2006). It also points to both regional and national scales of the earth system that identify various components of environmental services including functions associated with economic development, and, assessment of hazards and biophysical degradation. Despite a burgeoning literature on the human-environmental relationship, there is scant work that uses features of systems framing to evaluate the tradeoffs and interrelationship between the two subsystems in a developing country such as China. Yet it is becoming clear that China's rapid economic growth in the past three decades has likely increased the fragility of economic-natural systems that in turn calls into question just how the H-E system is to be managed. While some H-E system-related research was attempted in the 1990s (Wu, 2008), much of it focused on single (Fu *et al*., 2001; Liu and Chen, 2002; Liu *et al*., 2003; Chen, 2009; Liu *et al*., 2011; Li and Li, 2012; Sun *et al*., 2012; Liu *et al*., 2012; Zhang *et al*., 2014; Xu *et al*., 2015) than multiple components and their interrelatedness (Yang and Liu, 2016; Li *et al*., 2017). The scale of the study also tended to be local while it is becoming apparent that synthesis of various components at both regional and national level is relevant for understanding China's geography of ecological vulnerability that improves surveillance and governance.

This paper will attempt to address this lacuna. Under CHES, many dimensions and variables affect the sustainability of human and environmental subsystems. We develop a conceptual schema that help to abstract if not capture the essential elements of the way that the two subsystems interact. More specifically, this paper will attempt to assess the state of the H-E system that could potentially help shed light on the geography of regional vulnerability, that is areas in China that are experiencing harm from ecological and resource strain, pressure and stress (Liu *et al*., 2016). While early systems theories privilege closed systems of negative feedbacks that lend themselves to mathematical modeling, this paper draws on subsequent notions of soft systems that emphasize the more cognitive nature of systems approach, and the latter's openness (Nir, 2002). The usefulness of a softer form of the systems approach lies less in formal modeling here than in providing a cognitive schema for decomposing the H-E interrelationship in CHES. Furthermore, Moran (2005) has pointed out that such an approach requires a wealth of data and information demanding considerable interdisciplinary and team collaboration. This is the case here involving two main teams who collaborated on the collation of a large amount of data and mapping. This consisted of 9 indicators and another 29 sub-indicators which are condensed in Appendix 1.

2 Conceptual framework

Coupled human-environmental systems (CHES) recognizes reciprocal interactions and feedbacks between humans and their socio-economic activities, and the natural environment (Turner II *et al.*, 2003). While the world is ultimately the CHES system that scholars are interested in studying, they also recognize that it is made up of smaller systems across space and regions (Liu *et al.*, 2016). CHES is multi-tiered consisting of many components and sub-components that interact with one another. Moreover, the interactions can weaken or strengthen over time as both humans and the environment co-evolve. CHES prioritizes concerns of well-being, hence it is interested in issues of sustainability (Turner, 2010). Tian (2017) notes that well-being under CHES emphasizes the development of humans and their livelihoods, and the response of the natural environment to and from such activities. As many factors can influence the H-E relationship and CHES well-being including natural resources, human migration, pollution, desertification etc., Tian (2007) argues that a systems approach is helpful for distilling both the economic and environmental contexts by which human agents interact with their environments. It is important to note that well-being here refers not just to human well-being but also environmental well-being given the relevance of the latter in supporting people's livelihoods (Turner, 2010).

The systems approach rests on the premise that the earth system is made up of a large number of elements that interact with one another (Skyttner, 2005). Such interactions may be analyzed at the level of the region as a region constitutes a complex system that represents part of the earth system. The regional system may be decomposed into components and subsystems that bear some degree of internal coherence. But a systems approach also means that subsystems are not isolated components but part of a larger whole. Nir (1990) has long noted that the region is a relevant unit for studying the human-nature environment system because many elements characterizing a system may be found in a region. This includes population, communities, cities, agricultural and manufacturing production, ecological subsystems, etc. The collapse of the Maya in the Southern Lowlands region from drought for example may be understood using complex systems approach (Roman *et al.*, 2018). Others point to the usefulness of systems studies in warfare frequencies between clan communities in certain highland regions by examining their regulation of animal herds and horticultural fallow cycles (Moran, 2011). Indeed, the above illustrates just how wide the range of studies of human population, communities and the environment in regions may be using systems understanding of CHES. In this paper, we suggest that both the regional and national scales matter because the latter allows us to examine interactions between regions.

Human agents and their activities as well as the natural and physical environment constitute a complex interactive system. As social and economic forces gather force in an industrializing nation such as China, the ability of humans to influence environment-related factors of production has increased. Traditionally, the physical and natural environment is seen to be a container of resources that may be exploited to support human activities. Under CHES, pressure generated by human action directly affects the level of H-E well-being. The environment cannot support persistent intensive human activities indefinitely without cost to its well-being. As Turner II (2010) points out, CHES involves tradeoffs from human activities including losses from rising levels of pollution or land lost to desertification. Once an environmental regime's carrying capacity is exceeded at a given level of technology, this upsets the H-E balance and generates negative externalities. Hence some scholars have suggested that the human and environment subsystems compose of observable parts that interact to constrain one another (Newell *et al*., 2005). In this sense, the environment is not simply a container of resources; it can also constrain human activities and affect the provision of resources via the ecological system. The H-E relationship is not uni-directional so that causality flows from human to the environment but circular and dynamic as both components interact with one another. Indeed more recent systems thinking argues for bi-directional influences as shown in Figure 1 (Newell *et al*., 2005). The limits of ecosystems are increasingly being appreciated in China. A major criticism has been the country's relentless focus on economic growth that has begun to take a toil on humans and their well-being as the environmental subsystem begins to exhibit signs of degradation in the form of atmospheric pollution, drought and desertification (Wang *et al*., 2006; Wang *et al*., 2017).

As suggested above, environmental resources and services as well as human activities may be seen as an open system with important interactions between regional systems. Such interactions may involve exchanges between a city or urban system and its hinterland. Flows between municipalities and regions may be generated including human migration circulation as well as investment and trade networks. Liu *et al*. (2016) further argues that different coupled systems in different areas may also interact with one another. Whereas Socialist China constructed a number of administrative units that favored self-sufficiency and that were closed to global economic flows, the country's increased integration to international trade and investment networks in the past 20 years has led to unprecedented large-scale construction of transport networks that better connect regions to markets. Transport infrastructural development has in turn facilitated human migration and regional movements of economic activities as well as the ability to allocate resources between regions. Inter-regional interactions have the effect of transferring pressures and potentially easing local pressure and limited carrying capacity (Yu, 1991). For instance, population pressure in one area may now be alleviated through out-migration to another area. Hence, openness should be part of the H-E systems framework as shown in Figure 1.

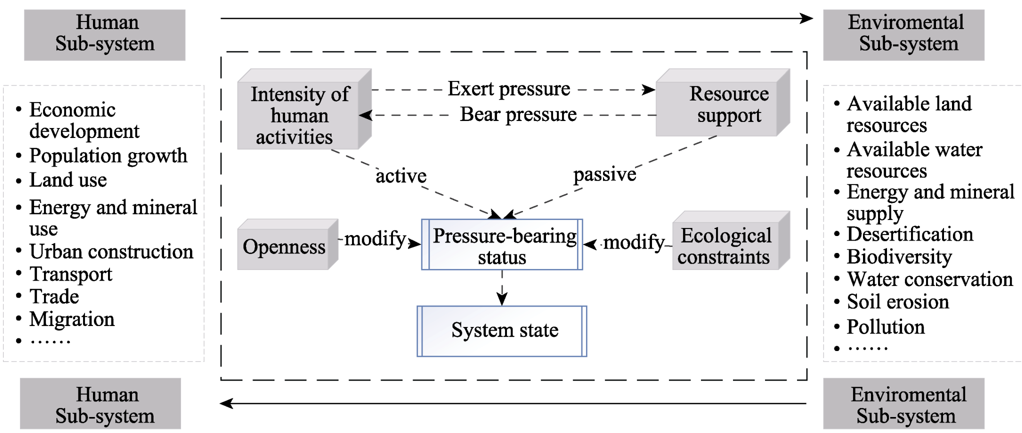

Figure 1 Components of the process of CHES well-being

Figure 1 summarizes the systems approach to CHES. The well-being of CHES at a given region in China depends on both human as well as biophysical or ecological processes and constraints as well as exogenous factors such as use of land for construction and urban development. These may be captured in four components, namely human activity intensity, resource support and its carrying capacity, ecological constraints, and the openness of the system. The first two components, that is intensity of human activities and resource support level, directly determine the capability of a region's environment. The economic action of humans exerts pressure on the environment but the capacity of the environment to withstand and support pressure inflicted by such actions is also greater with when the region's resource level is higher. Not surprising, the ability of a regional system to absorb and support human activities at a given resource level is influenced by ecological and biophysical constraints. Such constraints vary in space. At the same time, constraints may be offset by openness in the system if the system is able to ease constraints by transferring pressures and stresses exerted (e.g. population pressure) to another region. The more open a region, the larger the resource shift and the stronger the ability to alleviate strained capacity by transferring pressure to another region. In turn, openness encourages positive feedbacks that can help the system to maintain some level of steady state. Transfers help replace lost energy or information flows (for example in-migration alleviates scarce knowledge in a region). But constraints can also be exacerbated when inter-regional transfer adds pressure or stress to a neighboring region. As in the other three components, openness varies spatially and hence needs a classificatory scheme.

