Inclusive Wealth Index measuring sustainable development potentials for Chinese cities

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Abstract

The UN Sustainable Development Goals (SDGs) are the blueprint to achieve a better and more sustainable future. To achieve the goal, tracking progress — not just on a national level, but locally — is crucial to guide future policy development. While sustainability assessment at the national evel is quite advanced in China, similar assessments focusing at the regional or even at the city-level are currently lacking. Here, we advanced the Inclusive Wealth Index (IWI) framework, which is firstly proposed by the United Nations Development Programme, through taking water wealth into account and adjusting the variable based on data availability. Then we investigate the sustainability performance of 210 cities in China in 2016 via the advanced version of the IWI framework. The analysis makes a holistic assessment based on produced, human, and natural capital, as well as considering heterogeneities in economy, social, and environmental conditions across these cities. We find that cities clustered in the eastern parts of China are characterized by high levels of sustainability performance and increasing capacities for sustainability, largely driven by their high quality and quantity of human capital. In comparison, the western cities have a large amount of low-skilled human capital and low levels of produced capital, which determines their low sustainability performance. Cities clustered in the north are heavily dependent on low value-added products and resource-intensive industries. Furthermore, we make projections of the IWI and its three components for different cities from 2020 to 2030, referring to the index systems presented in city planning which describe the development speed of income, education, fixed asset investment, forests etc. In the future, cities in central and western clusters show considerable potential for increasing IWI per capita, whereas cities with a dominant energy sector in the north would face declining capacity for sustainability due to the exhaustion of fossil fuels and raw materials. By fully taking account of and adapting to local circumstances, we tailor-design pathways for different types of cities to grow their sustainability potentials. Those resources-dependent cities in the north could avoid the impending decline by gradually developing their human and produced capital while abandoning their resource dependency. Our study contributes to city-level sustainable development in China through the lens of per capita IWI and the potential future dynamics of changing compositions in their capital.

Introduction

Environmental degradation has become more widespread and severe, and are driven by drastically growing human activities(Gaynor et al., 2018, Waycott et al., 2009, Hutton and Symon, 1986, Stott, 2016), threatening development and triggering humanitarian crises across the globe (Markhvida et al., 2020, McMichael et al., 2006). The UN Sustainable Development Goals (SDGs) are an urgent call to integrate and balance economic growth, social inclusion, and environmental well-being(Sachs, 2012, Griggs et al., 2013). Due to the large population and scarce per capita natural resources, China faces socioeconomic challenges such as income and gender inequality(Xie and Zhou, 2014), and environmental challenges in land degradation, air quality, water conservation and ecological conservation(Zhang and Wen, 2008). Despite these challenges, China is committed to its international responsibilities in terms of the governance of global sustainability and attaches great importance to incorporating the 2030 SDG Agenda into its national development plan(China, 2017). In the achievement of the 2030 SDGs, although a top-down scheme is essential for macro-level governance, it is of equal importance to embrace a bottom-up approach that recognizes local efforts. Significant differences in economic development, industrial structure, resource endowment and physical geography inevitably impact regional sustainable development progress, requiring effective local governance and regional coherence of SDG implementation through identifying and responding to local context and gaps in sustainable development.

To achieve the ambitious SDGs, each member country needs to monitor progress towards all SDGs, thereby helping to identify problem areas to support targeted policies(Xu et al., 2020). Then a comprehensive and efficient evaluation system at the regional level is needed, which not only reflects economic performance of a society, but also reveals social problems and ecological limits. There have been increasing sustainability indices for monitoring progress towards sustainable development. Issue- or theme-based frameworks are mainly used in constructing indicators, usually focusing on the economic, social and environmental dimensions(Cohen, 2017, Chen and Zhang, 2020, Li and Yi, 2020). These frameworks are suited to monitor progress in attaining objectives and goals relevant for sustainable development(Xu et al., 2020, Rama et al., 2020, Chen and Zhang, 2020, van Dijk and Mingshun, 2005, Nations, 2007). For instance, the Urban Sustainability Index is constructed with a focus on urban status, urban coordination and urban potential, i.e. urban status index based on socioeconomic development index, environmental index and institutional capacity index (van Dijk and Mingshun, 2005).

The idea of inclusive wealth (IW) was first proposed by Arrow in 2003(Arrow et al., 2003b, Arrow et al., 2003a), and in 2012, the United Nations Environment Programme (UNEP) launched the first global Inclusive Wealth Report (IWR), acknowledging the importance of using the inclusive wealth index (IWI) as a new indicator to measure sustainable development(UNU-IHDP., 2012). This index looks at the productive base of an economy by taking all capital assets of the economy into consideration: natural capital such as forests; human capital including levels of education, knowledge, and creativity; and produced capital such as roads and factories. All forms of capital are expressed in monetary terms and the relative worth is assessed based on the contribution a marginal unit of capital asset is able to make to human well-being. The per capital IWI reflects the per capita resources that can be provided to meet the needs of human beings; its higher level indicates a productive base capable of supporting a higher standard of living in the future consistent with sustainable development(Polasky et al., 2015). Compared to the indicators mentioned above, IWI is more comprehensive, as it is a composite index and its analytical framework is based on capital theory, such that it evaluates the capital assets on which human well-being are based, measuring the determinants of well-being.

There are a growing number of city-level sustainability assessments in China (Chen and Zhang, 2020, Ding et al., 2015, van Dijk and Mingshun, 2005, Yin et al., 2014, Li and Yi, 2020, Yang et al., 2017). However, there is still a lack of more systematic studies with wider scope to include most Chinese cities and include less developed regions, which is important for a coordinated development approach across regions. Furthermore, most studies on sustainability assessment do not provide detailed analysis on the composition of different types of capital and the inherent trade-offs between economy, society and the environment, which is important to support targeted policy interventions and development pathways for diverse cities and regions.

