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Measuring sustainability: Development and application of the Inclusive Wealth Index in China

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ABSTRACT

It is increasingly common to use the Inclusive Wealth Index (IWI) to evaluate national sustainability; however, IWI's highly aggregated components and limited regional cases restrict its further application in achieving the Sustainable Development Goals (SDGs). This study extends the traditional three-component IWI framework into six disaggregated components, namely male/female human capital, advanced/ordinary produced capital, and renewable/non-renewable natural capital. We apply the modified framework to China and evaluate the sustainability performance at the provincial level. The results show that China continues to develop with an annual IWI per capita increase rate of 2.3%. Gender inequality is found to hinder the growth of IWI, whereas advanced product features benefit the growth of IWI. The results also suggest significant heterogeneity in provincial IWI primarily due to differences in economic development stages, geographic locations, and uneven IWI growth. IWI growth is largely driven by wealth accumulation resulting from human capital and advanced produced capital. In contrast, insufficient IWI growth is caused by a substantial amount of ordinary produced capital or a continued decline in natural capital. The study provides a basis for tracking progress toward the SDGs and measuring the heterogeneity of regional socio-economic development in China.

1. Introduction

From the redefinition of sustainable development in the *Our Common Future* report to the millennium development goals and the latest Sustainable Development Goals (SDGs) set up by the United Nations General Assembly, sustainable development has been regarded as a holistic concept encompassing economic development, social inclusion, and environmental sustainability (Glaser, 2012; Taylor et al., 2017; United Nations, 2012, 2016; World Commission on Environment and Development, 1987). The measurement of sustainability trajectories based on reliable data and unambiguous metrics can help countries identify pathways and progress toward sustainable development (Kubiszewski et al., 2013; Schmidttraub et al., 2017). While traditional economic indicators such as gross domestic product (GDP) help measure changes in economic flow, they are not sufficient to measure social well-being (Kubiszewski et al., 2013; Yoshida et al., 2018). For this reason, the Genuine Progress Indicator (GPI) has been developed to evaluate the economic performance and growth costs of countries (Andrade and Garcia, 2015; Daly and Cobb, 1989; Hayashi, 2015; Nourry, 2008). Furthermore, the Human Development Index (HDI) has been adopted to assess sustainable development via the addition of environmental indicators (Biggeri and Mauro, 2018; Moran et al., 2008; Baumann, 2021). Compared with these indexes, the Inclusive Wealth Index (IWI) provides a more comprehensive view of sustainable development from the perspective of total assets, including human, produced, and natural capital. This is in line with the three pillars of sustainable development

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(Ahmad et al., 2018; Ehrlich et al., 2012), and the IWI can therefore be used to directly assess whether economic development is sustainable, i.e., a non-declining IWI per capita indicates that the well-being of future generations will not be destroyed by the contemporary generation, thereby indicating a sustainable society (Arrow et al., 2004; Dasgupta, 2008, 2014; Polasky et al., 2015).

The IWI framework has been widely used to measure sustainability at the national level, including in both emerging countries (Kurniawan et al., 2021) and developed countries (Lange et al., 2018; Managi and Kumar, 2018; Polasky et al., 2015; UNU-IHDP and UNEP, 2012, 2014); however, it has rarely been applied at the state or provincial level, primarily due to data availability. Yoshida et al. (2018) performed the IWI assessment for Sado Island, Japan, in detail but only at a local scale, Mumford (2012) constructed an accounting of the capital assets of each of the 48 contiguous U.S. states, and Wang et al. (2020) focused on the performance of three types of capital in four different years in provinces of China. These studies represent reasonable attempts to provide IWI information for sub-national applications but were too broad or simple to explicitly collect time-series evidence and IWI components at a disaggregated level. Furthermore, while the current IWI framework is advanced in seeking a unified and inclusive metric to measure the sustainability of an entire society, it may not be sufficient to deal with the indispensable gender equality (SDG 5) and industrial structure (SDG 9) issues discussed in the SDGs.

In this context, in the present study, the three conventional aggregated capital components in the IWI are disaggregated into six components, i.e., male human capital (HC-*M*) and female human capital (HC-*F*), advanced produced capital (PC-*A*), and ordinary produced capital (PC-*O*), and renewable natural capital (NC-*R*) and non-renewable natural capital (NC-*N*), at the sub-national level. This modified framework is then applied to measure the IWI development of each province in China during 2000–2016. Information about men and women, such as their number of years of education, salaries, expected lifetime, and working period, is captured separately to reflect the gender difference in human capital. Moreover, the produced capital in 28 industries is respectively calculated and categorized into two groups, namely advanced and ordinary produced capital. The natural capital in each province, such as non-hydro renewable power, wind, and solar energy, is also included, and the renewable and non-renewable natural capitals are compared. As China exhibits unbalanced regional development due to different urbanization and industrialization levels, as well as unbalanced resource endowments (State Council of China, 2016), the assessment of the IWI progress of different provinces has significance for tracking China's progress toward the SDGs and measuring the heterogeneity of regional socio-economic development. From a broader perspective, the proposed IWI framework could also contribute to the measurement of the state of sustainable development in other developing countries and emerging economies, which can provide valuable insights to reduce the development gap at a sub-national level.

2. Methods and data

2.1. Male and female human capital

Human capital reflects the levels of education, labor, and salary in a region (Arrow et al., 2010; UNU-IHDP and UNEP, 2012, 2014). To capture the gender difference in human capital, male and female human capital are separately assessed, and their sum constitutes the total human capital (Eq. (1)). Thus, in the calculation process, rates of return on educational investments, education levels, salaries, and the expected lifetime working period are calculated separately for male and female workers to reflect the actual gender differences in China.

$$HC_{it} = \sum_{f=0}^{1} HCW_{itf} \tag{1}$$

where HC_{it} is the total human capital of province *i* in year *t*, and HCW_{itf} is the human capital by gender (male if $f = 1$ and female if $f = 0$), which can be further expressed by Eq. (2).

$$HCW_{itf} = h_{itf} \cdot P_{itf} \cdot \overline{Price_{shadow_{if}}} \tag{2}$$

where *h* refers to human capital per individual, which is related to educational attainment and the rate of return on education ρ (see Eq. (3)) (Arrow et al., 2012; Klenow and Rodríguez-Clare, 1997). Moreover, P_{itf} is the working-age population; according to the actual situation of China and the availability of statistical data, the working-age population of the provinces is considered to be 15–64. Finally, $\overline{Price_{shadow}}$ is the shadow price per unit of human capital, which is the average labor remuneration of per-unit human capital from 2000 to 2016 (see Supplementary Methods).

$$h_{itf} = e^{\rho_f \bullet \mathrm{Edu}_{itf}} \tag{3}$$

where *Edu* is educational attainment (the average number of years of total schooling per individual), and ρ is the rate of return on education, which is estimated to be 7.29% for males and 8.50% for females according to the household survey data used for the China Human Capital Report (2017) (see Supplementary Methods).