Next, we construct a taxonomy that attempts to take stock of the state of H-E well-being at the systems level (Figure 2). Tuner II *et al*. (2007) observed that there has been much progress in taxonomical exercises on land use changes. Yet assessments of CHES subsystems and their spatial arrays remain under-researched in the context of China. There is little work that quantifies the spatial extent of vulnerable areas that in turns allows for surveillance, monitoring and sensible land-use management. The goal of this paper is to develop such a taxonomy from systems interactions and understand CHES' explicit spatial outcomes, the latter of which is emphasized by Turner II *et al*. (2007). The Chinese government is paying attention to classificatory schemes as officials struggle to understand the regional implications of nearly four decades of post-Socialist economic growth and development. Indeed, one implication of the taxonomical analysis below is that it can aid policies by building information flows between academic scholars and government officials. It is fair to say that some of the data here are confidential. The Chinese government's amenability to the authors' report of the data at aggregate levels demonstrates their interest in trying to understand the coupled nature of humans and environment that contributes to more sustainable regional governance.

Overall, the assessment at the systems level resulted in five categories to describe the relationship, namely, "very unstrained, relatively unstrained, relatively balanced, relatively strained, and very strained". On the one end of the H-E relationship are areas that are still relatively unharmed and remain important sources of environmental services for human well-being. On the other end of the relationship are areas that may have reached or surpassed their environmental capabilities. These areas are highly strained and may be vulnerable to harm from ecological and resource degradation that in turn negatively impacts human livelihood and well-being. The "relatively balanced" category is subdivided further based on the stage of economic development and the resource carrying capacity of regions. They are: (i) "high level of balance", (ii) "antagonistic balance" and (iii) "low level of balance". When a

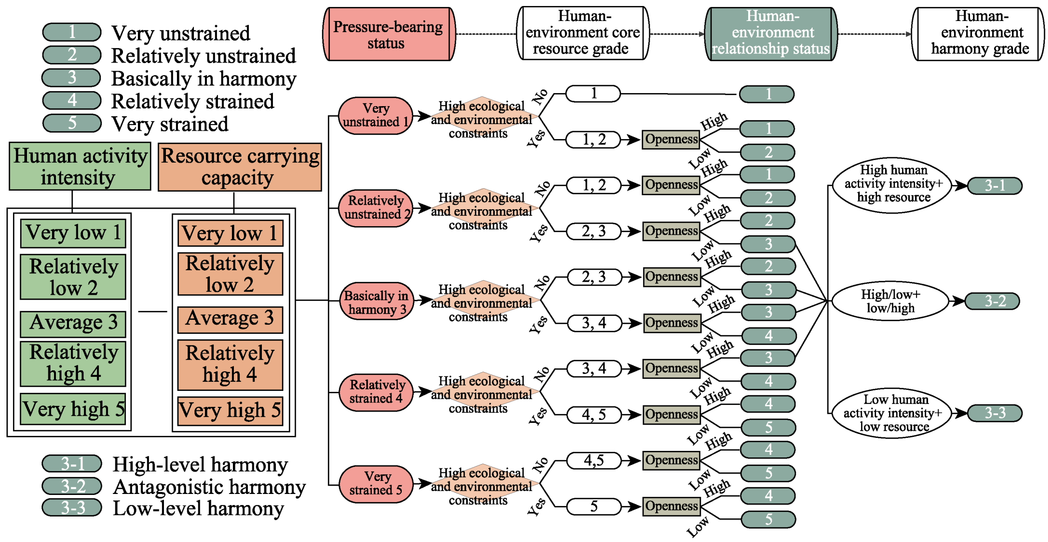

Figure 2 Framework for evaluating the H-E well-being

region is defined by high carrying capacity and high economic development level, it is said to have a high level of balance. When the region is underscored by both low carrying capacity and economic development level, we characterize it as "low level of balance". When the two indicators are opposite to one another – for example, a region is characterized by high economic development but low carrying capacity – then "antagonistic balance" is the outcome. Under antagonistic balance, the state of the H-E system is likely to be unstable and become vulnerable (Figure 2).

3 Operationalizing and measuring H-E systems components

Figures 1 and 2 outlined the major dimensions in understanding a region's H-E well-being in China. They are intensity of human activities, carrying capacity of core resources, level of ecological and environmental constraints, and openness of the system. This section will describe each component in greater detail.

3.1 Intensity of human activities

The expansion or growth of the economy and population affects H-E well-being through their effect on people's livelihoods and sustenance. Three indicators may be used to measure these activities, that is economic development level, population intensity, and land development intensity. Rather than use per capita income as is typically the case in examining economic development, this study will rely on an economic intensity indicator that is obtained by dividing a region's gross domestic product (GDP) over its land area. As construction activity is a good example of how exogenous human activity impacts land, the amount of construction land area as a proportion of an administrative area is used to measure land development intensity. Indeed Wang (2004) shows that construction activity is a large energy and carbon dioxide emitter.

Construction also decreases available green land and leads to the loss of water resources. A three-dimensional vector distance method is used to calculate the common effect of the three elements. From the above dimensions, human activities intensity (HAI_i) index may be derived using the formula below:

$$HAI_i = \sqrt{1/3(PI_i^2 + EI_i^2 + LI_i^2)} \quad (1)$$

$$PI_i = \frac{P_i}{A_i} \quad (1\text{-}1)$$

$$EI_i = \frac{E_i}{A_i} \quad (1\text{-}2)$$

$$LI_i = \frac{C_i}{A_i} \quad (1\text{-}3)$$

where HAI_i is the intensity of human activity of area i, and PI_i, EI_i, LI_i are population intensity, economic development intensity, and land development intensity of area *i*. P_i, E_i, C_i, A_i are the total population of permanent residents, economic output (GDP), land area under construction, and total area, respectively, of a region. It should be noted that economic development intensity and land development intensity are relative concepts as there is considerable variation in land area size. Nevertheless, they are reasonable indicators that act as proxies of an area's capacity to bear or withstand pressures arising from human activities as outlined in Figure 1.

3.2 Resource carrying capacity

Diverse resources provide basic guarantees and support for the healthy and sustainable evolution of the H-E system. It is not possible to evaluate every resource hence we will attempt to identify important core resources that have supported China's post-1980 economic development. In particular these resources are in relatively short supply such as land and fresh water, or are non-renewable like energy and mineral resources. We then evaluate the carrying capacity of these core resources individually and as a whole. To eliminate differences in population size between regions, we used per capita values. This results in the following resource indicators: (i) land per capita (land area is based on interpretation of remote sensing data and that is available and suitable for construction divided by resident population; (ii) water per capita where water refers to available local, inbound and exploitable water resources (available water volume in cubic meters divided by resident population); and (iii) energy and mineral resources per capita (industrial output in GDP divided by resident population). Given that land, water, and, energy and mineral are important resources in supporting China's economic development, they are given equal weighting such that:

$$RCC_i = \sqrt{1/3[L(P)_i^2 + W(P)_i^2 + M(P)_i^2]} \quad (2)$$

$$L(P)_i = L_{si}/P_i = [(G_i \cap A_i) - (A_{wi} + A_{wli} + A_{gi} + A_{di} + A_{ri} + A_{fi})] / P_i \quad (2\text{-}1)$$

$$W(P)_i = W_{si} / P_i = [(W_{sfi} + W_{gi})] / P_i \quad (2\text{-}2)$$

$$M(P)_I = M_{si} / P_i \quad (2\text{-}3)$$

where RCC_i, $L(P)_i$, $W(P)_i$, and $M(P)_i$ denote the resource carrying capacity, available land per capita, available water per capita, and, energy and mineral resources per capita respectively of area *i*. Ls_i is the land area suitable for construction, obtained by superimposing the natural and geographical conditions of gradient (G_i) and altitude (A_i) on land use types, and removing bodies of water (A_{wi}), woodland (A_{wli}), grassland (A_{gi}), desert (A_{di}), restricted development zones (A_{ri}), and forbidden development zones (A_{fi}) to estimate the amount of areas that is suitable for human activities; W_{si} refers to available water (calculated as the sum of average annual surface water and groundwater); and M_{si} is available energy and mineral resource measured in industrial outputs. M_{si} comprises ten sectors including mining and coal cleaning, extraction of petroleum and natural gas, mining and processing of ferrous metal ores, mining and processing of non-ferrous metal ores, mining and processing of non-metal ores, processing of petroleum and coking and processing of nuclear fuel, manufacture of non-metallic mineral products, smelting and pressing of ferrous metals, and, smelting and pressing of non-ferrous metals, manufacture of metal products.

