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Exploring the relationship between economic complexity and resource efficiency

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ABSTRACT

Improving resource efficiency (RE) is an important objective of the Sustainable Development Goals. In this study we find a strong exponential relationship between economic complexity index (ECI) and RE of countries. ECI measures the level of accumulated knowledge of a society enabling the products it makes. The relationship between ECI and RE is stronger for primary material importers and countries with stable institutions. Assessing a country's level of ECI also allows the outlook of future RE trends. We explain how ECI influences RE at the product level by establishing the product space for each country and by defining core products that contribute to a high product complexity index, high RE (i.e., unit price) and promising expansibility (i.e., core number), which indicates the potential to produce more advanced products in the future. Policies that improve economic complexity and invest in core products seem to be a priority to achieve sustainable development.

1. Introduction

A growing global population, processes of industrialization (Murphy et al., 1989) and urbanization (Grimm et al., 2008; Seto et al., 2012), changes in aspirations and lifestyles of a growing global middle class (Myers and Kent, 2003), and the production and consumption processes that service the fast-expanding demand for products and services all require ever-increasing amounts of natural resources. The global use of materials – biomass, fossil fuels, metal ores, and non-metallic minerals – was at 90 billion tonnes in 2017 and is projected to grow to 165 to 195 billion tonnes by 2060 (OECD, 2018; UNEP, 2019). The associated environmental pressures and impacts are surpassing global environmental limits and planetary boundaries (Steffen et al., 2015).

Resource efficiency (RE) – more from less – is seen as a promising and economically attractive way of improving the environmental performance of the global economy (UNEP, 2017; Zhang et al., 2018). In the short term, there are many opportunities for improving RE at low and sometimes negative costs (Allwood, 2018; Hertwich et al., 2019; Wang et al., 2022). In the long term, improving RE is superior to business as usual (Pauliuk et al., 2021). This study establishes a link between economic structure and RE, i.e. material productivity of the national economy, by employing an analysis of economic complexity and product complexity. By investigating the implications of economic complexity for RE we align economic and environmental policy objectives.

Since Adam Smith's time it has become common thinking that the wealth of nations depends on the division of labor and specialization (Hidalgo and Hausmann, 2009). To assess this relationship, novel measures known as the economic complexity index (ECI) and product complexity index (PCI) have been proposed to examine an economy's levels of human capital and specialization that are translated into its products (Hausmann et al., 2014; Hidalgo and Hausmann, 2009; Hidalgo et al., 2007; Jara-Figueroa et al., 2018). Using the indicators,

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economic complexity can be measured by average degree of sophistication of products that countries are able to make, and the economic complexity index has been particularly successful in explaining why gross domestic product (GDP) per capita varies between countries. It is also useful for forecasting economic growth (Hausmann et al., 2014; Hidalgo and Hausmann, 2009; Hidalgo et al., 2007).

Since human capital and knowledge are not only the basis of producing commodities, but also the basis of how to produce efficiently, from a sustainability point of view, it is vital to know how the level of economic complexity of a country affects its material usage and resource efficiency outcomes and links to environmental sustainability. Sustainable Development Goals (SDGs) 8.4 and 12.2 require countries to improve RE and to achieve sustainable consumption and production patterns by “doing more and better with less” (Lenzen et al., 2021; United Nations, 2015). In this context it is crucial to know whether investing in human capital and advanced products and increasing economic complexity are related to the decoupling of economic growth from material use. In other words, are economies with higher ECI more resource-efficient?

According to our literature review (see Table S1), concerning the relationship between RE and economic indicators, previous studies have mainly focused on the indicator of GDP; concerning the relationship between ECI and resource and environmental indicators, most studies have focused on indicators of carbon emissions and energy consumption. In this study, we construct an index of economic complexity for a large set of more than 100 countries for the period 1995 to 2015 calculated from detailed trade accounts. In addition, we used stabilized and average PCI to make the ECI of each country comparable between years. Employing panel data and regression analysis, we test the relationships between ECI and RE. This approach allows us to gain an understanding of how economic structure relates to natural resource consumption and the potential for decoupling material use from economic growth.

Moreover, previous studies have demonstrated an explanatory capacity of ECI for future economic growth. They have shown that the effect of ECI of future growth can be stronger for countries that are not relying on natural resources export (Hausmann et al., 2014) and have stable institutions (Brummitt et al., 2017). In this study, we investigate the extent to which ECI explains future RE for countries that are either net importers or net exporters of natural resources. We are also interested in how institutional stability changes the relationship between ECI and RE.

In this study, ECI and RE are empirically connected and provide insights into the dynamics of resource use and economic structure that can guide investment and policy decisions in the future to steer economies toward achieving the SDGs’ RE and sustainable natural resource management objectives.

2. Methods and data

To measure economic complexity, we employ standard analytical techniques established by Hidalgo and Hausmann (Hidalgo and Hausmann, 2009; Mealy et al., 2019) but calculate the complexity index using more detailed trade data compared to previous studies. We calculate and analyze a new economic complexity indicator (ECI) based on a stabilized product complexity indicator (PCI) and use network analysis to identify a country’s product space. We identify core products with high PCI, high RE (i.e. unit price) and high expansibility (i.e. core number). By analyzing product space and core products, we can answer why countries’ RE are different and why ECI might influence RE growth rates. The detailed methods and data are shown as follows.

2.1. The economic complexity and product space methods

Economic development requires the accumulation and application of productive knowledge. The economic complexity index (ECI) measures a country’s or region’s productive knowledge level, while the product complexity index (PCI) shows the complexity of knowledge required to produce a specific product. A country with higher ECI value produces more products with higher PCI values, and products with higher PCI values are more likely made by countries with higher ECI values. Based on the relationship between the ECI and PCI, Hidalgo and Hausmann (Hidalgo and Hausmann, 2009) proposed as a general method that ECI is a function of PCI, and PCI is a function of the ECI. They estimate ECI and PCI by �continuous iterations between the two indicators. The method can also be regarded as a dimensionality reduction technique to predict and explain future economic growth (Hidalgo and Hausmann, 2009; Mealy et al., 2019).

If products complexity represents the level of knowledge embodied in products, PCI should be relatively stable. Thus, we use the average PCI for each product to generate the ECI for each country per year. In that way, ECI is comparable between different years for regression analysis. Because a country’s ECI value is the average of the stabilized PCI of products and countries produce products with high PCI but also products with low PCI, the ECI value of a country is typically lower than the highest value of the PCI.

The product space is a network showing the similarity of productive knowledge between different products, where nodes represent products and links connect products likely to be exported together. The probability of a pair of products being co-exported contains information about the similarity (Hidalgo et al., 2007). By drawing on each country’s product space and each product’s complexity and resource efficiency, we show and explain productive capabilities and resource efficiency gaps between different nations.