Furthermore, the human capital per capita for each gender is calculated by the ratio of human capital to the corresponding population by gender (Eq. (4)). Therefore, the human capital per capita of each province is consistent with the produced capital per capita and the natural capital per capita but is not consistent with the sum of the human capital per capita of male and female workers.

$$PHC_{itf} = HC_{itf} / POP_{itf} \tag{4}$$

In Eq. (4), *PHC* is the human capital per capita, *HC* is the total amount of human capital, and *POP* is the total population of the province.

2.2. Advanced and ordinary produced capital

In terms of sector division, the produced capitals of 11 major sectors and 28 sub-manufacturing sectors in 30 provinces of China from 2000 to 2016 were calculated. The 11 major sectors include Agriculture, Mining, Manufacturing, Electricity, Construction, Wholesale, Transportation, Social Services, Finance, and Scientific Research, Education and Culture, and Health and Sports (SEAH), as well as Other Services including Real Estate. The specific sector aggregation and disaggregation processes are provided in the Supplementary Methods. Advanced manufacturing capital and modern service capital are collectively referred to as advanced produced capital, while ordinary manufacturing capital and traditional service capital are collectively referred to as ordinary produced capital.

Specifically, produced capital (advanced and ordinary) is calculated as follows:

$$PC_{it} = PCS_{it} + PCN_{it} \tag{5}$$

where *PC* is the total produced capital, *PCS* is the advanced produced capital, which comprises the produced capital of advanced manufacturing and the modern service industry (including the sectors of Finance, Social Services, Education and Scientific Research, and Real Estate), *PCN* is the ordinary produced capital, which includes the produced capital of the Agriculture, Mining, Ordinary Manufacturing, Electricity, Construction, and Traditional Services sectors (including Wholesale, Transportation, and Other Services, and excluding Real Estate). It should be noted that Real Estate is categorized as advanced produced capital with reference to the design of the statistical standard of the modern service industry proposed by Xu and Chang (2004) (see Supplementary Methods).

Following King and Levine (1994), Easterly et al. (1993), and the

United Nations Development Programme (UNDP) (UNU-IHDP and UNEP, 2012, 2014), the perpetual inventory method (PIM) is used to calculate the produced capital of each element:

$$K_{ist} = \sum_{T=1}^{t} I_{isT}(1-\delta_s)^{t-T} + (1-\delta_s)^t K_{is0} \quad (6)$$

where K_{ist} is the produced capital of industry s in province i in year t ($T \leq t$), I_{isT} is the corresponding new investment, δ is the depreciation rate of the industry differentiated by sector (see Supplementary Methods), and K_{is0} is the produced capital of industry s in the base year, 1996, which is determined according to data availability. The produced capital per capita is derived by dividing the total amount of produced capital by the total population.

2.3. Renewable and non-renewable natural capital

When measuring economic development, changes in natural resources are often overlooked (Fenichel et al., 2016; Lu et al., 2015; Schmidttraub et al., 2017); however, these changes are vital factors in sustainability measurement. The calculation of natural capital is included in this study, and natural capital is classified as renewable and non-renewable resources to identify the sustainable development of natural resource utilization (Eq. (7)). It should be noted that stocks of non-renewable resources will always decline, i.e., they are characterized by a decreasing wealth component, so their contribution will be negative to the total IWI. In addition, unlike in the framework used by the United Nations Environment Programme (UNEP) (UNU-IHDP and UNEP, 2014), solar and wind energy are incorporated into the natural capital accounting framework, and the key parameters are updated and refined based on actual data to make more reliable estimations.

$$NC_{it} = NCR_{it} + NCN_{it} \quad (7)$$

where *NC* is the total natural capital, *NCR* is the renewable natural capital, and *NCN* is the non-renewable natural capital. The natural capital per capita is obtained by dividing the total natural capital by the total population.

Furthermore, the renewable natural capital is assessed by Eq. (8), and the non-renewable natural capital is assessed by Eq. (9).

$$NCR_{it} = WCL_{it} + WPL_{it} + TIW_{it} + ESW_{it} + WFI_{it} + WRW_{it} + WRS_{it} \quad (8)$$

where *NCR* represents renewable natural capital, and *WCL, WPL, TIW, ESW, WFI, WRW,* and *WRS* are the total wealth in croplands, pasturelands, timber, non-timber forest resources, fisheries, wind energy, and solar energy, respectively, which are calculated by different approaches (see Supplementary Methods). In particular, for the calculation of the wealth of non-timber resources, the economic benefits of non-timber resources are respectively evaluated as two separated prices for high-income provinces and other provinces via the method proposed by Lampietti and Dixon (1995). Moreover, a new method is put forward to evaluate fish stocks based on production and optimal fishing times; and the wind/solar energy wealth can be obtained by multiplying the wind/solar resource potential (excluding those already explored) with its rental price, where the renewable resource potential is calculated by multiplying the corresponding exploitable potential with the technically feasible utilization hours in a year (see Supplementary Methods).

$$NCN_{it} = WFO_{it} + WM_{it} \quad (9)$$

where *NCN* represents non-renewable natural capital, *WFO* is the wealth of fossil energy, including coal, oil, and natural gas, and *WM* is the wealth of metal and mineral resources, including bauxite, copper, iron, lead, phosphorus, zinc, and pyrite. These values are estimated by multiplying the resource stock and unit rental price. The ending year of reserves is set as 2016 and the corresponding stock in the year *t*-1 is derived from the production and stock in year *t*. Rental prices (a newly defined terminology) are obtained by multiplying the natural resource prices and the corresponding sectoral rental rates derived from the UN University–International Human Dimensions Programme (UNU-IHDP) and UNEP (2012).

2.4. Total inclusive wealth index

The total value of capital assets, or wealth, is concretely measured by summing the social worth of each type of capital of a nation, where the social (or shadow) price per unit of capital acts as a weight in IWI calculation (UNU-IHDP and UNEP, 2012, 2014). After calculating the human capital (male/female), the produced capital (advanced/ordinary), and the natural capital (renewable/non-renewable), the total IWI is obtained as follows:

$$IWI_{it} = HCW_{it0} + HCW_{it1} + PCS_{it} + PCN_{it} + NCR_{it} + NCN_{it} \quad (10)$$

where IWI_{it} is the total IWI of province i in year t.

2.5. Data sources

2.5.1. Human capital

The data on education levels, the 15- to 64-year-old population, and the wages of on-the-job workers were sourced from the China Statistical Yearbook 2001–2017. Moreover, the proportion of the employed population was determined from the China Labor Statistical Yearbook 2001–2017. The data of the proportion of women's wages to men's wages in all provinces were sourced from the Executive Report of the 3rd Survey on the Status of Chinese Women. However, the data of Jilin, Zhejiang, Jiangxi, Henan, Guangxi, Chongqing, Guizhou, Yunnan and other provinces were lacking. Therefore, the average of three-year survey data from the China General Social Survey was used as the proportion of female wages to male wages in these provinces. The provincial age-specific and gender-specific population data were derived from the China Census 2000 and 2010 and were interpolated from the 2000 and 2010 census population data.