3.3 Ecological constraints

Constraints of ecological systems indicate the importance of structural functions as well as the environmental capacity of a region (Xu *et al*., 2016). Ecosystems are affected by the negative consequences of human activities, hence they are relevant for understanding the level of H-E well-being. A system that is subjected to intense human economic activities is vulnerable to pressure. An ecosystem that is under high pressure is also likely to become imbalanced. Taking into account the upper limit of development of an ecological system, and with no damage to the quality of the ecological system as the lower threshold, the level of pressure that an area is experiencing depends on its ecological fragility, ecological significance, and environmental capacity. The notion of an ecological threshold is an important concept in CHES as it helps to define some level beyond which harm is likely to lead to vulnerability (Liu *et al*., 2016). The selection and integration of these pressure system indicators is drawn from data collated by Xu *et al*. (2016) and the Ministry of Environment Protection (2014). Ecological constraints may be expressed as:

$$EC = f_{max}\ \{ECO_f,\ ECO_s,\ EC\} \tag{3}$$

$$ECO_f = max\ \{SE_v,\ SD_v,\ D_v,\ SS_v\} \tag{3-1}$$

$$ECO_s = max\ \{WC_i,\ SC_i,\ WSC_i,\ B_i,\ SE_i\} \tag{3-2}$$

$$ENC = ENC_s - ENC_p \tag{3-3}$$

where EC is the ecological constraint, ECO_f is the fragility of the ecosystem, ECO_s is the significance of the ecosystem, and ENC is environmental capacity. SE_v, SD_v, D_v, and SS_v stand for soil erosion vulnerability, stony desertification vulnerability, desertification vulnerability, and soil salinization vulnerability respectively; WC_i, SC_i, WSC_i, B_i, and SE_i refer to the importance of water conservation, soil conservation, wind prevention and sand fixation, biodiversity, and special ecosystems. It is worth mentioning that given the multi-level nature of components and subcomponents in CHES, ECO_f, ECO_s and ENC are derived from further sub-classification of environmental attributes. For example, ECO_s is estimated from its sub-components as follows: First the importance of water conservation WC_i is obtained by classifying river basins into three kinds of basins. Each basin is in turn subdivided into four types of biophysical systems namely forest, wetland, grassland and desert. The four systems describing the country's biophysical sphere are then mapped on to a 1-km grid. In the next step, water conservation data is overlaid on the grid cells and its importance is rated "low", "average" or "high" depending on the extent of water conservation. Likewise, ENC is made up of two sub-components. The first ENC_s refers to the national standard for environmental performance and the second ENC_p is the environmental quality of the areas based on the presence of typical atmospheric pollutants such as carbon dioxide.

3.4 Openness

As spatio-temporal flows of people and goods have increased in modern China, it is increasingly difficult for a system that is geographically-circumscribed to be closed. Spatially a system is subjected to inflows from and outflows to other regions so that a fourth component for understanding H-E well-being is the system's openness. The degree of a regional system's openness is examined through a network of linkages that connect the region and other extra-territorial regions. The network provides an idea of external transfers that shape the region's H-E relationship. This may be done using measures of traffic accessibility or inter-regional transfer capability. But data on inter-regional transfer capabilities is difficult to find, hence we rely on a common measure of inter-regional flows, namely population migration flows. Transport infrastructure increases access to resources required for regional economic activity, and it can enhance both the region's resource carrying capacity and its ability to transfer environmental risks. We also draw upon Jin's (2008) indices of transport accessibility which provide measures of network density, grade, passenger and freight capacity, distance from different types and grades of trunk routes. Together, inter-regional transfers driving openness may be expressed as:

$$SO_i = \sqrt{1/2(T_i^2 + NMP_i^2)} \tag{4}$$

$$T_i = \Sigma_{i=1}^{e}(RD_i * w_1 + LTR_i * w_2) \tag{4-1}$$

$$NMP_i = IMP_i - OMP_i \tag{4-2}$$

where SO_i is a regional system's openness, T_i transport accessibility, and NMP_i net migration. RD_i is road network density, LTR_i grade level of trunk route, W the weight as used by Jin *et al*. (2008) and Feng *et al*. (2009). Finally IMP_i refers to in-migration and OMP_i to out-migration flows.

3.5 Data

The study requires a large volume of data that were collated from national, provincial and county statistical yearbooks as well as remote sensing data. Specifically, it includes data from the *China County-Level Statistical Yearbooks*, *China Statistical Yearbooks for Regional Economy*, *New China in 65 Years*, *China Statistical Yearbooks*, *China City Statistical Yearbooks*, *China Energy Statistical Yearbooks*, *China Statistical Yearbooks on Environment*, *China Water Statistical Yearbook*, *China Environment Yearbook*, *China Land Resources Statistical Yearbook*, *China Water Conservancy Yearbook*, *Annual Statistical Report on Environment in China*, and *China Transportation Statistical Yearbook*. We also extrapolated remote sensing data, data on environmental quality, as well as physiographic and topographic data provided by the Data Center for Resources and Environmental Sciences of the Chinese Academy of Sciences. Finally, data was supplemented by statistics from county-level yearbooks and websites of county-level statistical bureaus. The principal year for study is 2015 where data is most complete compared to more recent years.

4 Results

4.1 Intensity of human activities

Before assessing China's H-E system as a whole, we first describe each of the four decomposed components. The spatial distribution of human activity intensities HAI_i is mapped in Figure 3. Intensities are based on a relative distribution that is scaled from 0 to 100. Identifying natural breaks in the scale, areas were classified from level 1 to level 5 in order of intensity. Of the counties evaluated in this study, 688 counties are classified as level 4 human activities with MAI_i values of higher than 67 and they account for just under 10% of China's land area. Only 2.4% of the country's national land is subjected to this level of intense activities suggesting that economic activities are very concentrated in a few areas geographically. There is a clear east-west spatial divide: 99% of level 4 and above activities are found in eastern China especially along the coast. This is consistent with a relatively large literature highlighting the eastern coastal areas as major sites of industrial and investment activities (Zhang, 2014).The vast majority of areas to the west of China remains relatively unaffected by human activity. In part, this is explained by the more hostile physical environment of the west where water resources are limited due to its arid climate. But it is also explained by a general eastward drift of younger migrants towards centers of manufacturing and more recently, financial activities along the coast.

In a sense, the above pattern broadly conforms to the historical Heihe-Tengchong Line that was drawn by demographer Hu Huanyong in 1935. He had suggested that China's population may be divided into two regions: the west makes up some two-thirds of land area but supported only 4% of population in the 1930s; meanwhile one-third of land is found in the east which supported some 96% of the population. Because economic activities are largely an urban phenomenon in that much of China's modern economic development is driven by the clustering of firms, labor and human capital in large cities, the latter has also been major areas of intense human activities. Wang *et al*. (2017) found that there is a certain spatial mismatch between urban and population distributions. As cities grow, the amount of rural land also expands because out-migration leads to fewer people in rural areas. Meanwhile human activities intensify in cities with in-migration. This is particularly the case in urban agglomerations that are becoming city-regions as small towns and villages are absorbed into the hinterlands of urban systems. Having passed the 50th percentile mark in 2011 for its urban population, Chinese cities are expected to host another 310 million people by 2030 (Wang *et al*., 2017). This is only going to exacerbate the high human activity levels in urban agglomerations.