Hence, our research contributes to the city-level sustainable development in China through making assessment with a wide scope and providing policy guidance to make trade-off on different components. The main objectives of this study are to undertake a preliminary analysis of sustainable development potentials for Chinese cities, to carry out a comprehensive analysis of the various components of wealth, and to help formulate policies based on the notion of asset portfolio management. Specifically, this paper assesses the sustainability performance of four municipalities and 206 prefecture-level cities in 2016, covering more than two thirds of all cities and including all major cities in each province, excluding Tibet due to the data availability. The basic IWI framework from the *Inclusive Wealth Report* which consists of human, produced and natural capitals is adopted, and some sub-indicators are adjusted based on local data availability, to create an approach that is suitable for Chinese cities. For instance, regarding produced capital accounting, in the absence of gross fixed capital formation and fixed asset investment price index, we adopted the modified fixed capital investment and implicit investment deflator instead. Local conditions are fully considered when we make decisions on subtypes of capital. Here we focused on 12 types of mineral wealth including coal, oil, natural gas, iron, manganese, vanadium, bauxite, magnesite, phosphate, copper, lead and zinc, which are the most important minerals in China. And ecosystem services of water are valued and taken account into the IWI framework considering its essential role in the development of human society. We illustrate the methodological and data issues regarding the Inclusive Wealth in the Method Section and give more details in Supplementary Method. In the Result Section 1 and 2, the heterogenous distribution pattern of per capita inclusive wealth among Chinese cities is analyzed, and the composition of the capital structure is discussed for different types of cities. Furthermore, in the Result Section 3, we describe the dynamic patterns of IWI and its three components from 2020 to 2030 according to the current official planning, to explore Chinese cities' potential sustainable development pathways for the coming decade. It is urgent that cities with a dominant energy sector in the north need transfer their development mode, otherwise they would face declining capacity for sustainability. Existing problems, potential challenges and development focuses are fully discussed for cities with different geographical contexts, demographic structure, industrial structure and resource endowments, to shed light on the potential of diverse development pathways.

Methods

Advanced Framework of Inclusive Wealth Index

The idea of inclusive wealth (IW) was proposed by Arrow et al.(Arrow et al., 2003b, Arrow et al., 2003a). The Inclusive Wealth Index (IWI) offers a capital theory based approach to sustainability accounting for different types of capital and their productive capacity. The Index seeks to measure the social value of capital assets of nations by going beyond the traditional economic concept of manufactured (or produced) capital. The Index is inclusive in the sense that it accounts for key inputs as important components of the productive base of the economy, including natural capital (land, minerals, water and other natural resources), human capital (health, education, etc.) and produced capital (infrastructure, etc.). The basket of assets (or productive base) is measured by adding up the social worth of each capital type of an economy, resulting in the IWI.

Based on the framework proposed by UNEP, we advanced the IWI to account for the sustainability of different types of capital and their productive capacity for 210 Chinese cities in 2016. Firstly, we localized and adjusted variables according to local data availability. Secondly, we explored methodologically and empirically wealth accounts for water-related ecosystem services. This section illustrates the methodological and data issues regarding the Inclusive Wealth (more details shown in **Supplementary Method)**. The results are calculated in the constant price of 2000 with the currency of yuan (¥).

(1) Human Capital Wealth Accounting

Following a method proposed by IWR(UNU-IHDP., 2012), the income approach is adopted for human capital computation, based on the idea that the educational attainment yields return to human capital. The human capital wealth (*HCW)* is calculated by the stock of human capital (*H*) and the shadow price per unit of human capital (*PH*), which can be expressed by Eq. (1).

$$HCW = H \cdot PH \tag{1}$$

The formula for calculation to the stock of human capital (*H*) is as follows, which is determined by education attainment (*Edu*), rate of return on education (ρ) and working age population (*P*), shown as Eq. (2):

$$H = e^{(Edu \cdot \rho)} \cdot P \tag{2}$$

The shadow price per unit of human capital (*PH*) reflects the present value of lifetime income, which is obtained by the average salary ($\overline{r}$) from 2000 to 2016 and the expected working years *(T),* as shown in Eq. (3). The discount rate is δ=8%.

$$PH = \int_0^T \overline{r} \cdot e^{-\delta \cdot t} dt \tag{3}$$

Data for Human Capital Accounting. The data for mortality, income, etc. is provided by the *Statistical Yearbook* of each city. The education attainment, age structure, working age population, etc. is mainly collected from *1% Population Sample Survey Data* in 2015. See **Supplementary Method** for a list of indicators and their corresponding data source used in this paper.

(2) Produced Capital Accounting

The produced capital refers to the physical infrastructure, land, property, and facilities of private firms, houses, etc. Upon calculation, the perpetual inventory method (PIM) is employed to measure capital, which is a simple summation of gross investment net of depreciation in each year. This method can be written as follows(UNU-IHDP., 2012):

$$K_t = K_0(1-\delta)^t + \sum_{j=1}^{t} I_j (1-\delta)^{t-j} \tag{4}$$

In Eq. (4): the initial capital stock (K_0) is estimated by assuming a steady state of capital-output ratio (for details see **Supplementary Method**) and the benchmark year is set at 1978; the depreciation rate δ is constant at 6%; I_t stands for the investment at year *t*, which adopts the indicator of gross fixed capital investment and is collected from the *Statistical Yearbook* of each city.

(3) Natural Capital Accounting

Based on the available data and abundancy of resource reserve, three fossil fuels (coal, natural gas, and oil), nine metals and minerals (vanadium, copper, iron, lead, manganese, phosphorus, zinc, bauxite and magnesite) are selected. The formula for the mineral wealth (*MW*) is as follows:

$$MW = STM_{ik} \cdot PM_i \cdot RM_i \tag{5}$$

where STM_k, PM_i and *RM* respectively refer to the basic reserves of resource in the city k, shadow price and rental rate of the minerals, and i represent the type of fossil fuels, metals and minerals. The shadow price is calculated by the average market price of the minerals from 2000 to 2016.

Agricultural land refers to arable and pasture land. The methodologies for accounting these two parts are quite similar. Take arable land as an example, the arable land wealth (*ALW*) is defined as the area of arable land available per year multiplied by its shadow price (*PA*), and the shadow price (*PA*) is calculated through net present value method (NPV) as shown below.

$$CW = PA \cdot A \tag{6}$$

$$PA = \sum_{t=1}^{\infty} \frac{\overline{WA} \cdot RC}{(1+r)^t} = \overline{WA} \cdot RC \left(1 + \frac{1}{r}\right) \tag{7}$$

where *A*, *RC* and *WA* are the amount of arable land, rental rate and wealth value per hectare of the arable land, respectively. The average of the wealth value per hectare of arable land from 2000 to 2016 is used to reduce the bias. The rental rate is constant at 0.28 derived from net profit of listed companies in the agriculture sector. Due to the complexity of pastureland production, the shadow price of pastureland in the city is assumed to be equal to arable land as IWR proposed(UNU-IHDP., 2012).