2.5.2. Produced capital

The data of fixed asset investments in different industries in different provinces from 1996 to 1998 and in 2002 were sourced from the China Fixed Assets Statistical Yearbook, and the data for 1999 were sourced from the China Real Estate Statistical Yearbook 2000. Data for 2000 and 2001 were not available, so they were obtained by interpolation based on the data for 1999 and 2002. The data of fixed asset investments in different industries in different provinces from 2003 to 2016 were sourced from the China Statistical Yearbook. Finally, the data of fixed asset investments in China's urban manufacturing industry were sourced from the China Fixed Assets Statistical Yearbook.

2.5.3. Natural capital

The data of the harvested area, yield, production cost, and market price of rice, wheat, maize, soybean, peanuts, flue-cured tobacco, sugarcane, sugar beet, and other crops in the provinces from 2000 to 2016 were all sourced from China Rural Statistical Yearbook 2001–2017, and the land price data were sourced from the TULIU website. The pasture area of each province from 2000 to 2016 was derived from the China Statistical Yearbook, and because the statistical results are calculated every five years, the interpolation method was used to calculate the data of the intermittent years. The standing stock of timber resources and the forest area data were all derived from the China Forestry Statistical Yearbook. The agricultural prices were sourced from the China Agricultural Products Price Survey Yearbook, and the agricultural output data were sourced from the China Fisheries Statistics Yearbook. The data of wind energy resource potential were sourced from the China Renewable Energy Prospect 2016, while the data of solar energy resource potential and installed capacity were sourced from the National

Renewable Energy Centre. Coal price data were sourced from the WIND database, and oil and gas price data were sourced from the World Energy Statistics Yearbook. The average price of power coal from January to December in 2010 was considered the coal price during the study period. Finally, the reserves of metals and minerals were derived from the database of the National Bureau of Statistics, and the production data were derived from the WIND database.

3. Results

3.1. Analysis of China's IWI with provincial heterogeneity

3.1.1. China's IWI shows sustainability along with increasing provincial heterogeneity

Both the national and per capita IWI of China continued to increase from 2000 to 2016. The national IWI increased from 598 trillion yuan to 941 trillion yuan (at 2010 constant prices, the same below), with an average annual growth rate of 2.9% (Fig. S1). The IWI per capita also continued to increase from 476 thousand yuan to 684 thousand yuan, with an average annual growth rate of 2.3% (Fig. S2), which indicates that China was developing sustainably during this period (Arrow et al., 2012; Arrow et al., 2003; World Commission on Environment and Development, 1987). Changes in the structure of per capita IWI indicate that produced capital, including PC-*A* and PC-*O*, is becoming the primary driving factor of IWI per capita. For instance, during the period of 2010–2016, the contributions of PC-*A* and PC-*O* to China's IWI per capita growth reached 58.1% and 41.8%, respectively, whereas human capital only contributed 5.7%, although it was the most significant component of the IWI (Figs. S3 and S4).

Evident spatial heterogeneity in the per capita IWI was also observed during 2000–2016 and was primarily due to differences in the economic development stages and geographic locations of the provinces. Fig. 1 presents the IWI and GDP per capita of China's 30 provinces in 2000, 2005, 2010, and 2016. Provinces with a high per capita IWI are largely located in China's eastern regions, which are its most developed areas containing most of the higher-level talents (human capital) and developed manufacturing bases (produced capital); in 2016, Beijing, Shanghai, and Tianjin respectively ranked first, second, and fourth in IWI per capita. In particular, Beijing and Shanghai had similar IWI structures (Fig. S5), in which human capital accounted for nearly 80% of their total IWI, and advanced produced capital contributed about 80% of their total produced capital. Some provinces rich in natural resources, such as Inner Mongolia, Shanxi, and Ningxia, also ranked high in IWI per capita, respectively ranking third, fifth, and sixth in 2016, due to their abundant resource endowments and relatively small populations.

In contrast, the provinces with low rankings of IWI per capita are mainly in less developed areas in central and western China with limited higher-level talents (human capital) and underdeveloped manufacturing bases (produced capital), such as Sichuan, Gansu, and Jiangxi, which respectively ranked 28th, 29th, and 30th in 2016. While the leading three provinces (Beijing, Shanghai, and Inner Mongolia) remained unchanged in 2000–2016, the bottom three provinces varied significantly, except for Jiangxi, which always remained at the bottom of the per capita IWI ranking. Moreover, the provincial IWI gap between the high- and low-ranking provinces remained considerable over the same period.

3.1.2. The increased heterogeneity in provincial IWI per capita due to uneven IWI per capita growth

The IWI per capita growth is an intuitive indicator by which to measure the sustainable development of a region in a given period, reflecting its wealth investment and progress. Consistent with the national IWI growth, the total and per capita IWI of each province were found to have improved to different extents from 2000 to 2016 (Fig. S6). The universal growth of IWI per capita in China's provinces was very different from the situation in other countries, among which 55 of the world's 140 countries (40%) experienced a decline (UNU-IHDP and UNEP, 2012, 2014). Fig. 2 presents the IWI per capita growth of China's 30 provinces during the periods of 2000–2005, 2005–2010, and