The importance of understanding the H-E aspects of urban systems may be summarized in Table 1. Thirteen of such systems may be found including the Yangtze River Delta, Pearl River Delta, Beijing-Tianjin-Hebei, Chengdu-Chongqing, Middle Reaches of the Yangtze River, Central China Plains, and West Coast of the Taiwan Strait. They are home to 67% and 72% of levels 4 and 5 human activity intensities. In particular, just five urban agglomerations (Pearl River Delta, Beijing-Tianjin-Hebei, Chengdu-Chongqing, and Middle Reaches of the Yangtze River) are responsible for 44% and 53% of areas classified as levels 4 and 5 respectively. The Yangtze River Delta region alone accounts for 17% and 25% respectively, indicating the extent of dense industrial and socio-economic activities that may be found

Table 1 Human activity intensities (*HAI*) of major urban areas (%)

Name of urban agglomerations	Level 1	Level 2	Level 3	Level 4	Level 5
West Coast of the Taiwan Strait	0	46	30	12	12
Beijing-Tianjin-Hebei	33	30	9	20	9
Shandong Peninsula	0	0	23	63	14
Yangtze River Delta	1	18	33	27	21
Pearl River Delta	2	48	23	9	18
Central China Plains	3	25	24	40	7
Chengdu-Chongqing	32	25	24	16	3
Middle Reaches of the Yangtze River	6	44	34	12	4
Hohhot-Baotou-Ordos-Yulin	68	28	2	1	1
Central Guizhou	29	61	7	3	0
Lanzhou-Xining	66	33	0	1	0
Northern Slope of the Tianshan Mountains	89	9	2	0	0
Ningxia-Yellow River	87	9	1	3	0

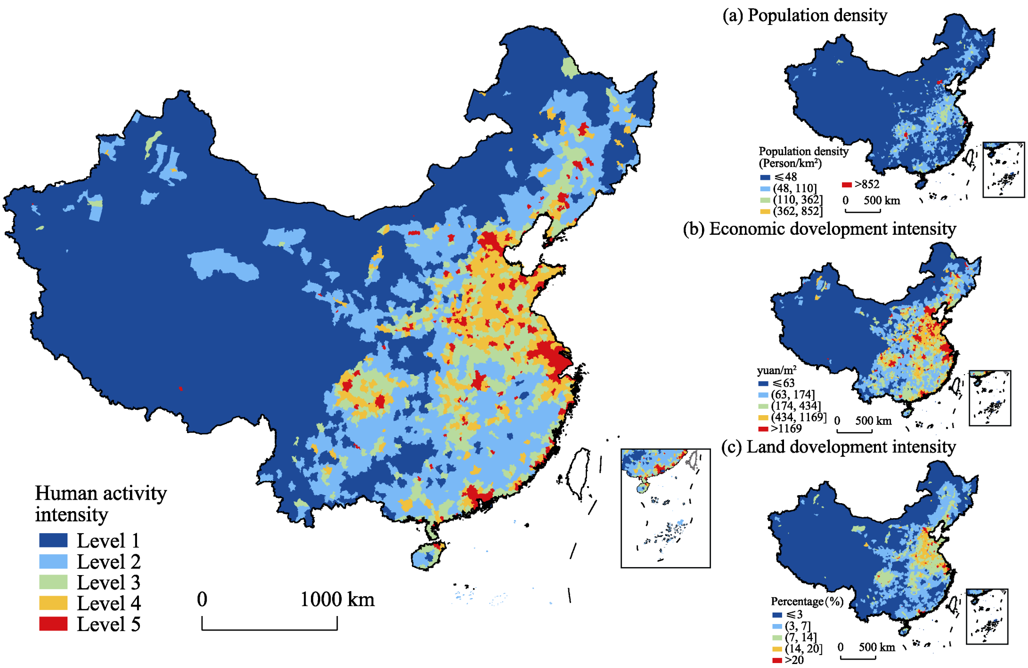

Figure 3 Spatial distribution of human activity intensity (2015)

here. The second most intense urban system is Beijing-Tianjin-Hebei but it is a distant second followed by the Pearl River Delta region. Conversely, the majority of urban regions in western China, including Lanzhou-Xining, northern slope of the Tianshan Mountains, and Ningxia-Yellow River urban agglomerations are characterized by low levels of HAI_i. As Figure 3 shows, these regions are described by low population densities, low economic development levels and low land development intensities.

Overall, areas that are classified as having level 4 and above tend to be urban. Figure 3 reveals that intensities in the Central China Plains and Shandong Peninsula urban agglomerations are mainly due to high population densities, but economic density and land development intensity there are lower than other national urban agglomerations. In addition, 19 and 15% of the Chengdu-Chongqing and Yangtze River urban agglomerations are affected by high-intensity human activity of at least level 4. In the future, with the implementation of a national urban agglomeration development strategy, the intensity of human activity in these three urban agglomerations is likely to increase further.

It is also interesting to note that high-intensity human activities are found along rivers, major trunk routes and transportation corridors in addition to the coast. For instance, the corridors of Beijing-Harbin, Beijing-Guangzhou, and Beijing-Kowloon transport routes, and areas along the middle and lower reaches of the Yangtze River and Yellow River all demonstrate linear distributions of at least level 4 activities shaped in part by the terrain. These include transport hubs such as Zhengzhou, Wuhan, Chengdu, and Chongqing. Overall however, the results indicate that high intensity human activities are more likely to occur at level 4 and only very few areas, particularly large urban systems, reach the level of 5. Together, both levels point to the possibility for increased tensions between humans and the environment as the latter is becoming, if not already, quite stressed.

4.2 Resource carrying capacity

Like HAI_i, the spatial pattern of resource-carrying capacity RCC_i is a relative indicator that is scaled from 0–100 (Figure 4). RCC_i is a composite relative measure and the figure shows that it does not display large areas of concentration for either very high (level 5) or very low (level 1) capacities. Counties in the provinces of Shandong, Hebei, Anhui, Hubei, and Zhejiang are characterized by lower resource carrying capacities than the national average. Low carrying capacities may also be found in the Southwest, Yellow River and Southern coastal areas. Meanwhile, high carrying capacities are more prevalent in the Northeast and counties south of the Yangtze River. Over 50% of counties in the provinces of Heilongjiang, Jilin, Liaoning, Inner Mongolia, Yunnan, and Guangxi, for example, have relatively high or very high resource carrying capacities. This is explained by their relatively abundant supply of land as well as energy and mineral resources. Meanwhile Yunnan and Guangxi's high carrying capacities are due to the presence of water resources. Overall, about 48% of counties have a carrying capacity at level 4 and above. Conversely, 37% have low *RCC* values and they are largely found in the difficult and fragile terrain of the Tibetan Plateau.

The amount of land that is available for further construction in the coastal areas is also quite low. Urban and industrial built-up areas are dense in the Yangtze and Pearl River Deltas (Figure 3). In the Northeast including many counties in the provinces of Heilongjiang, and Inner Mongolia, land availability as well as water and energy resources are low though it is possible to circumvent water and energy constraints through infrastructural development. For example the South-to-North Water Diversion, West-East Gas Pipeline, and West-East Electricity Transfer Projects. This may be why RCC_i is still at a reasonable level for counties in the northeast coast such as those in Jiangsu and Hebei.

Taken together, the resource carrying capacities of more economically developed cities such as Beijing and Shanghai are quite low. It is difficult to find a county in the two municipalities that has high or very high carrying capacities. Shenzhen, one of the first special economic zones to be established to facilitate China's integration to global trade and investment networks appears to be short of both land and energy and mineral resources explaining its low *RCC*. Other areas such as Qingdao's counties do not have high resource carrying capacities from lack of water resources. None of the province's counties made it to level 4 and above for RCC_i. The picture is slightly better for smaller industrial cities such as Tianjin and Chongqing where some 14% and 27% of counties respectively are found to have high carrying capacities. Nonetheless these figures are still below the national average of 30.9%. Notably, while provinces in the west are poorly endowed in water resources, they are also rich in energy and mineral resources.