In the forest accounting, the forest wealth (*FW*) is composed of timber value *(FTW)* and non-timber forest benefits (*FESW*). Eq. (8) illustrates the calculation method for the wealth of timber *(FTW)*:

$$FTW = Lt \cdot Ca \cdot PT_n \cdot RT \tag{8}$$

where *Lt* represents the volume of living trees; *Ca* refers to the percentage of commercially available wood with 0.38; *PT* stands for the provincial shadow price of timber; *RT* represents the rental rate of timber production with 0.76.

Following the existing method(UNU-IHDP., 2012), the formula for calculating the non-timber forest's ecosystem service wealth (*FESW*) is as follows:

$$FESW = \int_o^{\infty} Q \cdot F \cdot r \cdot e^{-\delta \cdot t} dt \tag{9}$$

Where *t*, *F*, *Q, r* respectively stand for the year of analysis, total forest areas, marginal contribution of ecosystem services to well-being, and the proportion of forests that can benefit humanity. The depreciation rate of forest capital δ is constant at 0.08, *r* is constant at 0.1(UNU-IHDP., 2012) and marginal contribution is 21061 per hectare per year(de Groot et al., 2012) (at 2000 price level).

Water plays an essential role in the development of human society because of its dependence on the services provided by ecosystems. To be specific, water contributes directly or indirectly to the provision of a wide range of services that include the production of food and raw materials, water supply and purification, nutrient retention, carbon sequestration, the protection of biodiversity, climate regulation, coastal and flood protection, recreational opportunities and tourism (Grizzetti et al., 2016). Considering its great contribution to well-being, water is an essential factor in the natural capital of IWI. As water becomes increasingly scarce, the need to value water ecosystem services has increased. The valuation helps identify the current status of water wealth and gives implications on trade-off between conservation and exploitation of water resources. Therefore, water capital wealth (WW) is added into the IWI accounting framework in the research. This research follows Zhao's method(Zhao et al., 2003), and refines the data sources to establish a reliable and applicable city-level water resources evaluation system (see details in **Supplementary Method**). The water capital can be divided into six sub water capitals (SWV_l) based on the four ecosystem services types:from 1 to 6 referring to the hydropower; water purification; carbon fixation and oxygen release; biodiversity maintenance; sediments transport; and leisure and entertainment values. Each sub water value (SWV_l) refers to the economic benefits of each service per year. The total water capital wealth (WW) is calculated based on calculated net present value method (NPV) shown as Eq. (10).

$$WW = \sum_{t=1}^{\infty} \frac{\sum_{l=1}^{7} SWV_l}{(1+r)^t} = (\sum_{l=1}^{7} SWV_l) \cdot \left(1 + \frac{1}{r}\right) \quad (10)$$

Data for Natural Capital Accounting. Data for indicators representing components of natural capital in the study were mainly obtained from the following authoritative sources: *Statistical Yearbook, City-level Land Use Data in China, China Forestry Statistical Yearbook, Urban Water Bulletin, 2016-2020 Periodical Plan for Mineral Resources*.

Besides the sound theoretical foundations of the Inclusive Wealth Index, one should bear in mind the uncertainties and restrictive assumptions inherent in the empirical calculations. Firstly, the problem of data availability makes it difficult and takes a long time to conduct a wide range of IWI assessment at the city-level, which restricts the application of IWI. The substitution of a simple index, or other available indices such as the remote sensing data, help simplify the calculation method. Secondly, the existing accounting framework is still not comprehensive and accurate enough as renewable energy and other natural resources are not included and environmental impacts are ignored (see details in SI Figure). Huge efforts need be put into advancing the framework. Last but not least, in order to stress the vital role of balanced capital structure in sustainability, it is better to consider the limits of the contribution of each capital to the total potential and the possible interaction among capitals including static interaction and dynamic trend similarity. The capital approach that assumes perfect substitutes among these three capital assests will not only undermine the essential role of natural capital in sustainable development but will also impede societal well-being at a broader range.

City Classification

City classification is important for understanding functionality, resource allocation, employment, and development(Rahman et al., 2019). However, the practice of city classification in sustainable development assessment is still new, because of the complexity of sustainability indices. Here, we used cities' capital structure and capital quality as indicators to group 210 Chinese cities, to expose the cities' pillar capital as well as their position in the sustainability progress.

The capital structures were calculated in the following way: (1) We calculated each city's share of three capitals: human capital, produced capital and natural capital. (2) We then sorted the cities according to their capitals' share from small to large and obtained the cities' rankings of each capital. In this way, we first grouped the 210 case cities into three groups using each city's capital structure (see details in SI Method). HC-dominated (human capital, HC) cities included 78 cities with a high ratio of HC, PC-dependent (produced capital, PC) cities included 76 cities with a high ratio of PC, and NC-dependent (natural capital, NC) cities included 56 cities with a high level of natural resources.

The cities that are similar in capital structure can be very different in capital quality. Therefore, this study further divided the three groups above into seven sub types according to the capital quality. The capital quality of HC-dominated and PC-dependent cities is calculated by city's labor productivity, which offers a measure of economic growth, competitiveness, and living standard within an economy and is widely used in research(Nordhaus, 2001, Maestas et al., 2016, Freeman, 2008). In this way, HC-dominated cities can be divided into 64 ordinary ones and 14 advanced ones, while PC-dependent cities can be divided into 52 ordinary ones and 24 advanced ones. For NC-dependent cities, capital quality is impacted by the share of renewable sources. Natural capital with a high share of renewables is by definition more sustainable, and if managed correctly, will not decline over time. Then we divide NC-dependent cities as follows: (1) We calculated each city's share of renewable resources in natural capital, then sorted the NC-dependent cities according to their renewable resources' share from small to large and obtained the cities' rankings of renewable natural capital. (2) We summed up each city's mineral wealth, then sorted the NC-dependent cities according to their mineral wealth from small to large and obtained the cities' rankings of nonrenewable natural capital. The landscape eco cities were defined with a high renewable resources' share in natural capital, energy cities were defined with a low renewable resources' share but high minerals wealth, and resource-exhausted cities were defined with a low renewable resources' share as well as poor minerals wealth (see details in SI Method).