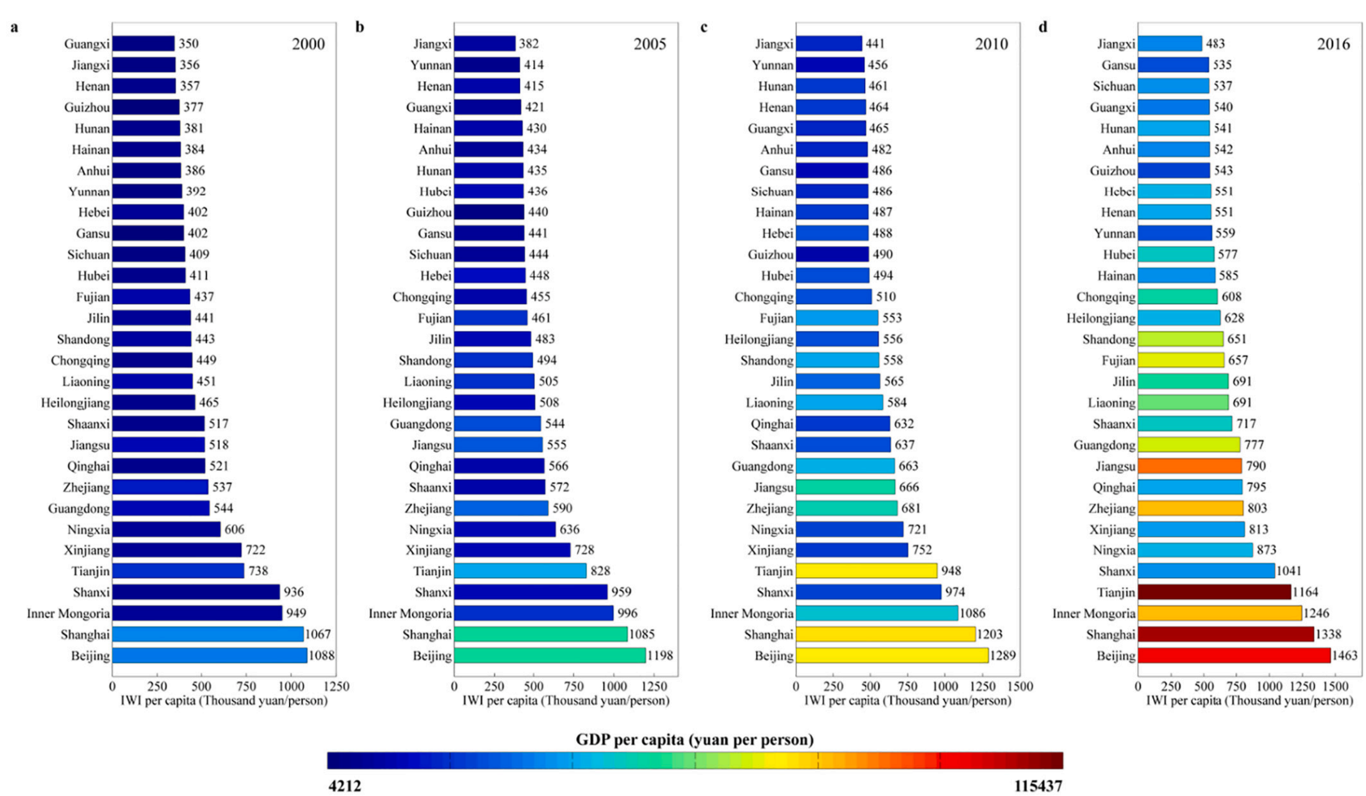

Fig. 1. The IWI and GDP per capita of China's 30 provinces: (a) 2000, (b) 2005, (c) 2010, and (d) 2016.

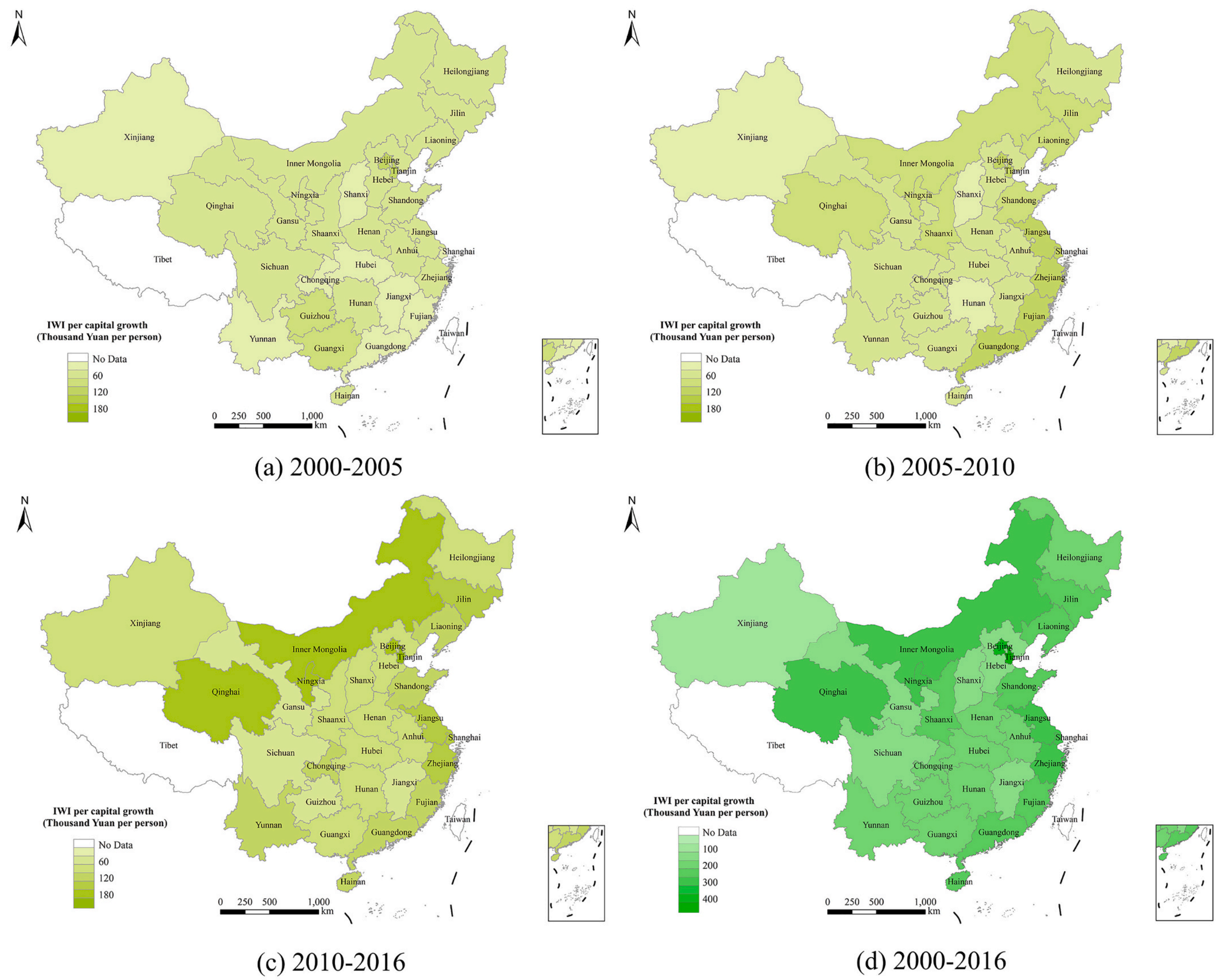

Fig. 2. The IWI per capita growth of China's 30 provinces during different periods: (a) 2000–2005, (b) 2005–2010, (c) 2010–2016, and (d) 2000–2016.

2010–2016, as well as the entire period of 2000–2016. The uneven IWI per capita growth was found to ultimately intensify the heterogeneity in provincial IWI per capita (Fig. 1). Specifically, Beijing, Shanghai, Inner Mongolia, and Tianjin exhibited prominent IWI per capita stocks and high IWI per capita growth, and respectively ranked second, sixth, third, and first in 2000–2016. In contrast, Jiangxi, Gansu, and Sichuan had small IWI per capita stocks and low IWI per capita growth, and respectively ranked 28th, 26th, and 27th in 2000–2016. Unlike IWI stocks, IWI growth can clearly reflect the differences in sustainable development processes across provinces, especially for those provinces with abundant resource endowments. For instance, Inner Mongolia, Shanxi, Ningxia, and Xinjiang all displayed high IWI per capita stocks; however, Inner Mongolia and Ningxia ranked high in IWI per capita growth (third and seventh, respectively), while Shanxi and Xinjiang ranked 28th and 30th, respectively. The significant differences in the IWI per capita growth of these provinces indicate that the natural capital decline caused by resource consumption contributed more to the human and produced capital growth in Inner Mongolia and Ningxia. In contrast, Shanxi and Xinjiang faced the considerable challenge of resource consumption and weak IWI growth.