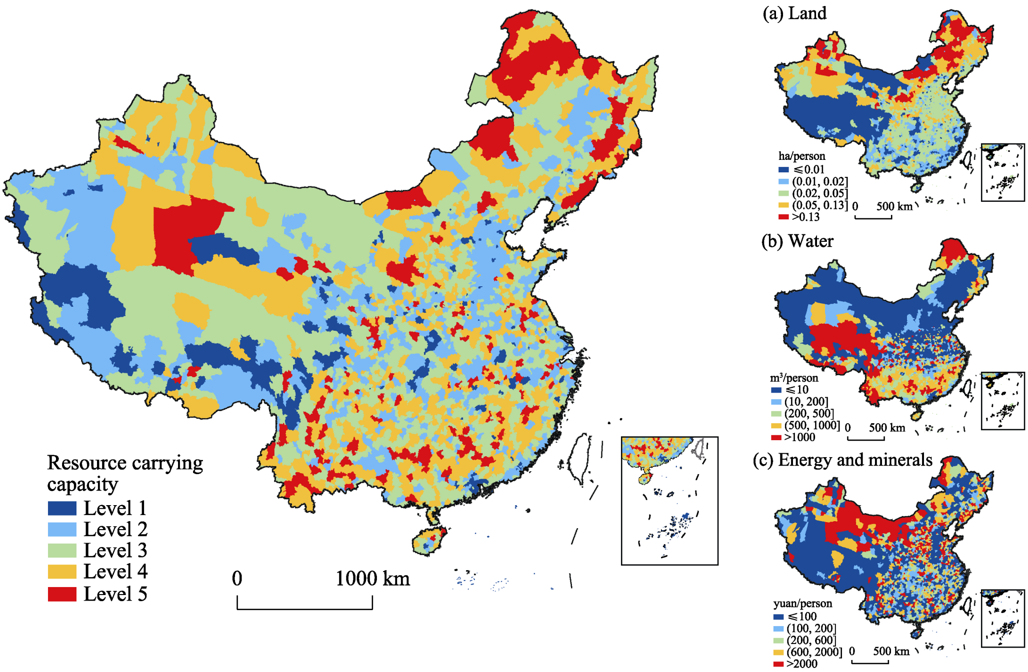

Figure 4 Spatial distribution of resource carrying capacities (2015)

4.3 Ecological constraints

In the third component of the H-E systems model, that is ecological constraints, E is estimated from equation (3) and presented in Figure 5. This estimation results in 821 counties that are found to have high level (levels 4 and 5) of ecological constraints. They cover about 28% of China's total land area. Of these 821 counties, 445 counties covering nearly 11.9% of total land area experience level 5 constraint. The remaining 570 counties' constraints are more minor (levels 1 and 2) and they account for 32% of total land area. The majority of the counties, that is 996 of them, are characterized by average ecological constraints (Figure 5). Looking at the spatial patterns, regions with a relatively high level of ecological constraints are mainly located at transport intersections on the Loess Plateau, Qinghai-Tibet Plateau, Yunnan-Guizhou Plateau and in Sichuan Basin, as well as the southwest of the Qinghai-Tibet Plateau generally. The pattern also conforms, to a certain extent, to the Heihe-Tengchong Line. This divide may be traced to the physical geography of the country with more fertile lowlands found south of the line.

We further decomposed ecological constraints into two categories as indicated in equations 3-1 and 3-3. The first category contains areas that have relatively fragile environments. As a result, they are candidates for conservation or protection by the Chinese government. This includes counties in the provinces of Guizhou, Yunnan, Chongqing, Sichuan, Tibet, Shanxi, Gansu, and Inner Mongolia. In total, 67% of counties in China with fragile environments may be found in these seven provinces and the municipality of Chongqing. Outputs from equation 3-1 shows a relatively high level of soil erosion on the west and northwest of China. The provinces of Inner Mongolia, Xinjiang and Tibet face the most serious level of soil erosion. Areas (km^2) that experience stony desertification (SD_v) cover over 455 counties in more than eight provinces. Stony desertification involves the transformation of karst vegetation and soil into rocky surfaces. Consequently, karst environments in the southwest (Yunnan, Guangxi, Sichuan, and Guizhou) are one of the country's most fragile biophysical systems (Li *et al*., 2015). Large areas that are undergoing desertification D_v may be found in the northwest including Inner Mongolia, Gansu, Qinghai and Xinjiang. These five provinces are responsible for 90% of China's desertification. On the other hand, the geographical coverage of soil salinization SS_v extends over some 20 provinces from Liaoning, Jilin, Hebei, and Henan to the coastal provinces of Fujian and Zhejiang. Not surprising, there is considerable spatial overlap between ecologically fragile areas, and, areas that have been designated for national protection.

The second category refers to ecological constraints that are predominantly influenced by insufficient environmental capacity (Figure 5). A typical example of this category is Shanghai. The municipality accounts for only 0.1% of the country's land area, but 53% of its counties or administrative units experience major problems with environmental capacity from negative environmental externalities. Only 2% of its administrative units' constraints from environmental capacity may be said to be minor. Low environmental capacity is explained by low environmental performance from a high level of carbon dioxide (CO_2) pollu-

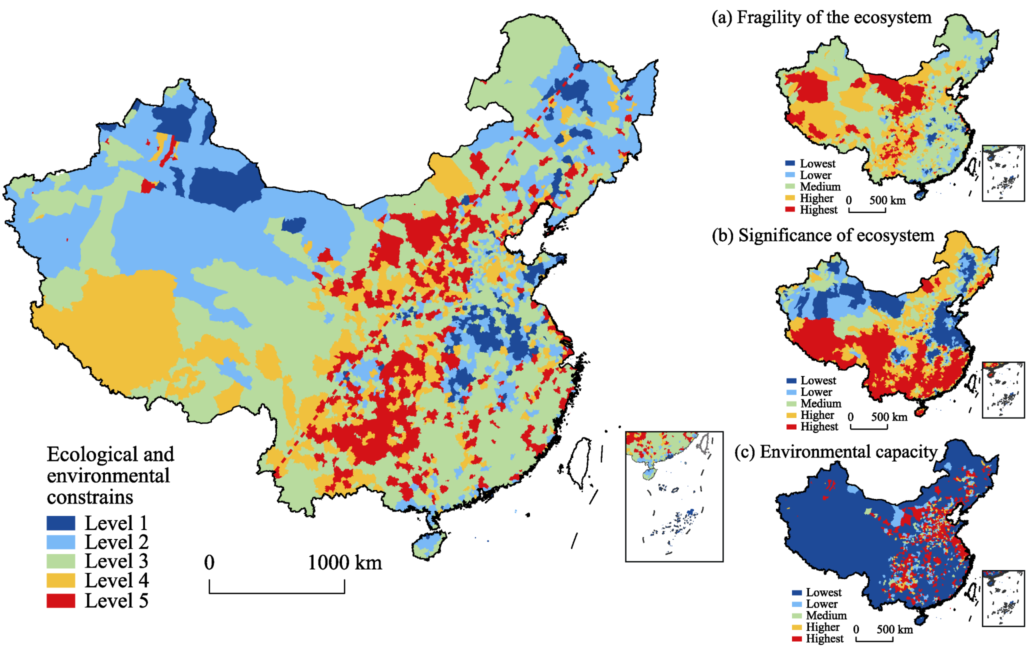

Figure 5 Geography of ecological constraints (2015)

tion. Similarly, 80% and 56% of Chongqing and Tianjin's counties suffer from relatively major ecological constraints due to high emissions of CO_2. Emission levels of the four largest cities in the country are well over 1100 million tons in 2015. This is higher than the total emissions of some 252 cities in the country. Likewise, Shanghai, Chongqing, Tianjin and Beijing are ranked first, second, sixth and twelfth respectively in industrial waste water discharge. Areas with relatively minor ecological constraints tend to be found in the northwest, northeast, and the Yellow and Huaihe river basins, especially the provinces of Heilongjiang, Jilin, Anhui and Xinjiang.

Turning to ECO_f which is an indicator of the fragility of the ecosystem, the most fragile areas are concentrated on the Tibetan, Loess and Yunnan-Guizhou Plateaus. Consequently, they are also areas that are candidates for greater soil and biodiversity conservation as demonstrated by their ECO_s values (significance of the ecosystem). Meanwhile, the Northeast China Plain, North China Plain, Middle and Lower Yangtze River Basin and the Pearl River Delta are the least fragile. In contrast to ECO_f and ECO_s, a high level of environmental capacity *ENC* may be found in the North China Plain, Jiangsu Province and Sichuan Basin and other more developed urban areas. This may explain why some cities do not seem to be suffering from a high level of ecosystem fragility despite their high level of economic development. They may be hosts to a relatively high level of air pollution but when examined in combination with other biophysical conditions such as soil erosion, salinization and desertification, these cities are not as susceptible to environmental degradation compared to their counterparts in the southwest.