In this way, the 210 cities were finally classified into seven city types with different pillar capital and capital quality. We named the city groups after their pillar capital or development pathways: 64 ordinary HC cities, 14 advanced HC cities, 52 ordinary PC cities, 24 advanced PC cities, 15 energy cities, 19 resource-exhausted cities and 22 landscape eco cities.

There still exists uncertainty in the classification of cities and differences between theory anticipation and practice are likely to be observed. The data we used for classifying is still not comprehensive enough to reflect various aspects in the society and different terrain, climate, or cultural concepts. It is worth remembering that local conditions need to be fully considered in the policy decision in addition to the general features of each category.

Scenario analysis

To reveal the patterns of IWI growth at the city level with different conditions and characteristics, typical cities for each category are selected as case cities in the scenario analysis, including Shenzhen (Adv. HC city in East China), Yantai (Adv. PC city in East China), Ganzhou (Ord. HC city in Central China), Pingxiang (Ord. PC city in Central China), Mianyang (Ord. HC city in West China), Ordos (Energy city in North China), Taiyuan (Resource-exhausted city in North China) and Ulanqab (Landscape eco city in North China). Referring to the index system presented in *the 13th Five-Year and 14th Five-year Plan*, *General Urban Planning (2011-2030)*, and *National Sustainable Development Pilots Programme* of the city, we simulated the IWI of each case city in 2020, 2025, 2030 respectively, to explore the potential sustainable development progress under the policy-guiding scenario. To be detailed, the variation of population, income, education, fixed asset investment, forest, cultivated land, pastureland, swamp area, water supply and consumption and minerals consumption are fully considered and discussed in the estimation of a city's IWI in the future. But the estimation methods varies among indicators due to the differences in the data source, which is shown as follows (see details in SI Method):

(1) Some can be directly adopted from the planning. For example, the 13th five-year plan of Yantai directly provides the data of growth ratio of fixed asset investment.

(2) Others are estimated indirectly on the basis of reasonable assumptions. For instance, for

Shenzhen, the increment of fixed investment assets is estimated according to the GDP, given the assumption of linear relationship between GDP and fixed investment assets.

(3) Linear interpolation is used to fill gap in time series. For instance, on the basis of projected income in 2020, 2025, 2030 given in the planning, we use linear interpolation to obtain the projected income in each year during 2016-2030, then calculate the shadow price of human capital by averaging the income in time series.

In addition to the policy-guiding scenario, this study simulated Ordos's IWI under the business as usual (BAU) scenario, to explore the dramatic effects of existing exploitation of mineral sources on IWI. Only Ordos is adopted as the case city in the BAU scenario, which may face imminent resource depletion without policies in place. In the BAU scenario, the variables regarding education, income, investment, minerals consumption etc. is assumed to remain constant. For instance, the annual minerals consumption of Ordos during 2016-2030 is estimated by averaging its annual minerals consumption during 2010-2016.

Results

China is faced with significant regional inequality

Among Chinese cities, there is a nearly nine-fold gap of IWI per capita from the lowest with 219 thousand yuan to the highest with 1,854 thousand yuan, compared to the four-fold gap among Chinese provinces. To describe the regional inequality of sustainability in China, we recognized four clusters according to the geographical location, per capita IWI and capital structure. Cities in the eastern cluster generally have high levels of IWI per capita, about a quarter of which exceed the mean plus standard deviation with 653 thousand yuan and two thirds exceed the average level with 464 thousand yuan. For instance, Shanghai and Nanjing are the top cities in the eastern cluster with IWI per capita of 850 and 830 thousand, respectively. Their high levels of IWI per capita are mainly contributed by human capital with 72% and 63% respectively (shown in Figure 1). In the eastern cluster, natural capital is at low level with 17.26 thousand yuan per capita, and mainly made up of water and agriculture land (shown in SI Figure). Based on the high share of human and produced capital in total IWI as well as the high share of renewable resources in natural capital (shown in Figure 1), the eastern cluster is recognized as the ascending cluster, having great potential to show growth in IWI and experience increasing capacity for sustainability in the future. Because the human and produced capital usually show an upward trend over time according to the existing evidence(Managi et al., 2019), and the renewable resources will not be reduced when utilized rationally.

The central cluster is recognized as medium level in terms of IWI per capita and as an ascending capacity cluster because of the high ratio of renewable resources of its natural capital. Its IWI per capita varies from 254 to 655 thousand, where human capital and produced capital contribute equally. The pattern of natural capital is similar to the eastern cluster, which is as low as 17.93 thousand yuan per capita and mainly made up of renewable resources.

Cities in western China form a low-IWI cluster, almost all are below 400 thousand yuan IWI per capita. Although some cities in the western cluster are close to the central cluster in terms of IWI per capita, their capital structure is very different. Here, human capital is the main contributor and contributes 64% of total IWI, whereas produced capital is very low, contributing only 27%. Fixed asset investments which constitute the produced capital are merely 22.3 thousand per capita on average in western cluster, which represent about 72% and 55% of that in the central and eastern cluster (shown in Figure 1). Despite its low level, IWI per capita of the western cluster is likely to increase due to the high share of renewable resources in natural capital. However, it is found that some cities in the western cluster are developing at a quite low speed in recent years; for example, GDP growth ratio in Baiyin was below 2% from 2015 to 2016. Low economic growth is likely to further slow the development of human and produced capital.

With abundant fossil fuel resources, the north cluster shows high IWI per capita as well as a high ratio of non-renewable capital. For instance, as an important energy base, nonrenewable natural capital of Ordos reached 780.7 thousand per capita, which is equal to 108% of the total IWI per capita in Suzhou in the eastern cluster. However, despite the high level of IWI per capita of the north cluster in 2016, the north cluster is recognized as a potentially declining cluster. Its local non-renewable resources are likely to decline rapidly over time due to the enormous energy demand. Furthermore, with the high dependence on the mining industry, resource depletion may lead to a reduction in employment and a decline in revenue, implying the slow growth of human and produced capital. As growing human and produced capital could not offset the dramatical declining nonrenewable wealth, the north cluster tends to face the prospect of total IWI declining over time. There is great need to stress the concerns about its sustainable development potential in the coming decade.