2.2. Similarity to the core products for each country

A k-core is a maximal subgraph that has nodes of degree k or larger. A node’s core number is the biggest value k of a k-core having that node (Batagelj and Zaveršnik, 2011). When the similarity between two products is no less than 0.6, we regard they are similar, and there is a link between the two products. A k-core of the product space is a maximal subgraph in which each product links at least k products. Products with a high core number are at the core of the product space from the perspective of network structures, and the larger the core number of a product is, the more expansibility it possesses. Products with a low core number are at the periphery of the product space.

Considering the productive knowledge embodied in products, expansibility and RE of products, we determine the core products with values of the core number being no less than 3 (around the top one fifth of products), average price no less than 10 USD/kg (around the top one third of products) and PCI no less than 0 (around the top half of products). After screening, we classify about one tenth of all products as core products. Multiple rounds of sensitivity checks allowing the three indicators to fluctuate between one fifth and half of their rankings shows no significant change to the overall trend shown in Figs. 4 and 5. Countries can determine their core products based on their development priorities for the three dimensions of productive knowledge, expansibility and resource efficiency when making policies.

These core products are advanced products, which embody high-level productive knowledge, high resource efficiency, and high possibilities of extending to other products. We calculate the similarity to the core products for each country:

$$Sc = \frac{1}{|p_i||q_j|}\sum_i\sum_j \Phi_{p_i,q_j} \tag{1}$$

Sc represents the average similarity between country *c*’s products and the core products. p_i denotes product *i* produced by country *c*, $|p_i|$ is the number of products produced by country *c*, q_j denotes core product *j*, $|q_j|$ is the number of core products, Φ_{p_i,q_j} is the similarity between the product *i* and *j* (Hidalgo et al., 2007).

2.3. Regression methods

We employ a panel fixed effect model (year-fixed effects) to estimate the effects from ECI and three control variables on two country-level socioeconomic indicators (Hartmann et al., 2017; Hidalgo and Hausmann, 2009). The estimation equation for measuring the average effect of ECI on these two socioeconomic indicators is:

$$\ln Y_{c,t} = b_1 E_{c,t} + b_2 \ln P_{c,t} + b_3 \ln S_{c,t} + b_4 \ln H_{c,t} + a_t + e_{c,t} \quad (2)$$

Here, $\ln Y$ denotes the natural logarithm of the analyzed socioeconomic indicators (GDP per capita and RE). E is the economic complexity indicator (ECI), P is the price per unit weight for products (e.g., the average trade price per kilogram of product for one country), S is the fraction of GDP in service (%), H is the Herfindahl-Hirschman Index (trade diversity). The subscript t denotes the year, and c denotes the country. Intercept a_t was included to control for year-specific effects, b_n are regression coefficients to be estimated, and e_t is the idiosyncratic error term.

We explore the effect of ECI and three controlled indicators on the growth potential of GDP and RE with a year-fixed effect panel model using the following equation (Hausmann et al., 2014; Hidalgo and Hausmann, 2009):

$$\ln\left(\frac{Y_{(c,\ t+\Delta t)}}{Y_{(c,t)}}\right) = b_1 lnY_{c,t} + b_2 E_{c,t} + b_3 \ln P_{c,t} + b_4 \ln S_{c,t} + b_5 \ln H_{c,t} + a_t + e_{c,t} \quad (3)$$

When analyzing the correlation between ECI and the growth of socioeconomic indicators during the period of t to $t+\Delta t$, we also consider the effect of the initial values ($Y_{c,t}$) of explained indicators (GDP per capita and RE). It is notable that when conducting the 15 years and 20 years period regression, we did not use year-fixed effect model because we only used two years' data for them (see Tables S11-S12 and the code file).

2.4. Data

To calculate resource efficiency (RE), we used domestic material consumption (DMC), which is a direct resource consumption indicator and equal to domestic extraction plus imported resources minus exported resources. DMC is an important indicator to generate RE by using GDP divided by DMC. In this study, we collected DMC data from the UNEP-IRP Global Material Flows Database (UNEP, 2020).

The ECI was constructed using international trade data for 1995 to 2015 taken from the United Nations COMTRADE database (UN, 2019), which includes imports and exports from country to country, with around 3000 products (SITC revision 3, the most detailed category). Missing data is an important concern when using the COMTRADE database. To solve this problem, we estimated the missing weight information using the world average price method (Dittrich and Bringezu, 2010). Similar to a previous study (Hidalgo and Hausmann, 2009), we cleaned the dataset by calculating exports based on records from importers, assuming that data on imports is more reliable than that from exporters, as imports receive more attention by governments to collect customs fees and ensure safety standards.

In order to build a more reliable database, we restrict the analysis to 108 countries based on the following criteria. First, we only use data from countries with annual exports of at least 1 billion dollars in 2015. Second, we only consider countries that have a population above 2000,000. Third, we excluded 20 highly fragile countries (country codes: AFG, CAF, CIV, COD, ETH, GIN, HTI, IRQ, LBR, LBY, PAK, PRK, SDN, SLE, SOM, SSD, SYR, TCD, YEM, ZWE) based on the Fragile States Index 2015 (peace, 2018), because the stability of society could influence data reliability. Fourth, we excluded two countries (Botswana and Namibia), which do not have trade data for the years 1995 to 2000. Finally, we removed three countries and regions (United Arab Emirates, Belarus and Hong Kong), as they do not have reliable resource use data.

In addition, when selecting the core products, we used the average prices of products between 1995 and 2015. They are calculated by the trade value divided by their weight data, sourced from the United Nations COMTRADE database (UN, 2019). We divided all 108 countries into net importers and exporters of natural resources by their physical trade values in 2015 in the IRP database (UNEP, 2020); we also grouped countries into stable countries (credit ≥BBB-) and unstable countries (credit <BBB-). The credit values are from Standard & Poor's (Poor's, 2019) and Fitch (Fitch, 2019).

3. Results

3.1. The evolution of economic complexity and resource efficiency

The history of economic development and natural resource use, as revealed by current socioeconomic metabolic profiles (Krausmann et al., 2008), has put different countries on different path dependencies and therefore created very specific conditions for sustainable development in each country (Weisz and Schandl, 2008). Our empirical results (see Fig. 1 and Tables S2) show the changes in ECI rankings and average values of ECI and resource efficiency (RE) of domestic material consumption from 1995 to 2015. We find that global ECI gradually increased between 1995 and 2010 and declined after 2010, mainly due to the impact of the 2008–09 global economic crisis on international trade. It is notable that ECI was much higher for stable countries (blue lines) and net importers of materials (gold lines) compared to unstable countries (red lines) and net exporters of materials (purple lines), and the gap between these groups of countries has gradually expanded. ECI of stable countries was also less affected by the economic crisis.