3.1.3. *The relationship between the IWI and GDP*

In general, a slightly positive correlation was found between the GDP per capita growth rate and the IWI per capita growth rate from 2000 to 2014 (Fig. S7), indicating that IWI growth is closely related to economic development. It is worth noting that the rate of increase of IWI per capita is usually significantly smaller than that of GDP per capita. Inner Mongolia, for example, had the highest GDP growth rate among the 30 provinces from 2000 to 2014, namely 15%, but its IWI growth rate was only 1.6%. Moreover, technological change can be regarded as another form of capital assets. Total factor productivity (TFP) is an approximate indicator of technological change, and the TFP growth rate can be added directly to the IWI growth rate if it has a shadow price of one (Mumford, 2012; UNU-IHDP and UNEP, 2012). Fig. S8 reveals a weak positive correlation between the GDP per capita growth rate and the IWI + TFP per capita growth rate from 2000 to 2005, and a slightly negative correlation from 2005 to 2014. This negative correlation after 2005 is consistent with that experienced in the United States (Mumford, 2012). After 2005, more provinces tended to have higher GDP growth rates as compared with lower IWI + TFP growth rates, especially Chongqing, Sichuan, and Guizhou (corresponding to the three dots at the bottom right of the figure). While these three provinces have achieved significant GDP growth, their sustainability level involving technological progress still lags far behind their GDP. On the contrary, Beijing and Shanghai are both characterized by the powerful effect of technological progress on sustainability.

3.2. Analysis of China's IWI growth from the perspective of the IWI per capita structure

3.2.1. Gender inequality

The IWI per capita structure was considered in the six-component context to capture the differences in gender, industry shifts, and resource types. The inner structure of human capital per capita in 2016 (Figs. 3(a-b) and S9) reveals that the absolute gaps between HC-*M* and HC-*F* in most of the 30 provinces were fairly significant, ranging from 154 thousand yuan to 293 thousand yuan, i.e., the HC-*F* per capita in each province was much lower than the HC-*M* per capita, leading to national gender inequality. The gender inequality in some provinces, mainly including Guangdong, Tianjin, Shanxi, Zhejiang, Anhui, and Hainan, was aggravated significantly from 2000 to 2016. The increased gap seemed to impact the IWI growth to a large extent, especially for provinces for which human capital was dominant in their total IWI. For instance, Guangdong exhibited the widest gender gap in 2016, namely 443 thousand yuan/person HC-*F* vs. 736 thousand yuan/person HC-*M*. Thus, from 2000 to 2016, Guangdong's IWI per capita growth gradually lagged, ranking 11th, whereas Beijing and Shanghai, which have similar IWI structures as Guangdong, narrowed that gap and achieved higher growth rankings of second and sixth, respectively. These results can be attributed to the different numbers of years of education and labor demands among provinces. Notably, the financial and service industries, which play the most significant roles in the economic development of Beijing and Shanghai, have a higher demand for female employees, who are considered more communicative, attentive, compassionate, and patient than males. On the contrary, Guangdong's secondary industry still accounts for nearly half of its GDP (e.g. 48.9% in 2016), indicating that more labor requiring physical attributes was needed. On the other hand, the number of years of education contributes to narrowing the gender gap and achieving more equality (Heymann et al., 2019; Okenwa-Emgwa and von Strauss, 2018). Beijing and Shanghai are the best-educated regions with an average educational attainment of 12.4 and 11.0 years, respectively, which is beneficial to achieving a small IWI gender gap.

3.2.2. Produced capital feature

The inner structure of produced capital per capita in 2016 (Figs. 3(c-d) and S10) reveals obvious inequality in the advanced and ordinary industrial output; 19 provinces had absolute gaps between PC-*A* and PC-*O* exceeding 20 thousand yuan/person, and the absolute gaps of seven provinces exceeded 50 thousand yuan/person. The inequality in some provinces tended to be significantly aggravated during 2000–2016; these provinces mainly included the six positive-gap (PC-*A* minus PC-*O*) provinces of Beijing, Shanghai, Tianjin, Jiangsu, Zhejiang, and Hainan, and the nine negative-gap provinces of Hebei, Shanxi, Heilongjiang, Gansu, Ningxia, Qinghai, Inner Mongolia, and Xinjiang. The aggravation of different produced capital structures may impact the IWI, with more advanced produced capital benefitting IWI growth, especially for provinces characterized by the domination of produced capital in their total IWI. Thus, from 2000 to 2016, the IWI per capita growth of Tianjin, Jiangsu, and Zhejiang gradually climbed to leading positions, ranking first, fifth, and eighth, respectively, whereas Hebei and Gansu, which have significant ordinary produced capital, achieved lower IWI per capita growth rankings of 25th and 26th, respectively.

3.2.3. Resource type

The inner structure of natural capital per capita in 2016 (Figs. 3(e-f) and S11) indicates that the absolute gaps between NC-*R* and NC-*N* in some provinces were fairly significant, with nine provinces exceeding 15 thousand yuan/person and six provinces exceeding 70 thousand yuan/person. However, changes in the absolute gaps between NC-*R* and NC-*N* would not directly impact the IWI. For instance, from 2000 to 2016, the gaps of Ningxia and Shaanxi exhibited similar changing trends from −112 thousand yuan/person to −75 thousand yuan/person, and from −107 thousand yuan/person to −73 thousand yuan/person, respectively (NC-*R* minus NC-*N*); however, their performances in IWI per capita growth during this period were obviously different, ranking 7th and 15th, respectively. This indicates that the resource type is not as important as gender inequality or the produced capital feature for influencing IWI growth.