Cities in the north and western cluster lag behind in individual welfare and production efficiency

It is vital to further discuss capital structure to gain insight into the developmental characteristics and potential challenges for different clusters and cities. Generally, for Chinese cities, human capital (HC) accounts for the largest part with an average proportion of 57.3%, followed by produced capital (PC) with an average of 34.2%. Natural capital (NC) accounts for the least with 8.4%. When looking deeper into the specific capital structure of each city, 210 cities can be divided into three categories with seven subcategories according to capital stock and quality: HC-dominated, PC-dependent and NC-dependent cities (shown in Figure 2A), which refer to high ratios of HC, PC and NC, respectively (see details in Method). Both of the HC-dominated and PC-dependent cities are further divided into ordinary and advanced subcategories according to their labor productivity, while NC-dependent cities are divided into landscape eco, energy-producing and resource-exhausted cities based on the resource endowment (see details in Method and SI Method).

Most cities in the north cluster are NC-dependent cities relying on natural resources to a certain extent for their further development. To be specific, more than half are energy-producing cities, with a dominant energy sector that usually serves as an important energy base for the larger economy. For instance, in Yulin (Shaanxi province), energy sectors accounted for 75.9% of total IWI. Their nonrenewable resources per capita are well above other capitals (shown in Figure 2B). However, both income and capital productivity in energy-producing cities are still significantly lagging behind advanced cities (shown in Figure 2B). This is mainly due to the low value-added of products in existing resource-intensive industries. For instance, in Inner Mongolia, more than 80% coal is consumed in cooking, heating, and power generation, but only a small part is used to produce high value-added of products in industries such as the high-tech chemical industry. Another challenge for energy-producing cities is that their IWI per capita has a high risk in declining to quite low levels when nonrenewable resources are quickly exploited without investment in other forms of capital. Countries with an abundance of nonrenewable natural resources tend to have less economic growth or worse development outcomes than countries with fewer natural resources, which is known as resource curse theory(Brunnschweiler and Bulte, 2008). This phenomenon can be explained by the manner in which resource income is spent, poor institutional quality, late industrialization among others(Mehlum et al., 2006, Lane and Tornell, 1996, Auty, 2007, Sala-i-Martin and Subramanian, 2012). It has been witnessed in multiple countries around the world including but not limited to the Netherlands, Venezuela, Angola and the Democratic Republic of the Congo. Similarly in the north cluster, there are three cities that face pressures from slow economic growth, mass unemployment and environmental impacts of increasingly inefficient resource extraction, and thus are classified as the resource-exhausted type. To take Taiyuan as an example, its high air quality index value corresponds to the great level of air pollution in 2005. Additionally, there are another two cities in the north cluster which own abundant renewable natural resources and are categorized into landscape eco type: Ulanqab and Bayannur. Despite the differences in the resource endowment among three types of NC-dependent cities, they all lag behind in individual welfare and productive efficiency.

In the western cluster, most cities belong to the type of ordinary HC-dominated, which means HC accounts for the largest part, yet they are plagued with low production efficiency. This type of city performs worst in both welfare and capital productivity among all seven types, due to low quality of both human and produced capital. For human capital, education attainment in HC-dominated cities is very poor with an average schooling of 8.76 years on average, which is even lower than the nine-year compulsory education in China. The backward industrial structure, which leads to fewer available jobs and lower levels of income, aggravates the problem of low-quality human capital. To offer greater detail, the ratio of tertiary and secondary industry in GDP is as low at 83%, compared to 88% in the central cluster and 95% in the eastern cluster. For the produced capital, the large amount of fixed asset investments in the western cluster have the lowest potential returns. For instance, in Dingxi, there are 35% fixed asset investments focusing on low-value-added sectors including agriculture, mining, construction and power industries, which are usually below 20% in the central cluster. Low-quality human and produced capital are linked to low capital productivity and lead to a slow growth of IWI in the future. Thus, the main task of the western cluster is to improve the structure and enhance the quality of capital, in order to reverse its position at the bottom.

The central cluster is mainly made up of ordinary HC-dominated with 54% and ordinary PC-dependent cities with 27%. A large part of ordinary PC-dependent cities are industrial cities such as Xianning and some recently transformed from resource-exhausted cities like Pingxiang. Its high produced capital ratio corresponds to a high ratio of secondary industry in GDP in PC-dependent cities (shown in SI Figure). Compared to the western cluster, the central cluster generally shows a balanced capital structure, where the share of human capital is similar to produced capital. Cities in the central cluster have higher dependence on manufacturing with a higher share of fixed asset investment, for example, with a ratio of 57% in Xianning. In addition, there are several advanced PC-dependent cities in the central cluster, which are usually provincial capital cities such as Wuhan. These cities could become a vital force in the sustainable development of the surrounding area.

The eastern cluster is mainly made up of advanced HC-dominated and PC-dependent cities, which are specialized on HC and PC respectively. Advanced HC-dominated cities are mostly located in the southern part while advanced PC-dependent cities are from the Shandong and Jiangsu provinces in the northern part. Both cities have developed, based on their favorable capital structure. The advanced HC-dominated type performs well in both individual welfare and capital productivity. They developed the economy through a focus on services, cultural and high-tech industries, and high quality and large quantity of human capital with knowledge and skills as the main source of competitiveness. For instance, the service industry in Shanghai accounted for 70% of GDP in 2016. In comparison, advanced PC-dependent cities rely more on secondary industry. Despite their greater performance in the IWI per capita among all types, advanced PC-dependent cities still lag behind advanced HC-dominated cities in terms of individual welfare. They are still on early or medium stages of development and there is large space for them to achieve higher sustainability. Additionally, natural capital is relatively low in both advanced HC-dominated and PC-dependent cities (as shown in Figure 2A and B). As renewable resources provide essential support that is necessary for the maintenance of ecosystems and human society, the low level of natural capital may pose a potential threat to sustainable development in the eastern cluster.