Domestic material consumption (DMC) is a national-level material flow accounting indicator, which quantifies the apparent consumption of materials, i.e. extraction plus imports minus exports (Eurostat, 2013; Fischer-Kowalski et al., 2011). RE is quantified as GDP divided by DMC and is the headline indicator of the "resource efficiency roadmap" of Europe's RE flagship initiative as part of the Europe 2020 strategy and the European Union (EU) sustainable development strategy (Commission, 2011; Eurostat, 2019). Moreover, the organisation for Economic Co-operation and Development (OECD) and the United Nations Environment Programme (UNEP) also regard GDP/DMC as an indicator of their SDG strategies (OECD, 2011, 2018; UNEP, 2011).

Global resource efficiency stagnated between 1995 and 2005 but grew by about 20% between 2005 and 2015, mainly driven by the rapid improvement in RE in resource importing and stable countries. From Figs. 1d–1e, we find that trends for net importing and net exporting countries and stable and unstable countries are substantially different. Economies reliant on imports of primary materials show, on average, higher resource efficiency and experienced faster improvements in resource efficiency compared to export-oriented economies. For example, resource efficiency in China, a middle-income country and net resource importer, has increased by 87.5%, and its ECI increased from –0.57 to –0.13 between 1995 and 2015. By comparison, Brazil, a middle-income export-oriented economy, experienced a 19.8% decrease in resource efficiency and its ECI decreased from –0.24 to –0.34 over the same period of time.

3.2. Strong correlation between economic complexity and resource efficiency

As argued previously, ECI reflects the level of productive knowledge embodied in an economy and is a driver of economic growth. Does ECI also explain the level of resource efficiency that can be achieved in an economy? Here, we find a strong and statistically significant correlation between ECI and RE (see Fig. 2 and Tables S3–S5), which we interpret to imply that increasing economic complexity is strongly related to improving resource efficiency. In our analysis, we control three

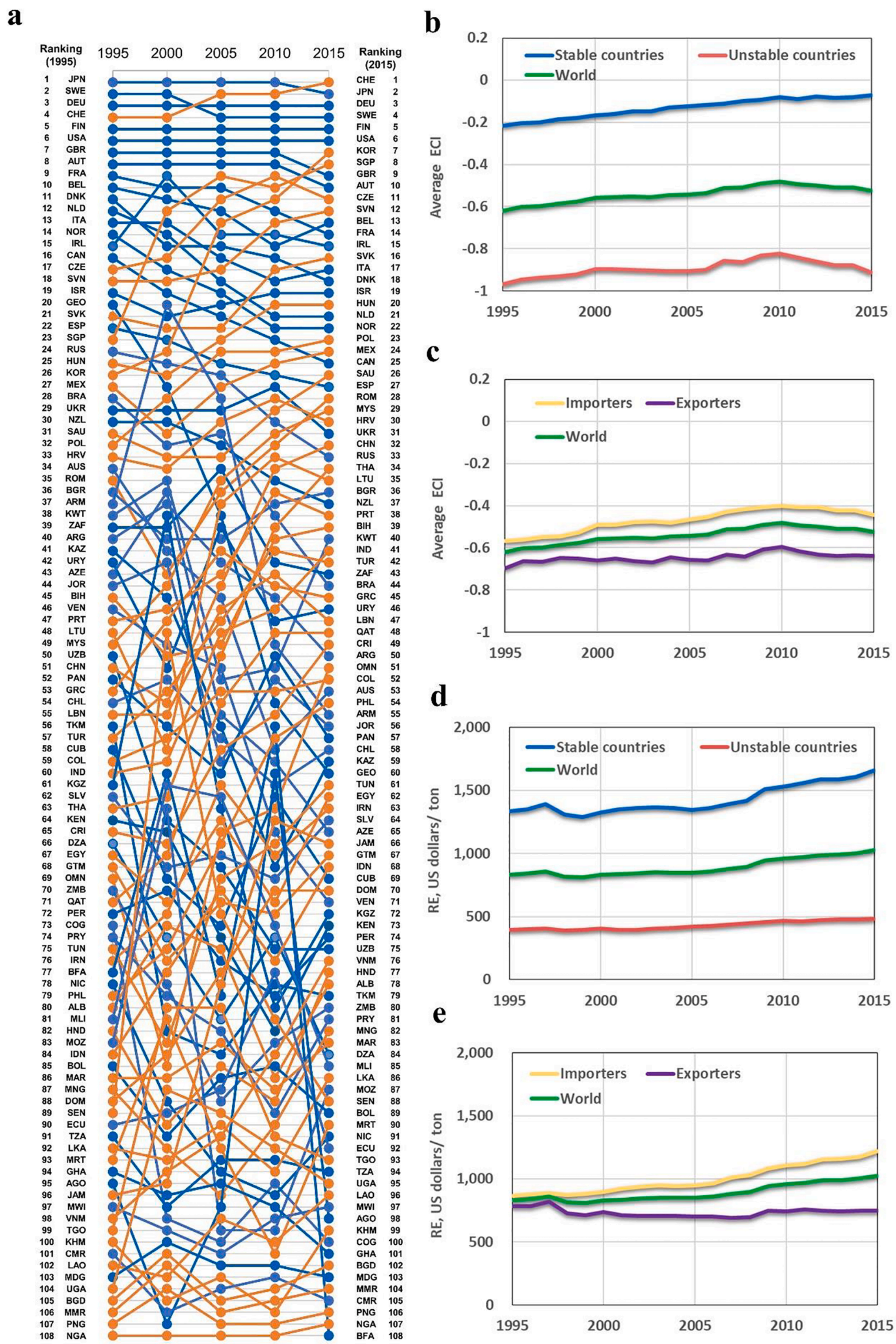

Fig. 1. Trends in RE and ECI of nations. Fig. 1a is the ECI ranking of nations (orange lines represent rising, blue lines represent constant or falling); Figs. 1b and 1d show the ECI and resource efficiency (RE) of domestic material consumption of the world, stable countries and unstable countries; Figs. 1c and 1e show the ECI and RE of the world, net importers and exporters of natural resources. The RE in Figs. 1d and 1e use the average values of resource efficiency of each country, rather than the total GDP divided by the total resource consumption of each group of countries.