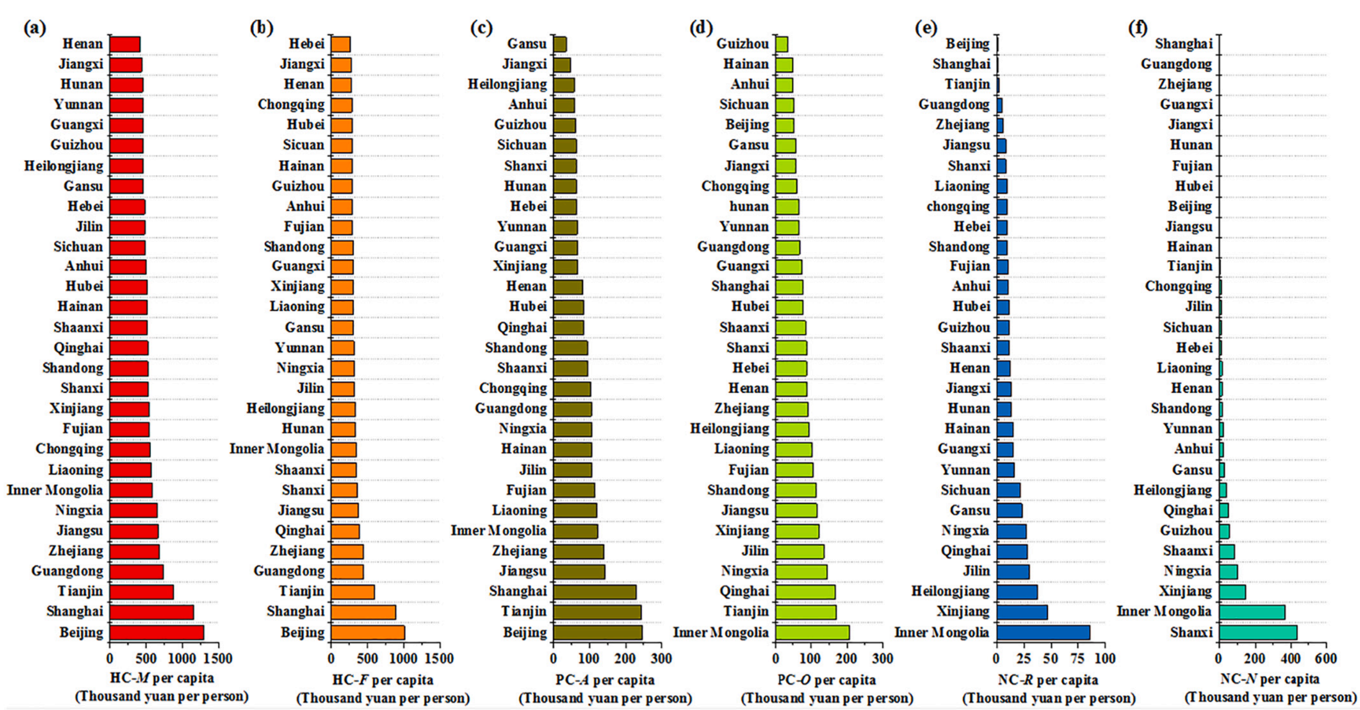

Fig. 3. The IWI per capita structure, including the HC-*M* and HC-*F*, PC-*A* and PC-*O*, and NC-*R* and NC-*N* of China's 30 provinces in 2016. (The IWI was calculated at 2010 constant prices.)

3.3. Diverse wealth accumulation patterns with provincial IWI driving factors

According to the relative contributions of different types of capital assets to IWI growth (Fig. S5 and S6), the 30 provinces can be classified into four categories, namely those associated with different driving factors corresponding to human capital, advanced produced capital, ordinarily produced capital, and natural capital, respectively (Fig. 4). The results demonstrate that provincial IWI driving factors lead to diverse wealth accumulation patterns corresponding to various

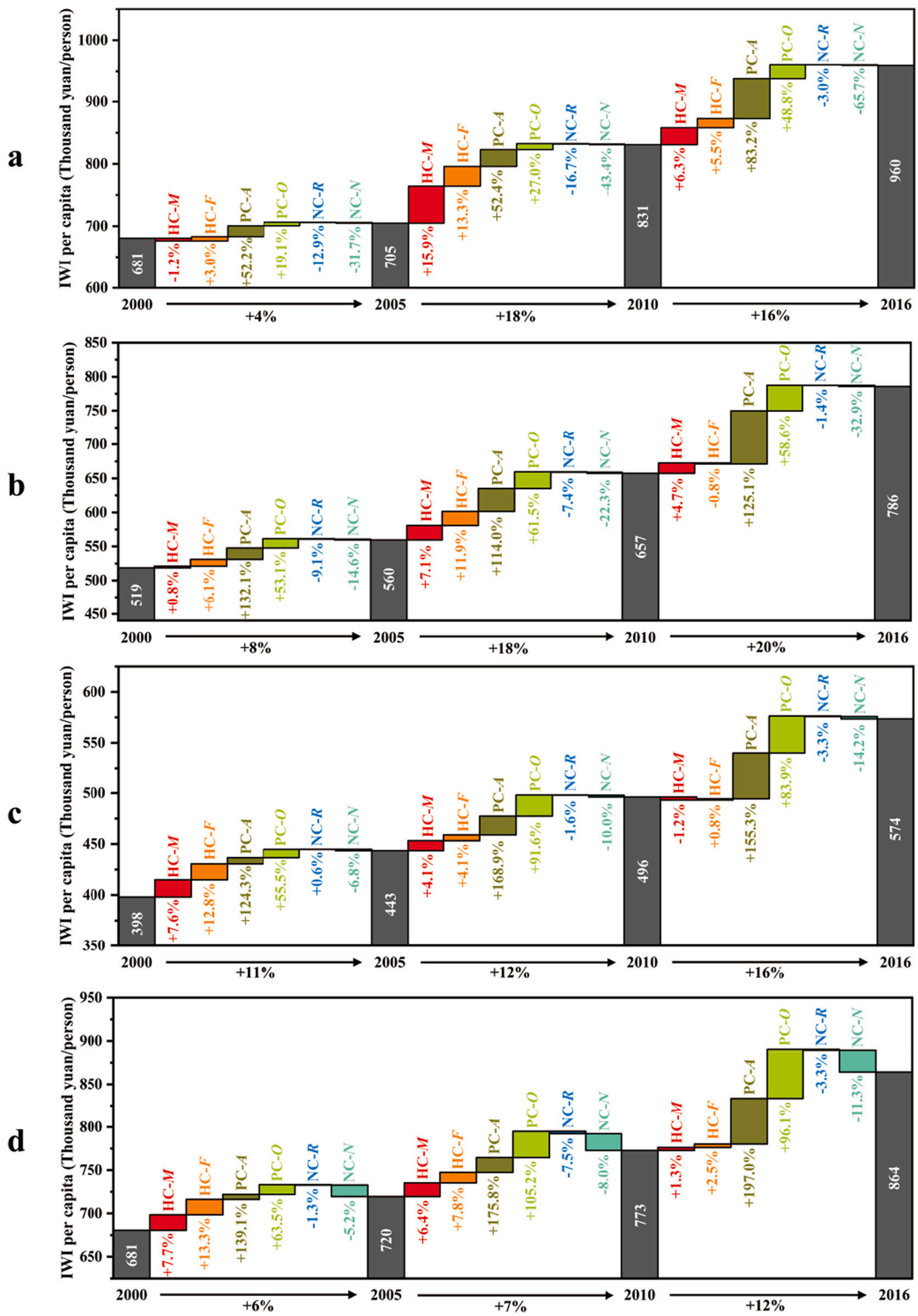

Fig. 4. The contributions of different driving factors to provincial IWI per capita in four categories from 2000 to 2016: (a) HC-driven category, including Beijing, Shanghai, and Guangdong; (b) PC-*A*-driven category, including Tianjin, Zhejiang, Jiangsu, Chongqing, and Hainan; (c) PC-*O*-driven category, including Jilin, Liaoning, Hebei, Shandong, Henan, Anhui, Hubei, Hunan, Jiangxi, Fujian, Guangxi, Yunnan, Guizhou, Sichuan, and Gansu; (d) NC-dependent category, including Heilongjiang, Inner Mongolia, Shanxi, Ningxia, Shaanxi, Qinghai, and Xinjiang.

pathways to regional sustainable development.