Transformation is needed for energy-producing cities in the north cluster, otherwise they may show slow progress in sustainable development

To understand Chinese clusters and cities' progress in the future, this section further describes the dynamic pattern of IWI and its three components from 2020 to 2030, referring to the index system in existing official plans which describe the development speed of income, education, fixed asset investment, forest etc. Typical cities for different clusters and types are selected as case studies to reveal different potential patterns for future IWI growth. These cases serve as representatives of different resource endowments and capital structures, their stages of development and challenges faced in sustainable development (see detailed description in SI Method). Results show the growth of IWI for all cities based on existing policies, but performances vary distinctly across cities (shown in the Figure 3).

For the north cluster, NC-dependent cities are gradually moving away from dependence on natural capital and developing towards PC-dependent or HC-dominated cities. The speed of IWI per capita growth varies from type to type. The energy-producing city (or 'energy city') Ordos performs worst in the growth of IWI per capita among all seven types and even faces a decline of IWI per capita in the BAU scenario. This could be attributed to the slow growth of human capital and the decline of natural capital. Similarly, as an energy superpower, Canada also achieves high level of per capital IWI contributed by abundant fossil fuels, but witnessed slow IWI growth with 0.8% annually in the last two decades compared to the US and the UK with 2.0% and 1.9% respectively(Managi et al., 2019). Thus, there is need to stress strong policy support and guidance on improving human and produced capital in energy-producing cities. In comparison, the resource-exhausted city Taiyuan is planned to upgrade local traditional industries and develop an innovative economy. It witnesses a higher growth ratio of IWI per capita with 109% from 2016 to 2030, where human capital is the largest contributor. Services are planned to become the main force to promote economic growth in

Taiyuan according to its 13th 5-year plan, with the ratio over 60% in GDP. Scientific and technological innovation capability is enhanced significantly, to build Taiyuan into an innovation-oriented city. As for the landscape eco city Ulanqab, although its IWI per capita is still at a low level compared to other cities, it has been growing quickly. Emerging industries are projected to be improved, to establish a multi-development modern industrial system.

Cities in the central and western cluster show fast progress toward sustainable development as measured by IWI. Pingxiang and Mianyang both have high levels of IWI per capita growth with 188%, and are projected to develop towards higher ratio of PC. In Pingxiang, the secondary sector will take the largest part with 55% according to its 13th 5-year plan. The new industrialization will be the development focus in the future, to accelerate the development of emerging and advanced manufacturing industries. In Mianyang, the ratio of the services (tertiary) sector in GDP is supposed to increase significantly from 34% in 2015 to 43% in 2020, which brings more jobs to local human resources. Such a development mode helps solve the existing dilemma between the excessive human resources and insufficient industries in the western cluster.

In the eastern cluster, cities show moderate growth speed in IWI per capita. The advanced HC-dominated city Shenzhen is projected to develop towards a dramatically higher ratio of HC. Its high quality and large quantity of human capital brings high profits to the local economy. At the same time, the growth of industries further drives development of human capital through investment in education and research. Comparatively, advanced PC-dependent city Yantai develops towards higher ratio of PC and becomes PC-dominated. It is supposed to establish a modern industrial system and transform from the traditional manufacturing to more service-oriented manufacturing industries.

In summary, the advantage of human or produced capital is more prominent in advanced HC-dominated and PC-dependent cities, respectively.

Discussion and Conclusion

Our study shows the huge differences in per capita IWI and composition of types of capital among 210 Chinese cities. The eastern cluster is recognized with a high and ascending sustainable development potential, while the cities in the western cluster perform worst in sustainability due to low-quality human and produced capital at current levels. In order to achieve overall regional sustainable development in China, more development opportunities need to be given to the western region to promote its fast SDG progress. As for the north cluster, despite its high level of IWI per capita, it lags behind with respect to productive efficiency and individual welfare due to the high dependence on the depletable mining industry.

A sustainable city not only requires high level of per capita IWI, but also, and more importantly, an ascending development trend in the long run. Eastern, central and western clusters are all projected to develop smoothly in the future. However, energy-producing cities in the north cluster are likely to face great challenges in the future, which show the slowest level of progress and even face declining IWI per capita without strong policies. In order to meet the SDGs, there is need to stress strong policies in supporting and guiding them to improve human and produced capital and conserve natural capital. Energy-producing cities in the north should transform local traditional industries towards a comprehensive modern energy industry system, which improves production efficiency by extending industrial chain and upgrading industrial technology. Specifically, it is suggested that cities in the north develop high-end manufacturing industries and become the high-end manufacturing center of China, on the basis of their heavy and light manufacturing industrial foundation. To modernize the current industrial structure, development and training of a large quantity and high quality of labor resources for the local economy is needed as well as higher level of investment in high tech sectors. In this way, energy-producing cities can enhance the quality and quantity of human and produced capital. To achieve such a transformation, national and provincial governments need to provide the necessary support infrastructure to facilitate technology transfer between companies and cities. On the other hand, these cities need to strengthen environmental governance and minimize the damages caused by mining. Actually, some resource-exhausted and landscape eco cities could serve as pilot cities in the north cluster, which are projected to steer away from the dependence on non-renewable natural capital towards a higher degree of produced or human capital. For example, due to the growing services industry as well as enhancing scientific and technological innovation capability, the resource-exhausted city Taiyuan will be built into an innovation-oriented city with very high growth speed of IWI per capita.

In addition to the development of human and produced capital, there is also need to enhance natural capital for most Chinese cities. Per capita natural capital of China significantly lags behind that of developed countries like the US, Germany, and Japan(Managi et al., 2019), and the share of natural capital is particularly low in the advanced HC-dominated and PC-dependent cities in the eastern cluster. In China, urban development often seeks rapid value-adding via enhanced human and produced capital, but neglects the long-term welfare of natural capital and its essential role in supporting life through ecosystem services. As such, that calls for a holistic and long-term vision planning to exert synergies and minimise trade-offs across natural, human, and produced capital towards sustainable urban development. Actually, China is pushing its sustainable development forward through building ecological civilization, which reinforces the symbiosis between economic development and environmental protection. For instance, as an Ecological Civilization Pilot city, Wuxi spent 10 years in restoring the lake and improving the aquatic ecosystem, then a lakeside park is established and serves as staging area for family trips. It is hopeful that the natural capital will be protected, conserved and enhanced in China, and be updated regularly to show the progress.