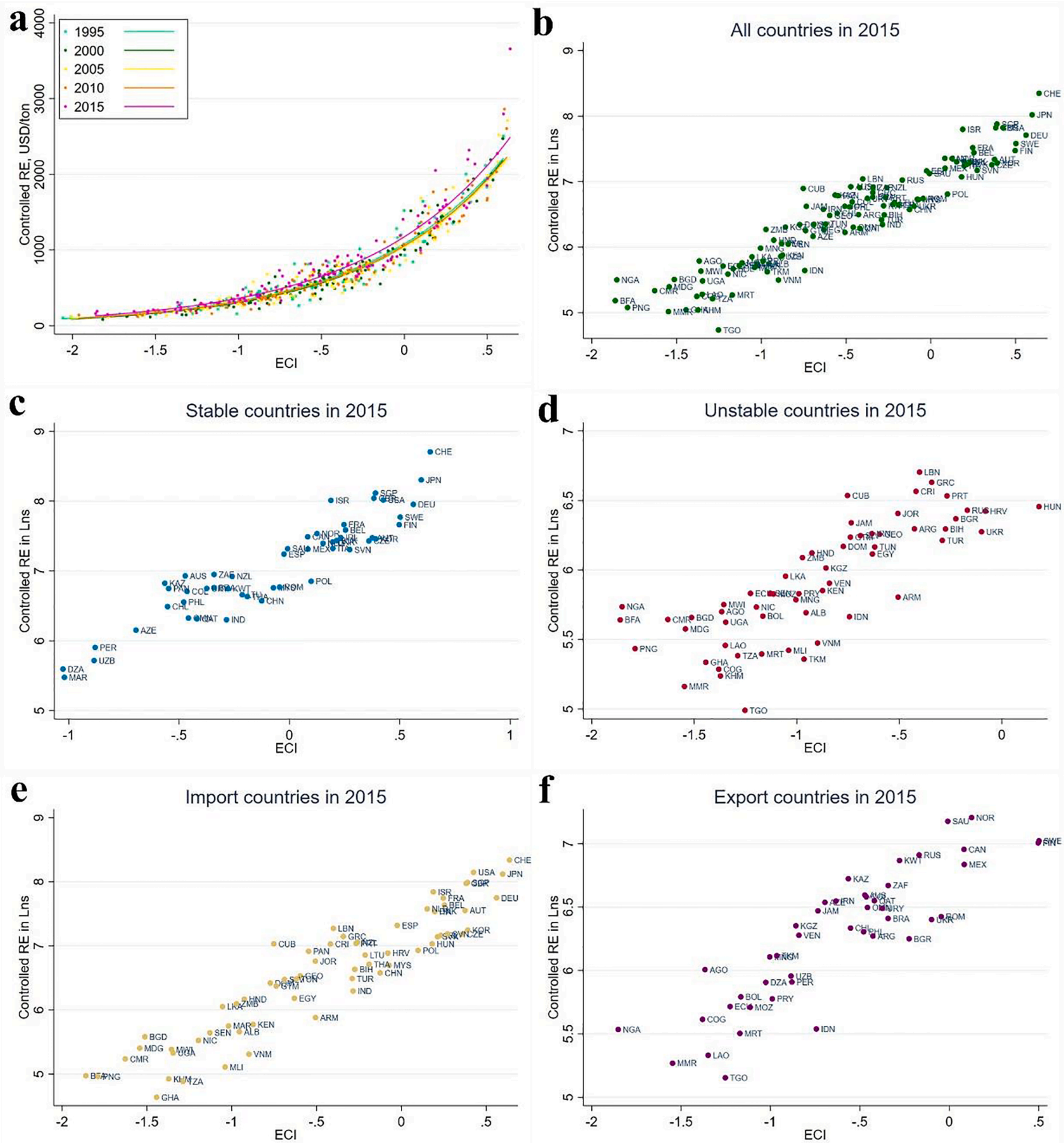

Fig. 2. Resource efficiency versus ECI. Figure 2a shows the relationship between resource efficiency (RE) and ECI in the years of 1995, 2000, 2005, 2010, and 2015. Figures 2b-2f show the relationship between RE (in natural logarithm) and ECI for all countries, stable countries, unstable countries, import countries, and export countries, respectively. The resource efficiency values shown on the y-axis are the natural logarithm values after controlling for the other three variables (product price, share of service activity in GDP, and HHI). The regression results are also shown in Tables S3–S4.

additional variables that cover aspects not addressed by ECI, namely the price of products, the share of service activity added value in GDP (%), and the Herfindahl-Hirschman Index (HHI), which represents product diversity.

Similar to the results for GDP (see Figure S1 and Table S6), ECI is statistically significant at the 1% level as an explanatory variable and, together with the other variables, explains 42–64% of the variance in RE among all 108 countries in each year during 1995 to 2015 (see Fig. 2a–b and Table S4). Specifically, when the other three variables are controlled for, RE grows exponentially with ECI growth. That is, a unit increase in ECI between countries is correlated with an improvement in RE by more than 106–132% in different years. When ECI is relatively low, improving ECI has only a limited effect on resource efficiency, but with continuous growth in ECI, the impact on resource efficiency becomes more obvious and RE increases strongly.

Previous studies have shown that a country's institutional and economic stability with high credit and its reliance on export of natural resources can significantly influence the relationship between ECI and GDP (Brummitt et al., 2017; Hausmann et al., 2014). We employ a year-fixed effect panel model and split countries by their credit, role in global trade, and income level (see Table S2 and Table S5), and find that nearly all country groups can enjoy a significant return to RE by improving ECI, except for low-income countries. Notably, the ECI coefficient (1.594) of stable countries is the highest among all groups and their R^2 is as high as 0.610.

Moreover, the impact of ECI on RE is very different for export- and import-reliant economies (see Figures 2e–2f and Table S4). Net resource exporting countries, such as Australia, Chile and Qatar, experience high economic growth and commensurate wealth not because of their human capital but because they are blessed with rich natural resource endowments of metal ores and fossil fuels. They are, however, confronted by phenomena summarized by the resource curse hypothesis (Costantini and Monni, 2008; van der Ploeg, 2011). Resource- and energy-exporting countries may experience extended periods of high economic growth, however, their development potential and resource efficiency are relatively lower compared with import-reliant countries at similar income levels. A much stronger correlation between ECI and RE is found for importers. For example, together with three controlled variables, ECI can explain 83% of variance in RE among net importers but only 40% for exporters. These findings are in good agreement with GDP levels (see Table S6). Considering that most high-income countries are stable countries or importers, this group's ECI coefficient and R^2 are much higher than low- and middle-income country groups. We also find that improving the share of service activity in GDP, product price, and HHI would further correlate with improving resource efficiency for certain country groups.

A comparative analysis of the ECI difference and RE difference between countries from 1995 to 2015 (see Figure S3) reveals that the difference between the two indicators of most stable countries and net resource importers is distributed in the same direction (that is, in the first and third quadrants). Notably, nearly all the stable importers are distributed in the first quadrant, that is, their ECI and RE increased in the same direction during this period (see Figure S3c).

Our results also show that the ECI index has a strong capacity to explain the future growth potential of RE (see Fig. 3 and Tables S9–S12). When conducting regression analyses for 5-year, 10-year, 15-year and 20-year intervals from 1995 to 2015, we find that the initial ECI has a strong positive influence on the growth potential of resource efficiency for nearly all the periods analysed. The effect for stable countries and importers is stronger compared to the other groups. It is also notable that initial high values of RE have a negative effect on the additional growth potential of RE, suggesting a saturation effect. This implies that countries like China with high ECI but low RE have excellent conditions for improving future resource efficiency. Moreover, the other three control variables have quite limited influence on future RE.