3.3.1. HC-driven category

Considering that the average HC growth of Beijing, Shanghai, and Guangdong was significantly larger than that of the provinces in the other three categories, especially during the period of 2005–2016, these provinces are classified into the HC-driven category, and their IWI per capita is driven by human capital (Fig. 4a). The average human capital growth of these three provinces from 2000 to 2016 contributed 48.5% (29.5% for HC-*M* and 19.0% for HC-*F*) of their IWI per capita growth, and accounted for 42.2% of the total human capital growth in China. Specifically, the human capital of Beijing, Shanghai, and Guangdong respectively contributed 46.7%, 37.3%, and 46.9% of their IWI per capita growth. The significant contributions of human capital are primarily attributed to the rapid expansion of the labor force (15–64 years old), especially skilled labor. The labor force of these provinces increased from 83.9 million in 2000 to 118.6 million in 2016 with a 2.2% average annual growth rate, which was much higher than the 0.8% national average (NBS, 2001-2017). Moreover, the reputation of high-quality education and competitive wages in Beijing, Shanghai, and Guangdong attract or retain many skilled and talented workers. For instance, the number of graduate students in these three provinces accounted for 36% of China's total in 2016 (NBS, 2018). As human capital contributes to returns through professional skills and innovation, Beijing, Shanghai, and Guangdong experienced significant IWI per capita growth from 2000 to 2016, ranking second, sixth, and 11th, respectively.

3.3.2. PC-A- and PC-O-driven categories

Tianjin, Zhejiang, Jiangsu, Chongqing, and Hainan are classified into the PC-*A*-driven category, considering that the average advanced produced capital growth of these five provinces was significantly larger than that of the provinces in the other three categories, especially during the period of 2010–2016 (Fig. 4b). The average advanced produced capital growth of these five provinces from 2000 to 2016 contributed 48.3% of their IWI per capita growth and accounted for 33.4% of the total advanced produced capital growth in China. The significant contributions from advanced produced capital related to the development of the high-quality manufacturing and modern service industries advanced the IWI per capita growth of these provinces by effectively stimulating wealth accumulation. Driven by advanced produced capital, Tianjin, Jiangsu, Zhejiang, and Hainan experienced significant IWI per capita growth from 2000 to 2016, ranking first, fifth, eighth, and 14th, respectively. For instance, the number of high-tech enterprises in Jiangsu increased significantly from 2980 in 2010 to 12,946 in 2016, an increase that was only lower than that of Guangdong, resulting in a substantial increase in the advanced produced capital that contributed 47.7% of the IWI per capita growth, whereas ordinary produced capital contributed only 32.3%.

Jilin, Liaoning, Hebei, Shandong, Henan, Anhui, Hubei, Hunan, Jiangxi, Fujian, Guangxi, Yunnan, Guizhou, Sichuan, and Gansu are classified into the PC-*O*-driven category, considering that the average ordinary produced capital growth of these 15 provinces from 2000 to 2016 was larger than that of the provinces in the PC-*A*-driven category (Fig. 4c). The average ordinary produced capital growth of these 15 provinces from 2000 to 2016 contributed 37.1% of their IWI per capita growth and accounted for 23.5% of the total ordinary produced capital growth in China (note that 23.5% is not dominant here, because a large proportion of contributions comprised those of other provinces classified into the subsequent NC-dependent category). Unlike the advanced produced capital-driven provinces, which usually occupied high growth rankings, the 15 provinces in this category ranked from ninth (Jilin) to 28th (Jiangxi) from 2000 to 2016. Although Shandong, Henan, and Sichuan have large populations, the poor talent base, traditional industrial structure, and insufficient natural endowment in most of those 15 provinces have become the crucial factors that have restricted the transformation of their economic structure and their long-term sustainability. For instance, 45.7% of the IWI per capita growth in Hebei was found to be driven by ordinary produced capital, and 40.0% was found to be driven by advanced produced capital, reflecting that Hebei still relies on the traditional low-skilled and semi-skilled industries. Hebei accounted for 23% of China's total steel output in 2016, playing a vital role in meeting the national steel demand; as the backbone of Hebei's booming economy, it will be challenging to significantly change the industrial structure in the short term. Although Hebei and Jiangsu both ranked in the top 10 in total IWI growth (Fig. S6), Hebei (25th) lagged far behind Jiangsu (fifth) in IWI per capita growth, suggesting that advanced produced capital is superior to ordinary produced capital in stimulating wealth accumulation.

3.3.3. NC-dependent category

Heilongjiang, Inner Mongolia, Shanxi, Ningxia, Shaanxi, Qinghai, and Xinjiang are classified into the NC-dependent category, considering that the average natural capital decline (especially that of NC-*N*) of these seven provinces from 2000 to 2016 was significantly greater than that of the provinces in the other three categories (Fig. 4d). The IWI per capita of the provinces in this category largely depends on the consumption of natural capital, especially non-renewable capital. The decline of the average natural capital of these seven provinces from 2000 to 2016 contributed to −33.9% of their IWI per capita growth and accounted for 79.4% of the total natural capital decline in China. The natural capital decline hindered the IWI per capita growth of these resource-dependent provinces to varying degrees. Severely affected by their natural capital decline, Heilongjiang (21st), Shanxi (29th), and Xinjiang (30th) are facing considerable challenges in sustainable development with relatively low growth rankings of IWI per capita. For instance, the non-renewable natural capital of Shanxi and Xinjiang respectively decreased by 10.2% and 15.5% from 2000 to 2016, thereby respectively offsetting 18.6% and 26.5% of their total human and produced capital growth, and their IWI per capita growth fell to the bottom of the ranking.