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Figures

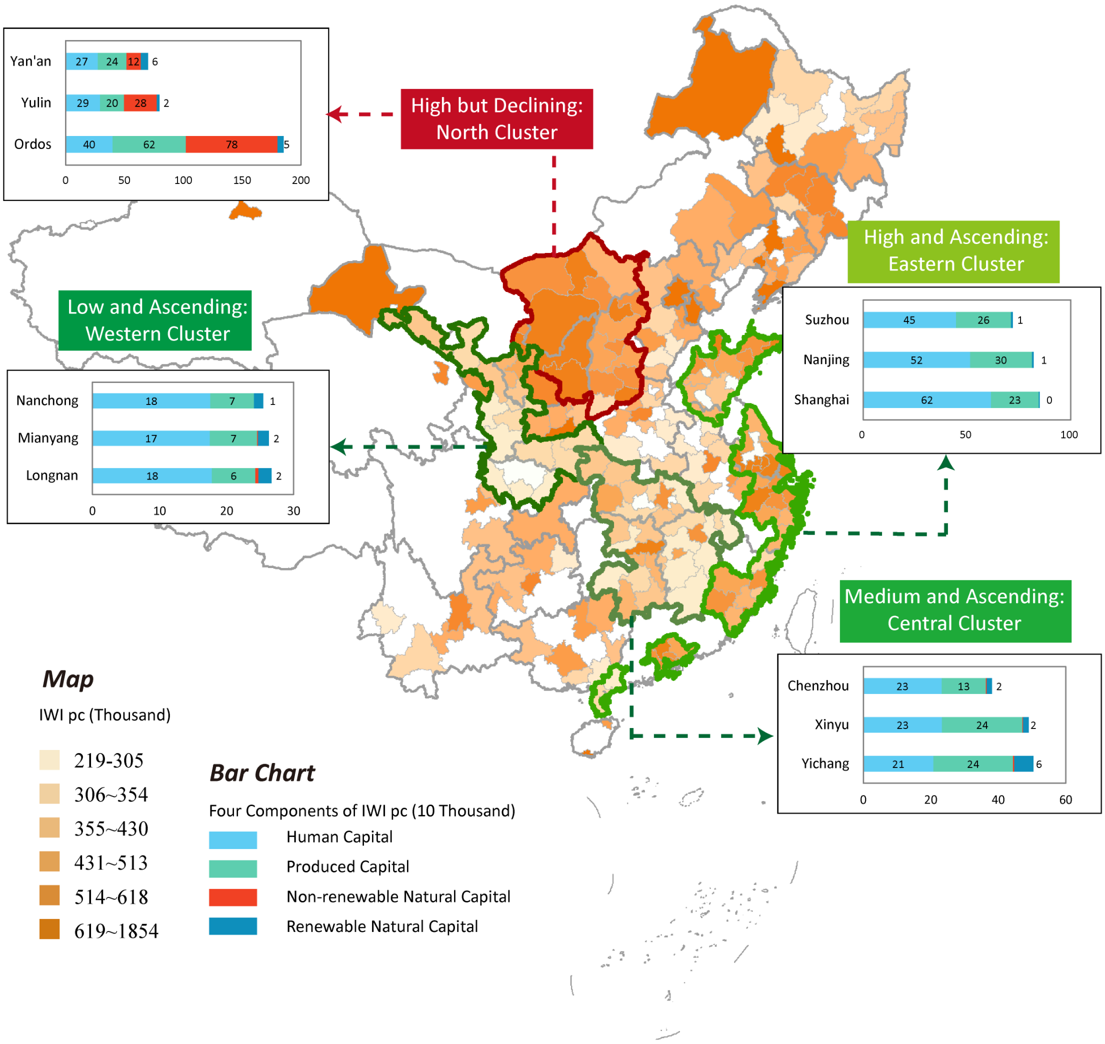

Figure 1 | Inclusive wealth in 210 Chinese cities in 2016. The color of the basic map corresponds to the per capita inclusive wealth (IWI pc, units: thousand), from the poorest in light shades to the wealthiest in dark. The four regions indicate the city clusters, and the bar chart indicates four types of capital for typical cities in clusters.