4.4 Openness

The fourth and final component describes the openness of the H-E system, that is SO_i. As in the other components, this is a relative measure that is categorized along five levels of openness with 5 being the most open. Based on transport accessibility T_i and net-migration NMP_i estimates (see Figures 6a and 6b), ArcGIS was used to identify natural breaks for the five levels. Figure 6 shows that the most open areas lie on the eastern side of the country, particularly along the coastal provinces. The east is responsible for 63% of all open (level 4 and above) counties. This is hardly surprising as cities and special economic zones here have historically been centers of international trade and investment. They are also major magnets in attracting migrant labors which relocate in droves to work at factories associated with global supply chains established here. Parts of the Northeast, particularly the counties of Dalian, and Jinzhou in Liaoning, are also very open. The urban agglomeration of Liaoning includes the core cities of Shenyang and Dalian which are relatively developed though not as developed as Beijing or Shanghai. This is because they are part of the old industrial base that had supported the capital-intensive programs of then Socialist China. Hence the quality of the area's transportation infrastructure is still quite good. Together however, they form only one-fifth of the total land area. Of the remaining three-fifths of the 2,387 counties that are characterized by a low level of openness, 78% are found in the west. Only 2% of counties in western China may be said to be open. One explanation is that much of human migration is from west to east, hence openness of the east is shaped by a relatively high level of in-migration. Cities such as Shenzhen, Dongguan, Beijing, Shanghai and Guangzhou all experienced a net migration inflow (over 5 million) from 2000 to 2010. This is also the case for Wuhan, Tianjin, Nanjing, Zhongshan, Dalian, Hangzhou and Xiamen. Conversely, most cities in the west experienced a net outflow. Eastern China is also more urbanized. The urban areas of Beijing, Shijiazhuang, Shanghai, Guangzhou, Hefei, Nanjing, Jinzhou and Shenzhen are well-placed in terms of road density. Only three cities in the west are characterized by a high road density namely Chengdu, Xi'an and Kashgar. But road density is not the only indicator. We also evaluated airport, port, railway, highway and fairway's capacities. All of the eastern cities described above show high T_i values (Figure 6a).

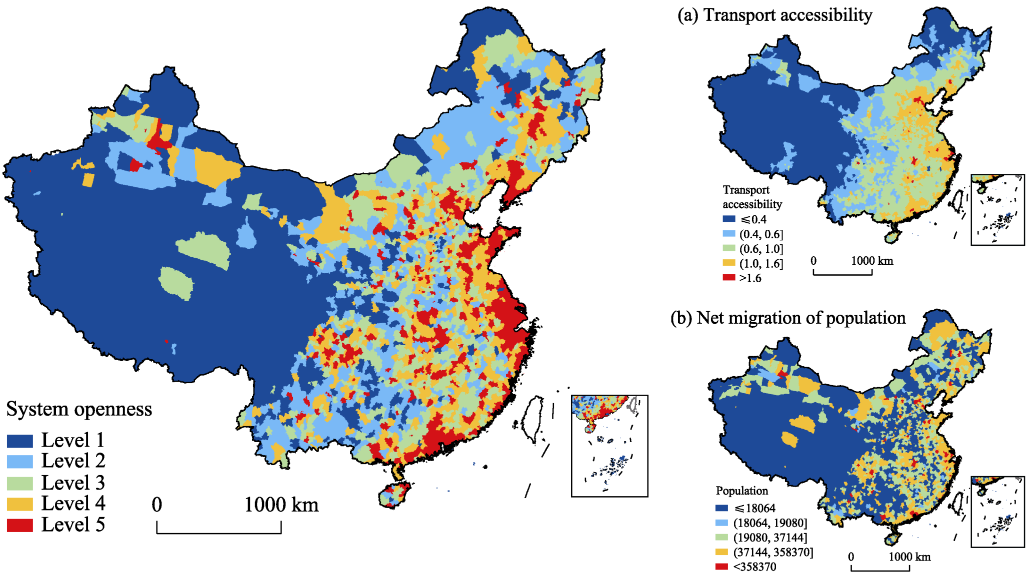

Figure 6 Geography of openness (2015)

Overall Figure 6 reinforces the observation that large urban areas are the most open. They account for 82% of all open areas. Many of them are located in core urban agglomerations including the Yangtze River Delta, Pearl River Delta, Beijing-Tianjin-Hebei, Middle Reaches of the Yangtze River, West Coast of the Taiwan Strait, Chengdu-Chongqing, and Shandong Peninsula urban agglomerations. These seven urban agglomerations contain 57% of counties with a high level of openness (level 4). The Yangtze River Delta urban agglomeration alone accounts for 17% which puts it far ahead of other areas. It is also a main industrial and manufacturing center. It is interesting that although Beijing-Tianjin-Hebei and Chengdu-Chongqing are national urban agglomerations, they do not have a high proportion of counties that are classified as highly open. This may be due to stricter residency rules ("hukou") of Beijing, Tianjin and Hebei as well as Chengdu and Chongqing. Although the Shandong urban agglomeration is a regional rather than nationally-classified urban agglomeration, it has a number of counties that are highly open (level 5), that is 72%. This proportion exceeds that of the Pearl River Delta urban agglomeration. One obvious explanation based on Figure 6 is that Shandong has high values for transport accessibility and net-migration. It is notable as well that Changchun (Harbin-Changchun) and Shenyang (Liaoning), Zhengzhou, Wuhan, Nanchang, Qingdao, Beijing, Shanghai, Guangzhou and Xiamen host a number of open counties.

4.5 Integrating the H-E relationship

A key feature of the systems approach is its holistic framework. Indeed Turner II *et al* (2007) see synthesis of assessment exercises to be valuable in aiding land-management decisions because it helps to identify the characteristics of vulnerable regions that negatively affect human and environmental well-being. This final section seeks to integrate all four components of the H-E system in Figure 1. Part of the analysis in the previous section was to first break down the system into its parts and components. The final step here is to build up the components by synthesizing their interactions. Demetis and Lee (2016) suggest that such integration marks the main theoretical contribution of the approach by facilitating interpretive theorizing.

Five categories are used to describe the H-E relationship according to the county's level of strain or harm. As outlined in Figure 2, we first examined interactions between the two main components (human activity intensity and resource carrying capacity) by calculating the *HAI* and *RCC* levels to estimate an area's pressure-bearing status. Next, the pressure-bearing status of the area is compared against its ecological constraint *EC*. If *EC* is high, then this adversely impacts the area's pressure-bearing status thus raising the level of strain or harm. But the area's pressure-bearing capacity is also influenced by the fourth component that is openness *SO*. An area that is not open may not be able to use resources from another area or diminish pressure by transferring out those pressures. A low *SO* should increase the level of strain.

Between strained and unstrained states, we also identified a "balanced" category that represents a regional system that is neither strained nor unstrained and appears on the surface to be in balance. As described in an earlier section of the paper, we suggest that a balanced system, may in fact, be quite unstable depending on the interactions between economic development and the resource carrying capacity. To reiterate, three types of balance may be identified: (i) "high level of balance" which refers to a system state that is characterized by both high economic development and resource carrying capacity, (ii) "antagonistic balance" when economic development and resource carrying capacity are in conflict with one another, and (iii) "low level of balance" which describes a state that is characterized by both low economic development and resource carrying capacity.

Of all the counties that were evaluated, 569 (46.9% of China's total land area) are not considered to be strained or unstrained (Table 2). If we were to aggregate the "very unstrained" and "relatively unstrained" areas together, then some 85.6% of land area is not yet strained beyond their carrying capacity (Figure 7). On the other hand, 13.3% may be described to be relatively strained and 1.1% as very strained. Hence 14.4% of areas may be said to be undergoing stress that adversely influences human and environmental well-being. The relatively low share may be rather surprising but it highlights the geographical concentration of human activities in a few coastal areas and urban systems. The ten eastern coastal provinces account for 64.5% and 26.7% of all the relatively strained (level 4) and very strained regions (level 5) in China respectively. More specifically, these areas are mainly located in the Yangtze River Delta, Pearl River Delta, Beijing-Tianjin-Hebei, and Shandong Peninsula urban agglomerations. Large areas of land particularly in the west and northwest remain relatively unstrained largely because they are well-endowed in resources while population density and economic development are still relatively low. Western China is host to over 80% of areas that are not found to be strained.

Table 2 H-E integration: distribution of counties

Level	Count	Total area (km^2)	Proportion (%)
Very unstrained	42	666810	7.0
Relatively unstrained	527	3795953	39.9
Balanced	976	3671385	38.6
Highly balanced	112	186130	1.96
Antagonistic balanced	626	1865094	19.62
Lowly balanced	238	1620161	17.04
Relatively strained	689	1266533	13.3
Very strained	153	106345	1.1
Total	2387	9507026	100.0

Note: Total area is less than China's national territorial land area because it excludes Taiwan, Hong Kong, Macao and islands.