3.3.4. Representative cases of Heilongjiang and Inner Mongolia

Heilongjiang meets the stereotype of a province subject to a double decline in the growth rankings of both IWI (declining five positions) and IWI per capita (declining six positions) from 2000 to 2016, which was mainly due to its natural capital decline and insufficient growth of human and produced capitals (Fig. S6). The non-renewable natural capital of Heilongjiang decreased by 37.0% from 2000 to 2016, almost offsetting 12.9% of its total human and produced capital growth. Heilongjiang has suffered from insufficient human capital development and relatively low wages; the proportion of its elderly population (over 65 years) increased from 5.4% in 2000 to 15.3% in 2016, indicating that the aging trend has led to insufficient human capital growth (NBS, 2018). Moreover, the produced capital of Heilongjiang was found to be far lower than that of most other provinces, with respective PC-*A* and PC-*O* rankings of 28th and 11th in 2016 (Figs. 4(c-d)). Overall, Heilongjiang's large consumption or exportation of natural resources, especially coal, oil, and gas, has failed to boost significant IWI per capita growth, and the province is characterized by gloomy sustainable development prospects.

Inner Mongolia also experienced a significant natural capital decline from 2000 to 2016, with its non-renewable natural capital falling by 14%. However, Inner Mongolia exhibited remarkable growth in its IWI per capita, and ranked third from 2000 to 2016; this notably sets it apart from Heilongjiang and some other NC-dependent provinces. Supported by the refinement of the IWI accounting framework, the IWI per capita structure indicates that the natural capital decline caused by resource consumption contributed more to the human and produced capital growth (both PC-*A* and PC-*O*) in Inner Mongolia. Overall, Inner Mongolia has explored more sustainable development pathways, thereby contributing to a rapid IWI per capita growth. The fast development of its traditional and modern manufacturing industries has benefitted from high resource utilization and conversion efficiency, which can both boost its rapid IWI growth and provide experience for the economic transformation for other resource-rich provinces.

4. Discussion and conclusions

In this study, the IWI framework was updated and improved to develop a more detailed approach; the modified framework includes the disaggregated content of six components at the sub-national level (Fig. S13). This improved IWI framework can better reflect the changes in IWI per capita in more detail and the heterogeneity in China's provincial IWI patterns. From a national perspective, China is developing sustainably. From 2000 to 2016, its total and per capita IWI continued to increase at average annual growth rates of 2.9% and 2.3%, respectively, which was mainly driven by the growth of produced capital, especially advanced produced capital. However, the heterogeneity in the provincial IWI patterns is becoming more significant, reflecting the different sustainability levels of China's provinces. Moreover, based on the IWI per capita and population of 140 countries, it was found that China's per capita IWI in 2010 was still at a lower level (23,834 USD per capita) in global terms (UNU-IHDP and UNEP, 2012), whereas it was found to be able to reach a median level (86,908 USD per capita) according to the results of the present study. This difference may be caused by the parameter determination and the accounting method. Regional studies indicate that, in 2010, Guangdong, China's largest IWI contributor, had a total IWI comparable to that of Colombia, and Beijing had the highest IWI per capita, which was on the same level as that of Serbia (Fig. S12). The total IWI of Qinghai, China's lowest IWI contributor, was found to be only 1/18 that of Guangdong, and the IWI per capita of Jiangxi, China's lowest IWI per capita contributor, was found to be only one-third that of Beijing. The various economic development stages, geographic locations, and uneven IWI growth reflect this heterogeneity. It is worth noting that China has also faced the situation of the relatively slow growth of its IWI per capita as compared with its GDP per capita, especially after 2005. Thus, transferring its GDP growth into inclusive wealth seems vital to China's sustainable development.

Furthermore, the improved IWI framework highlighted that China's IWI per capita growth is hindered by the aggravation of gender inequality, but benefits from advanced produced capital. In general, men in China have a higher employment rate than women, with female employment in urban China accounting for only 35.0–38.1% of the total employment from 2000 to 2016 (NBS, 2001-2017). Moreover, women's average educational attainment was found to be 0.7–1.1 years less than that of males (NBS, 2018), and women had wages ranging from 49.7–78.2% of that of men in 2010 (ACWF, 2011). Therefore, taking actions to improve women's social status, for example, by providing opportunities for women to receive better education and higher salaries, would narrow the IWI gender gap and stimulate IWI growth. The results also indicate that advanced produced capital is superior to ordinary produced capital in stimulating wealth accumulation, which depicts the transition of China's economic structure toward high-tech industries, electronic information, bio-medicine, aerospace, resources, and environmental technology. On the one hand, the GDP share of the modern service industry increased from 14.2% to 27.5% (NBS, 2002, 2018), requiring advanced produced inputs. On the other hand, the transformations and upgrades of China's manufacturing industry have changed from the generation of a narrow range of low-value commodities to high-value products. High-technology enterprises in China have been set up in large numbers, increasing from 20,867 in 2000 to 100,012 in 2016, and their output value exceeded 21 trillion yuan in 2016 (THTIDC, 2017). Thus, attention should be focused on the provinces that still rely on the traditional low- and semi-skilled industries and are facing a dilemma during the transition, as their industrial structure patterns may significantly challenge their long-term sustainability.

The results of this study show that provinces with diverse IWI driving factors must formulate different sustainable development strategies. HC-driven provinces are expected to develop a mature labor market to transform the accumulation of knowledge and technology into IWI growth points, promote emerging industries, and reduce both gender inequality and the social burden of younger workers. PC-driven provinces also face new difficulties, even with more advanced produced capital. For instance, once the fastest-growing region in China, Tianjin is currently experiencing a precipitous drop with an annual GDP growth rate of only 3.5% since 2017, reflecting that the driving force of produced capital is showing signs of weakness. Thus, PC-driven provinces should focus on high-quality development instead of speed, such as by avoiding excessive urban expansion caused by rapid capital accumulation, strengthening the green transition of economic and social development, and promoting coordinated development with the broader economic hinterland. NC-dependent provinces are encouraged to upgrade their traditional resource-based industries into diversified ones via measures such as strengthening the application of innovative technologies, adjusting the industrial structure, and promoting talent cultivation. In addition, this study could provide important support for the feasibility of future IWI accounting at different scales of concern by the National Statistical Office.

Overall, the inclusive wealth framework is still fraught with some limitations, particularly gaps in data availability, limitations of the capital scope, uncertainties of future effects, and the inability to account for regional dependencies and the component distribution. Moreover, improvements in the IWI via the inclusion of oil capital gains/losses, ecosystem services, and carbon damages were not included in the modified IWI framework, as it is difficult to measure these factors accurately or to adjust individual capital assets without a unified global accounting standard (Engelbrecht, 2016). To develop a satisfactory sustainability indicator, the dependencies among, and physical thresholds of, capitals should also be considered in future research to address the interconnectedness of the various assets that constitute wealth, their complex evolutions over time, and the associated implications for the assets' shadow prices (Roman and Thiry, 2016; Dasgupta, 2021). Furthermore, the adjusted IWI is worthy of in-depth exploration for it to act as a correct representation of capital asset factoring in specific aspects, such as the incorporation of the inequality of carbon emissions and non-market ecosystem services across various regions (Polasky et al., 2015; Mi et al., 2020).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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