3.3. Interpreting the relationship between ECI and RE

Individual countries improve their economic development by upgrading their products, and the differences in productive knowledge they hold are a key determinant of income gaps between rich and poor countries (Hausmann et al., 2014). Product space, which describes the network of relatedness between products (Hidalgo et al., 2007), provides a vital reference for comparing productive knowledge among countries. Within the product space, countries tend to transfer from familiar products that they can produce to adjacent products that

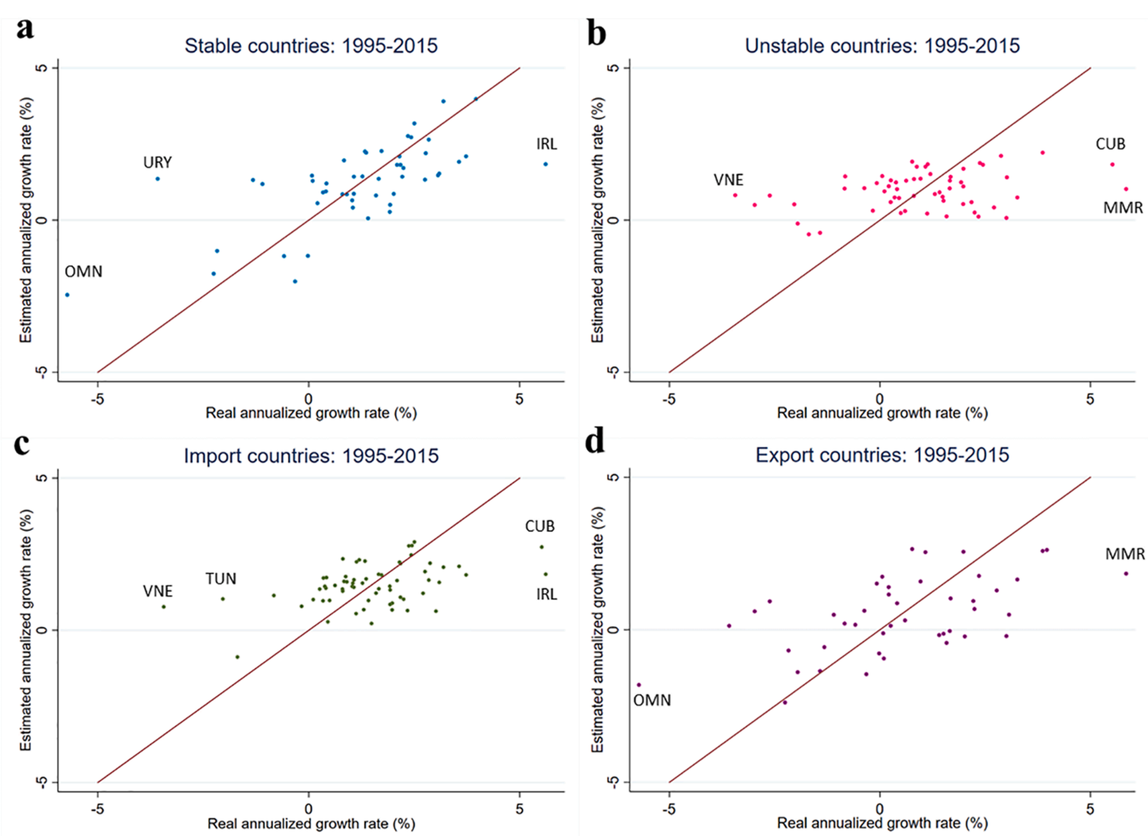

Fig. 3. Comparison between estimated and historical values for 20-year interval RE growth rate by country groups. Figs. 3a-3d show the comparison between estimated and historical values for stable countries, unstable countries, import countries, and export countries, respectively. The regression results are also shown in Table S12.

require similar skills and knowledge. Using product information and related methods (see the Methods and data Section), we can calculate a product complexity index (PCI) (see Fig. 4a) and determine whether this product is a core product (see Fig. 4b), the unit price of the product (i.e. price per unit of weight, can be used to measure resource efficiency at the product level, see Figure S5), the core number of the product (see Figure S6 and the Methods and data Section), and the category of the product (see Figure S7).

We analyze product space for 2988 products at the leaf level (most detailed category)of SITC-3 and the connections between them. Considering product's complexity, resource efficiency, and expansibility, we define products with PCI≥0, unit price≥6 USD/kg, and core number≥3 as core products. In Fig. 4, we find that products with high PCI (representing the degree of sophistication of a product) and core products (embodying high-level productive knowledge, high resource efficiency, and high possibilities of extending to other products, see the Methods and data Section) are located in the middle area. These core products mainly include machinery, electronics, road vehicles, and medicinal products (see Figure S7 and Table S13). In the middle above, there is a solid circular cluster of garments and textiles.

Product level analysis reveals that high ECI values for the national economy rely on high PCI values of its products, and from Figure S8 we find that products' PCI is positively related to their price, and this correlation explains that product price has only limited influence on RE when controlling ECI. However, if one country can produce products that achieve a higher price, its economic system will, therefore, be more