As indicated earlier, areas lying between the strained-unstrained continuums may be described to be balanced. Although some 927 counties may be said to be balanced, this does not quite capture a more nuanced picture. Only 5.1% of counties experience a high level of balance. They are concentrated in the Yangtze River Delta and are underscored by reasonably high RCC values largely from abundant water resources (Figure 8). Meanwhile 44.4% have a low level of balance and 50.8% are in a state of antagonistic balance. Of these, we identified quite a few counties in Shandong and Jiangsu that are in antagonistic balance. This is also the case for the other provinces along the coast. The balanced state thus offers further insights if the level of strain may be taken to be an indicator that negatively affects H-E well-being. Economic development and resource carrying capacity are in conflict for slightly over half of the 927 counties. Areas in antagonistic balance are likely to be unstable, but those experiencing a low balance too are at a fragile state. Most of the counties that are lowly balanced are found in ecologically fragile provinces such as Tibet, Xinjiang, Sichuan and Gansu. They may also be found in Guangdong and Zhejiang where economic development is intense. The latter does not have much capacity to expand and is likely to become strained with further intensification of human activities.

Overall Figure 7 shows that areas under some level of strain are concentrated in central and eastern China. Only 20% of land here experience low levels of strain. Indeed slightly over half of all counties in the country that are said to be in balance experience some form of conflictual relationship and are confronted with some level of conflict and tension between economic development and resource carrying capacity. Indeed, it is quite difficult to locate counties that are not under some level of strain in central and eastern China. Some 73% of counties here suffer from an antagonistic relationship and may adversely affect both human and environmental well-being (Figure 8).

5 Conclusions

The CHES framework promotes an understanding of the coupled nature of human actions and biophysical environment. It advocates for a more integrated assessment of the H-E relationship to reveal the complex interactions at work in the system that influence human and environmental well-being. This paper sought to decompose the components of this system in the context of rapidly industrializing and developing China. Specifically human (human activity intensity) and environmental (ecological constraints) components are conceptualized to be influenced by their interactions with one another as well as with two other components, that is resource carrying capacity and openness.

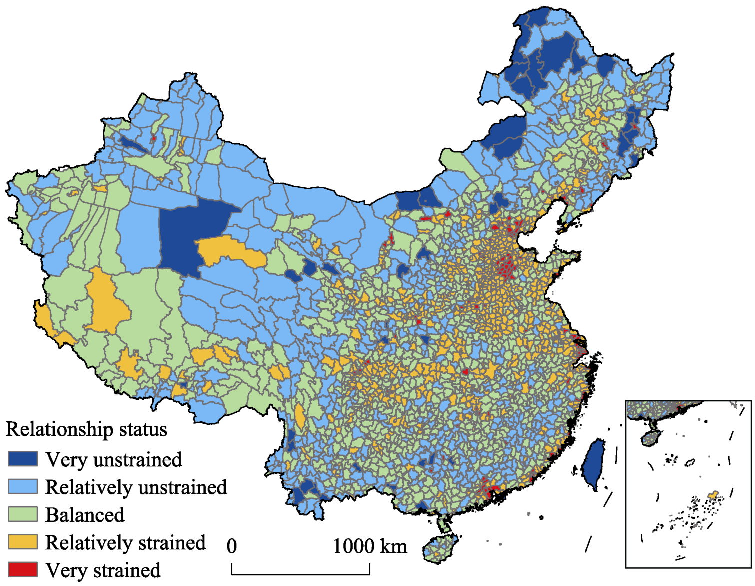

Figure 7 Geography of H-E systems

Region	Low-level harmony	Antagonistic harmony	High-level harmony
East	8.2%	66.1%	25.7%
Central	16.3%	73.0%	10.7%
Northeast	27.6%	65.8%	6.6%
West	55.6%	43.3%	1.1%

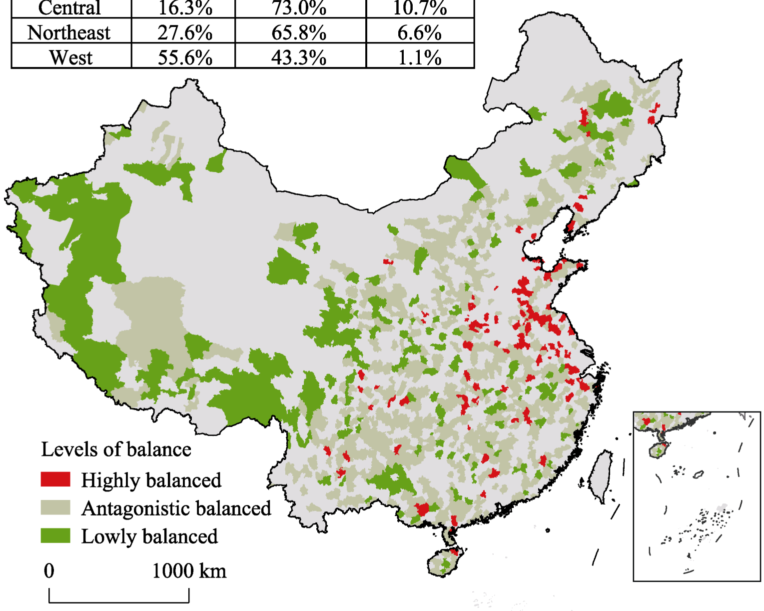

Figure 8 Balanced H-E relationships (2015)

In analyzing indicators and sub-indicators that measure the above four components this paper finds the following. First, human activities are geographically concentrated in urban agglomerations and eastern coastal areas of the country. Despite this spatial concentration, many areas here appear relatively resilient because of their open nature. There are significant interregional flows of people that seem to alleviate information loss (e.g. knowledge and skill level) but these flows also harm certain urban areas. Large cities like Shanghai and Beijing for instance are ecologically stressed from high levels of negative externalities in the form of high CO_2 emissions. Second, resource carrying capacity is the highest among western provinces but this is because they are relatively well-endowed in energy and minerals. Yet these are also areas that are ecologically constrained because they are suffering from desertification and lack of water resources. Likewise, the southwest is under a high level of ecological stress from the transformation of fragile karst terrains to rocky surfaces with economic development.

Third and perhaps most importantly from an integrated point of view, some 14% of counties in China are found to be experiencing a relatively high level of ecological and resource stress or strain. These areas are most likely suffering from low human and environmental well-being. The low share however hides the fact that the majority of areas experience a conflictual relationship between human economic development and resource carrying capacities. These areas are therefore unstable and show signs of vulnerability. Combining areas that are at a low level of balance and those where resource carrying capacity is being strained by a high level of economic development, the share of areas that are becoming vulnerable to strain is closer to 38.6%. Together their H-E well-being is expected to decline and will require increased land-use monitoring and management.

The main contribution of this study is to provide a taxonomy of China's CHES using the systems approach by decomposing the country's human-earth system into their major components and re-integrating them back to understand the whole. By quantifying interactions between the components, the paper shows that overall both human and environmental well-being is under threat along the eastern seaboard and mega urban systems of Beijing, Chongqing and Shanghai. While some of the threats do not seem yet to be obvious, this paper shows that they are experiencing a conflicting relationship that lends itself to increased vulnerability. While large parts of the west are still relatively unstressed, the physical environment is also quite fragile especially the Tibetan Plateau so that it does not take much human activities to adversely affect their environmental well-being. Finally, a limitation of the study is the lack of a temporal investigation that can help quantify the evolution of China's CHES. Part of the reason lies in the number of indicators and data that were used here and the extent of time (over one year) to collate them. This is an area for further research.

References

Chen S Y, 2009. Energy consumption, CO_2 emission and sustainable development in Chinese industry. *Economic Research Journal*, (4): 41–55.

Demestis D S, Lee A S, 2016. Crafting theory to satisfy the requirements of systems science. *Information and Organization*, (26): 116–126.

Feng Z M, Liu D, Yang Y Z, 2009. Evaluation of transportation ability of China: From county to province level. *Geographical Research*, 28(2): 419–429. (in Chinese)

Fu B J, Liu S L, Ma K M, 2001. The contents and methods of integrated ecosystem assessment (IEA). *Acta Ecologica Sinica*, 21(11): 1885–1892. (in Chinese)

Galvani A P, Bauch C T, Anand M *et al*., 2016. Human-environment interactions in population and ecosystem health. *Proceedings of the National Academy of Sciences of the United States of America*, 113(51): 14502–14506.