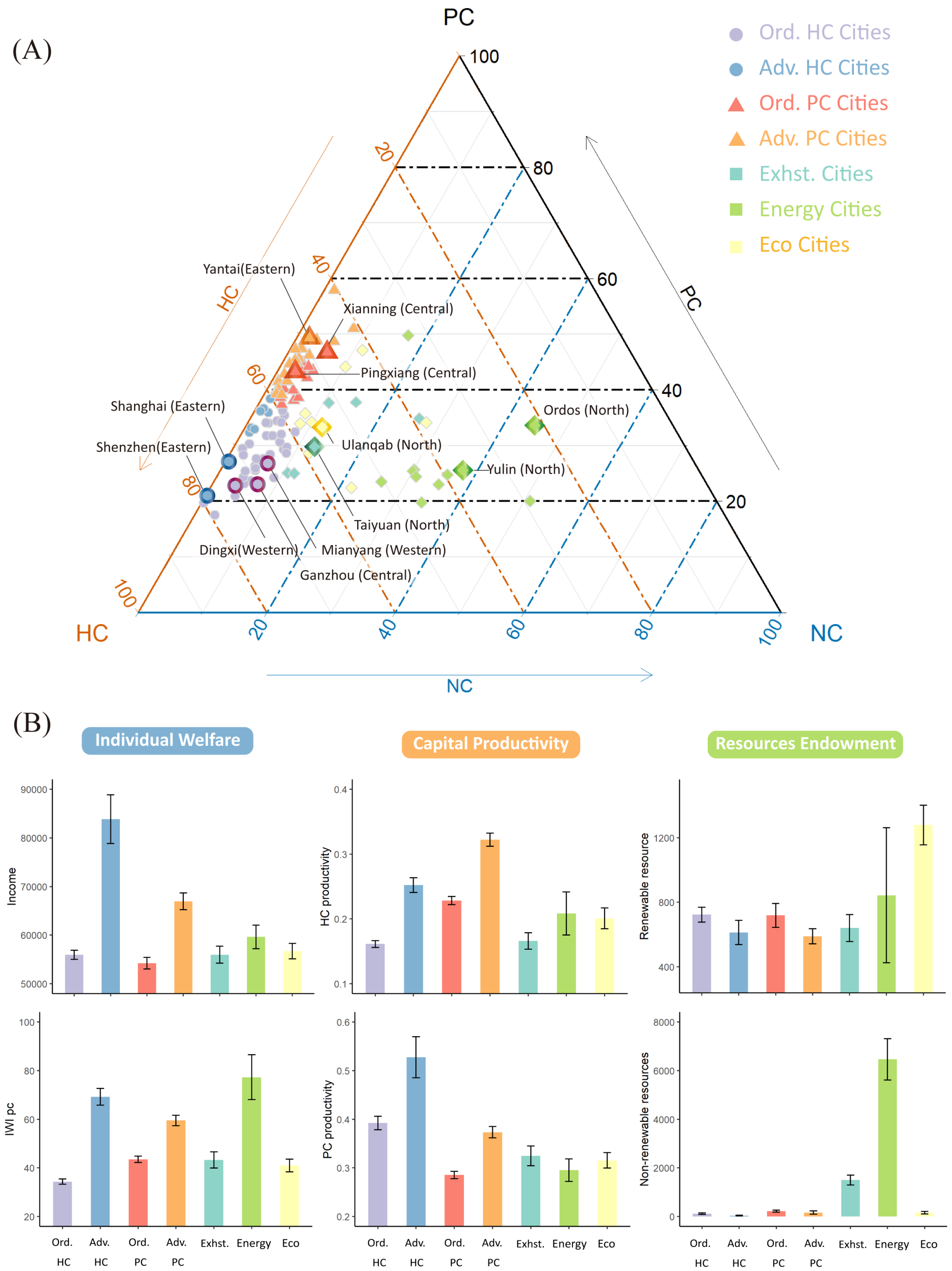

Figure 2| Inner structure of the three capitals for the 210 cities. Figure A shows the distribution of the share of three capitals for each city, with color and shape indicating the categories. The bar chart in Figure B corresponds to the description of individual welfare (thousand yuan), capital productivity and resource endowment (billion yuan) for each type. Ord and Adv refer to the ordinary and advanced subcategories; HC and PC refer to human capital and produced capital; Eco, Energy and Exhst refer to the landscape eco, energy-producing and resource-exhausted subcategories in Natural Capital (NC)-dependent cities.

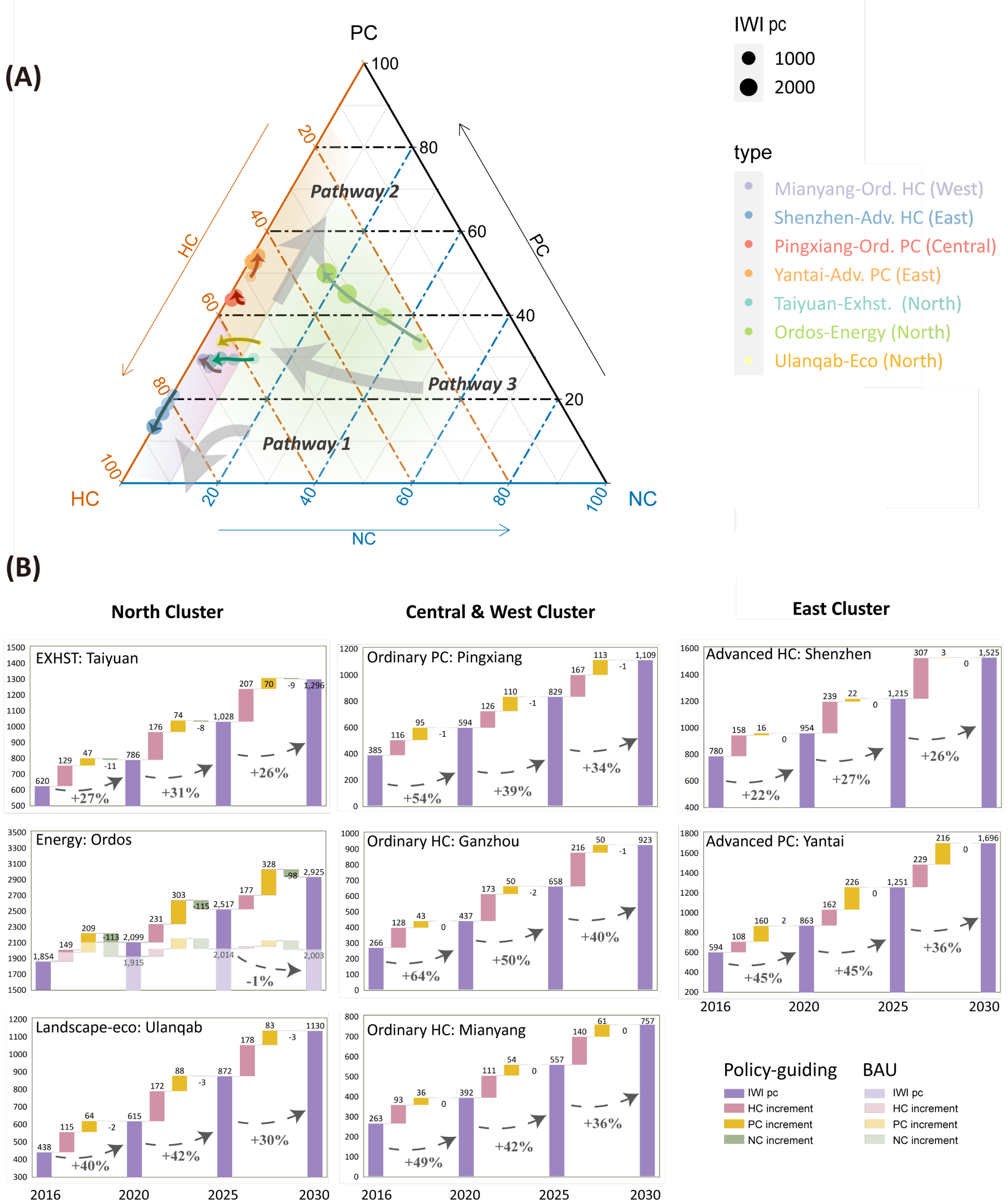

Figure 3| The dynamic pattern of capital structure and IWI growth for typical cities from 2016 to 2030. The triangle scatter figure (A) shows the change of capital ratio and IWI pc (unit: thousand) for each typical city with the arrow indicating the time direction, while the waterfall chart (B) shows the change of capital stock (unit: thousand). BAU refers to the business as usual.