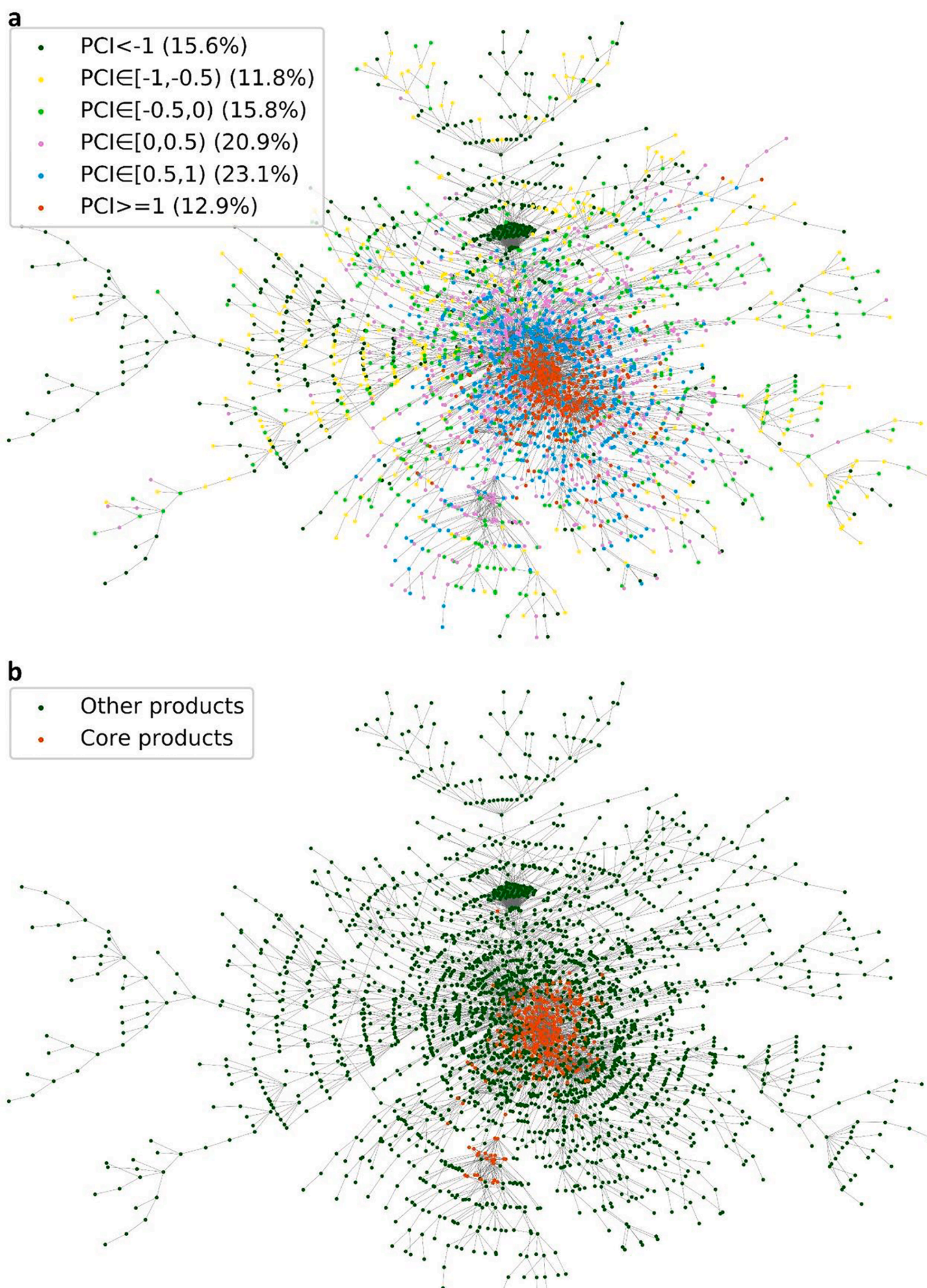

Fig. 4. The product space. Figs. 4a and 4b show the PCI of each product and core products in the product space, respectively. The high-PCI and core products are mostly located in the middle area, mainly including machinery, electronics, road vehicles, and medicinal products (see Figure S7).

resource-efficient. For this reason, RE is strongly correlated with ECI at the country level.

We also use ECI to estimate the growth of RE in the future. If a country's ECI value is high, this means its exported products are closer to core products (see Fig. 5), indicating the future ability and likelihood to produce more advanced products with high embodied knowledge and contributing to higher RE (see the Discussion Section). This explains the long-term effect of ECI on future RE. By scanning the product space of a country, we get an in-depth picture of the human capital and productive knowledge that a country holds, of its development path and development potential.

Based on analysis of the product space, we select six typical countries representing different income levels, and including both resource net importers and exporters at different income levels, to interpret how ECI influences RE. The trends in ECI and RE indicators for Japan, China, India, Australia, Brazil, and Indonesia from 1995 to 2015 are shown in Figure S4.

Similar to the regression results we obtained above, resource importers are more likely to improve ECI and RE compared to resource exporters. As a high-income economy dependent on primary material imports, Japan's ECI has been at a high level (ranking consistently in first place in the world, see Figs. 1a), whereas as high- and middle-income exporters respectively, Australia and Brazil's ECI declined steadily over the two decades. In contrast, China, India and Indonesia, which represent low- and middle-income countries, steadily increased ECI. For RE, China, India and Japan enjoyed relatively high growth rates of 3.2%, 2.8% and 2.2% per year, respectively, whereas Australia and Indonesia had growth rates of 2.0% and 0.6% per year, respectively, and Brazil's RE declined by around 1.1% per year.

From the regression results for these six typical countries we find that higher ECI implies higher RE in historical trends. The situation in Australia is, however, somewhat different (Hatfield-Dodds et al., 2015; Schandl et al., 2008). Even though Australia's ECI declined rapidly, RE still increased. There are two main reasons. Before 2000 Australia's ECI was relatively high, which we expect would have a long-term impact on the growth of future RE; the other reason is that its service sector share of GDP increased from 62.3% to 67.3%, which contributes to improving its RE in spite of decreasing ECI. However, compared to Japan, which has the same level of income, Australia's RE is only 30% of that of Japan.

Figs. S11–S17 shows the evolution of each country's core products and product categories, respectively. For Japan, its product space has more core products, focusing on machinery, electronics, metal products, organic chemicals, and transport vehicles, all of which have relatively higher PCI and price (see Figure S12 and Table S13) and support Japan's exceptionally high RE. In contrast, the evolution of the two exporters, Australia and Brazil (see Figure S13-S14), looks very different. The share of core products with high PCI and price they create has been declining over time and their products are becoming increasingly dispersed. They are moving toward agricultural products and mineral products which need less advanced knowledge to produce. As ECI is also a long-term predictor of RE, the decline in ECI in Australia and Brazil is likely to affect future RE negatively.

The emerging economies of China, India and Indonesia over the past two decades have spared no effort to improve their ECI. China increased its ECI from –0.57 to –0.13 and significantly increased the number of core products between 1995 and 2015 (see Figure S15), and the newly added products are mainly in the machinery, electronics, metal products, and organic chemicals clusters. Moreover, products produced in China, such as electronics, are beginning to have cluster effects. These changes have significantly increased China's competitiveness in international trade and have contributed to growing RE. India's advancement is mainly due to the addition of organic chemicals and metal products (see Figure S16), whereas Indonesia is beginning to show competitiveness in electronics (see Figure S17). It is worth pondering that Indonesia, as a resource exporter, has embarked on a fantastic path. Indonesia appears to be unsatisfied with exports that rely on natural resources and introduces technology to improve ECI.