Harden C P, 2012. Framing and reframing questions of human–environment interactions. *Annals of the Association of American Geographers*, 102(4): 737–747.

Jin F J, Wang C J, Li X W, 2008. Discrimination method and its application analysis of regional transport superiority. *Acta Geographica Sinica*, 63(8): 787–798. (in Chinese)

Li J Y, Li L J, 2012. Water resources supporting capacity to regional socio-economic development of China. *Acta Geographica Sinica*, 67(3): 410–419. (in Chinese)

Li X Y, Yang Y, Liu Y, 2017. Research progress in man-land relationship evolution and its resource-environment base in China. *Journal of Geographical Sciences*, 27(8): 899–924.

Li Y B, Xie J, Luo G J *et al*., 2015. The evolution of a karst rocky desertification land ecosystem and its driving forces in the Houzhaihe area. *Open Journal of Ecology*, 5(10): 501–512.

Liu D, Feng Z M, Yang Y Z, 2012. Ecological balance between supply and demand in China using ecological footprint method. *Journal of Natural Resources*, 27(4): 614–624. (in Chinese)

Liu J G, Hull V, Carter N H *et al*., 2016. Framing sustainability of couple human-environment systems. In: Liu J G, Hull V, Yang W *et al*. (eds). Pandas and People: Coupled Human and Natural Systems for Sustainability. Oxford: Oxford University Press, 15–32.

Liu J J, Dong S C, Li Z H, 2011. Comprehensive evaluation of China's water resources carrying capacity. *Journal of Natural Resources*, 26(2): 258–269. (in Chinese)

Liu J Y, Zhang Z X, Z D F, 2003. A study on the spatial-temporal dynamic changes of land-use and driving forces analyses of China in the 1990s. *Geographical Research*, 22(1): 1–12. (in Chinese)

Liu Y S, Chen B M, 2002. The study framework of land use/cover change based on sustainable development in China. *Geographical Research*, 21(3): 324–330. (in Chinese)

Ministry of Environment Protection of the People's Republic of China, Chinese Academy of Sciences, 2014. The Remote Sensing Investigation and Evaluation of National Ecological Environment Decade Changing (2000–2010). Beijing: Science Press. (in Chinese)

Moran E, 2011. Human-Environment Interactions and Sustainability. New York: Wiley-Blackwell.

Moran E F, Elinor O, 2005. Seeing the Forest and the Trees: Human-Environment Interactions in Forest Ecosystems. MIT Press.

National Research Council of the National Academies, US (NRCNA), 2010. Understanding the Changing Planet Strategic Directions for the Geographical Sciences. California: National Academies Press.

Newell B, Crumley C L, Hassan N *et al*., 2005. A conceptual template for integrative human-environment research. *Global Environmental Change*, 15(4): 299–307.

Nir D, 2002. Region as a Socio-Environment System. Boston: Kluwer Publishing.

Roman S, Palmer E, Brede M, 2018. The dynamics of human-environment interactions in the collapse of the classic Maya. *Ecological Economics*, 146: 312–324.

Skyttner L, 2005. General Systems Theory: Problems, Perspectives, Practice. Singapore: World Scientific Publishing.

Sun D Q, Zhang J X, Zhu C G *et al*., 2012. An assessment of China's ecological environment quality change and its spatial variation. *Acta Geographica Sinica*, 67(12): 1599–1610. (in Chinese)

Tian Q, 2017. Rural Sustainability: A Complex Systems Approach to Policy Analysis. Amsterdam: Springer.

Turner II B L, 2010. Vulnerability and resilience: Coalescing or paralleling approaches for sustainability science? *Global Environmental Change*, 20(4): 570–576.

Turner II B L, Lambin E F, Reenberg A, 2007. The emergence of land change science for global environmental change and sustainability. *Proceedings of the National Academy of Sciences of the United States of America*, 104(52): 20666–20671.

Turner II B L, Matsond P A, McCarthye J J, 2003. Illustrating the coupled human-environment system for vulnerability analysis: Three case studies. *Proceedings of the National Academy of Sciences of the United States of America*, 100(14): 8080–8085.

Wang N, 2004. The role of construction industry in China and sustainable urban development. *Habitat International*, 44: 442–450.

Wang W, Zhang X, Wu Y *et al*., 2017. Development priority zoning in China and its impact on urban growth. *Cities*, 62: 1–9.

Wang X, Chen F, Dong Z, 2006. The relative role of climatic and human factors in desertification in semiarid China. *Global Environmental Change*, 16(1): 48–57.

Wu C J, 2008. Man-earth Relationship and Economic Layout: Collections of Wu Chuanjun. Beijing: Xueyuan Press. (in Chinese)

Xu Y, Sun X Y, Tang Q, 2015. Human activity intensity of land surface: Concept, method and application in China. *Acta Geographica Sinica*, 70(7): 1068–1079. (in Chinese)

Xu Y, Zhang X F, Li L J *et al*., 2016. Regional differentiation and classification for constraints of national resources and environment carrying. *Bulletin of Chinese Academy of Sciences*, 31(1): 34–43. (in Chinese)

Yang Q S, Mei L, 2001. Human-activity-geographical-environment relationship, its system and its regional system. *Economic Geography*, 21(5): 532–537. (in Chinese)

Yang Y, Liu Y, 2016. Progress in China's sustainable development research: Contribution of Chinese geographers. *Journal of Geographical Sciences*, 26(8): 1176–1196.

Yu X S, 1991. Calculation of the population carrying capacity of the land resource and its significance in the study of man-nature relation: A case in Binhai and Suzhou of Jiangsu province. *Journal of Natural Resources*, 6(2): 117–126. (in Chinese)

Zhang K H, 2014. Globalization and regional industrial performance: Evidence from China. *Paper in Regional Science*, 93(2): 269–280.

Zhang W Z, Yu J H, Wang D *et al*., 2014. Study on Sustainable Development of Resource-based Cities in China. Beijing: Science Press. (in Chinese)

Appendix 1 H-E system components and their indicators

Main components	Indicators	Sub-indicators	Notes
Human Activities Intensity (HAI)	Population intensity (PI)	Total population of permanent residents (P)	i. Statistical data ii. Use area as the denominator to estimate intensity
	Economic development intensity (EI)	Economic output (E)	
	Land development intensity (LI)	Land area under construction (C)	
Resource Carrying Capacity (RCC)	Land area suitable for construction per capita (L(P))	Gradient (G), Altitude (A), Area of water (A_w), Area of woodland (A_{wl}), Area of grassland (A_g), Area of desert (A_d), Area of restricted development zones (A_r), Area of forbidden development zones (A_f)	i. Intersect G and A to get alternative land, based on remote sensing data ii. Remove A_w, A_{wl}, A_g, A_d, A_r and A_f to estimate available land iii. Evaluate per capita land area
	Available water per capita (W(P))	Surface water (W_{sf}), Groundwater (W_g)	i. Sum average annual W_{sf} and W_g to estimate available water ii. Evaluate per capita available water resources
	Energy and mineral resources per capita (M(P))	Available energy and mineral resource measured in industrial outputs (M_s)	i. Based on ten categories of energy and mineral resources ii. Calculate by output value to eliminate dimensional effects of various energy and mineral resources.
Ecological Constraints (EC)	Fragility of the ecosystem (ECO_f)	Soil erosion vulnerability (SE), Stony desertification vulnerability (SD), Desertification vulnerability (D), Soil salinization vulnerability (SS)	Methodology based on references 38 & 39
	Significance of the ecosystem (ECO_s)	Importance of water conservation (WC), Importance of soil conservation (SC), Importance of wind prevention and sand fixation (WSC), Importance of biodiversity (B), Importance of special ecosystems (SE)	Methodology based on references 38 & 39
	Environmental capacity (ENC)	National standard for environmental performance(ENC_s), Environmental quality of the areas based on the presence of typical atmospheric pollutants (ENC_p)	Estimated from the difference between EC_s and EC_c
Openness of the System (SO)	Transport accessibility (T)	Road network density (RD), Grade level of trunk route (LTR),	i. D is a composite index of main transportation infrastructure (rail, highway, fairway, airport and port). Infrastructure grade and distance to trunk routes are used to estimate the road network density. ii. See references of 42&43.
	Net migration (NMP)	Migration in-flow (IMP) Migration outflow (OMP)	Statistical data