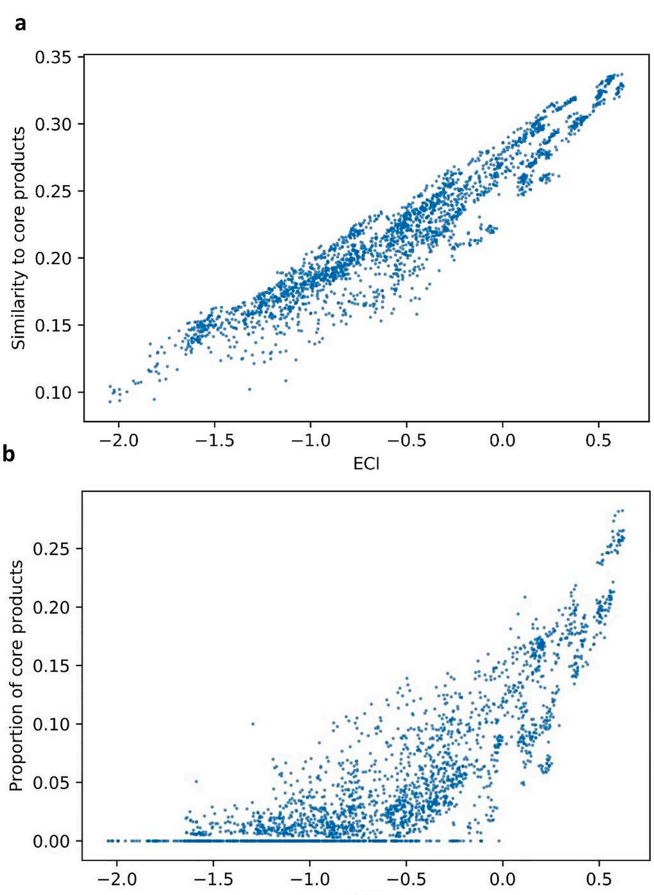

Fig. 5. Relationship between ECI values and core products. Fig. 5a shows the relationship between ECI values and the indicator 'similarity to core products' (similarity of exported products to core products) for countries in 2015, and the method used to calculate the similarity to core products is shown in the Methods and data Section. Fig. 5b shows the relationship between ECI values and the indicator 'proportion of core products' for countries in 2015, and the dots which are at the bottom means that some countries don't produce core products.

4. Discussion

4.1. Why ECI is positively correlated with RE

According to previous study (Mealy et al., 2019), the ECI is mathematically equivalent to a spectral clustering algorithm which partitions a similarity graph into two clusters; countries with higher ECI are probably likely to have more similar exports to each other than they have with countries with lower ECI. In this study, we confirm this finding. From Figure S18, we find that countries with high ECI consequently tend to have export baskets that are more similar to countries with high ECI and more dissimilar to countries with low ECI, and the maximum cosine similarity is about 0.5 and most of the values range from 0 to 0.4 (1 means totally same, and 0 means totally different). From Figure S19, we know that when countries' ECI values have a big difference, the similarity of their products is relatively lower, but for some cases when countries' ECI values are very similar, their products can also be different and most of the similarity values of their products are below 0.4.

Furthermore, we test the relationship between difference in ECI values and similarity for the top 50 countries with high ECI (Figure S20). In addition, we find that for these countries with high ECI, the values of

Pearson correlation coefficient between difference in ECI values and similarity in products is −0.26, Spearman correlation coefficient is −0.23 and Kendall correlation coefficient is −0.15, which means there is not high association between the two indicators for those top 50 countries, either. From Figures S21-S23, we can directly observe that France (FRA)'s products are not very similar to Ireland (IRL)'s, and Saudi Arabia (SAU)'s products are different from Spain (ESP)'s, even though their ECI values are almost the same.

Based on the above analysis, we can conclude that the observation that ECI correlates with RE is not because countries with similar ECI are likely to have similar exported products which cause similar RE, but what causes the strong correlation between RE and ECI?

ECI is not only a spectral clustering indicator of countries, but previous studies (Hausmann et al., 2014; Hidalgo and Hausmann, 2009; Mealy et al., 2019) have also shown that ECI is calculated based on the products' PCI values, which infer information about countries' productive capabilities and knowledge from their export baskets. So, the ECI and PCI methods reflect that countries having higher ECI values produce more advanced products than countries with lower ECI values. Countries who invest in advanced products with high PCI can improve their ECI and national competitiveness.

Therefore, to answer this question, it is necessary to explain it at the product level. In this study, we find that products' PCI is positively related to their price (Figure S8). That is the main reason why RE is strongly correlated with ECI on the country level. More importantly, we can use ECI to estimate the growth of RE in the future. We define core products and calculate the 'similarity to core products' and 'proportion of core products' for each country. Fig. 5 shows there is a strong correlation between the indicator 'similarity to core products' (similarity of exported products to core products) and the ECI values, and the indicator 'proportion of core products' is also correlated to the ECI values. As shown above, core products are relatively advanced products in the center of the product space with a high level of productive knowledge, RE and expansibility. The products with a high core number are cores of the product space from the perspective of network structures, and the larger the core number of a product is, the more expansibility it has.

Based on the above analysis, we know that higher ECI values are usually associated with the core products with a higher core number, PCI values and price, which indicates countries with higher ECI have the ability to produce more advanced products with higher knowledge and RE. This can explain both the present and the long-term effect of ECI on RE at the product level.

4.2. Policy implications

Improving resource efficiency is one of the main targets in the 2030 SDGs (United Nations, 2015). This study identified that ECI has been strongly correlated with RE over the past two decades and can also be used to estimate future RE. High ECI at the country level is strongly related to the proportion of core products, which also indicates the potential to produce more advanced products in the future. For this reason, in aiming to improve economic growth and resource efficiency, it is beneficial for countries to invest in core products with high PCI, high RE (i.e. unit price) and high expansibility (i.e. core number). It is important to note that the global economy will continue to rely on the supply of raw materials which will limit the capacity of resource exporting countries to improve their ECI unless they invest in domestic value adding.

Fig. 6 and Table S13 show the average PCI, average price, and the proportion of core products for each product category. Product groups C18 Machinery, C19 Electronics, C16 Road Vehicles, and C13 Medicinal Products (in orange circles) all require a high proportion of embodied knowledge, achieve a high unit price, and benefit resource efficiency. Should they be targeted by a country's economic and industrial policy, it would enable a good alignment of environmental and economic objectives simultaneously. In contrast, solely focusing on a primary material based economic development path (e.g. C1 Raw Agriculture Products, C2 Meat Eggs & Milk Products, C3 Food Processing, C4 Wood & Wood Products, and C5 Mineral Products) would be less beneficial for future economic growth and the improvement of RE in the long run.

Importantly, we found that ECI is not only a good explanatory variable for GDP growth, but also of the growth of RE, which enables an outlook for RE potential before the SDGs target year of 2030 (see Fig. 7, Figure S9, and Table S14). It is not surprising that countries with high ECI, such as Germany, Japan, Switzerland and the United States, have a high potential for RE improvement. At the same time, benefiting from the improvement in ECI and the original low level of income and RE, emerging economies like China, India, Thailand and Vietnam can enjoy solid improvements in resource efficiency while achieving high economic growth. If natural resource exporters, such as Algeria, Australia, Kuwait, and Qatar, cannot reverse their downward trend in ECI, their economic and RE growth potential will be adversely affected over the coming decades, and they will depend on the variability of high world market prices with little ability to steer their own economic future.

From the perspectives of both historical trends and future potential, ECI is a critical reference indicator for improving GDP and RE.

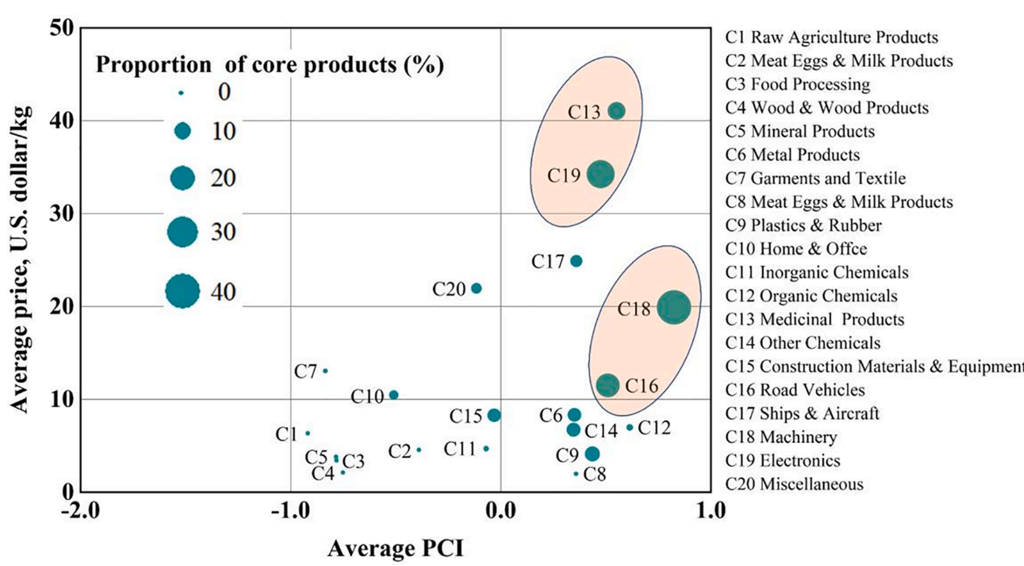

Fig. 6. Characters of product categories.

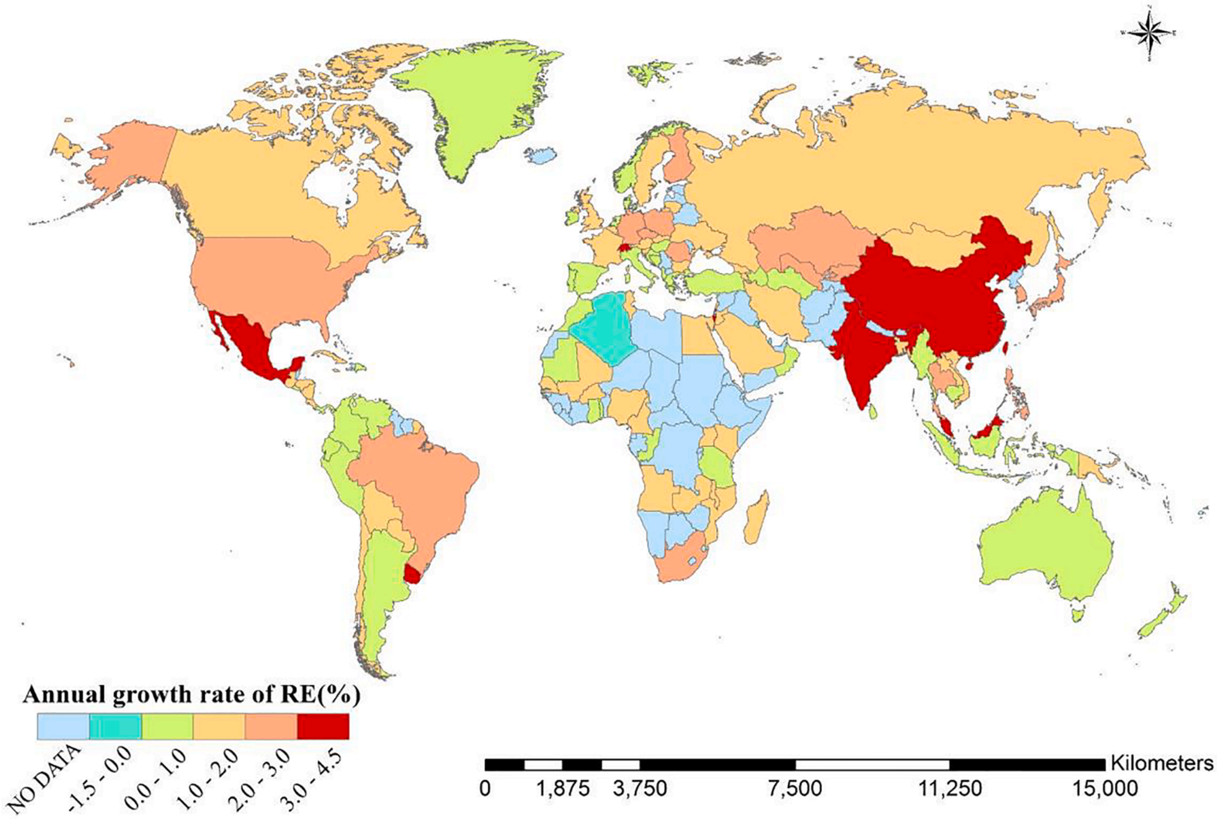

Fig. 7. Outlook of world RE growth during 2015–2030. The growth rates of resource efficiency (RE) are average annual growth rates. The growth rates are estimated by the two groups: stable and unstable countries. The results from unstable countries could have more uncertainties (see Table S14).

Improving economic complexity by increasing the proportion of core products, therefore, seems to be a priority of integrated environmental and economic policy to achieve sustainable development outcomes at the national level. In addition, this study can provide enlightenment for studying other environmental issues, such as reducing carbon emission intensity according to the Paris Agreement.

4.3. Uncertainties and limitations

This study investigates the relationship between ECI and resource efficiency for countries which is an analysis that has certain limitations. First, since there is no service product data in the UN Comtrade database, we did not consider service product, but we included the fraction of GDP in service (%) to explain resource efficiency (RE). Second, when explaining the RE of countries, we include indicators for economic complexity (ECI), the price per unit weight for products (e.g., the average trade price per kilogram of product for one country), the service sector share of GDP, and the Herfindahl-Hirschman Index (trade diversity). In addition, we also considered institutional stability and whether countries are net importers or net exporters of natural resources. However, many factors can affect aggregate resource efficiency, and it is difficult to control for all. Third, we did not consider the price fluctuation of certain products for the regression of RE and the average trade price for a country. Since one country often exports hundreds or thousands of products, we assume large fluctuations in the price for one or a few categories of products usually do not affect a country's overall export prices much.

5. Conclusion

This research has established a framework for examining the relationship between economic complexity and resource efficiency for nations. We have tested whether economic complexity is positively related to resource efficiency, i.e., if higher economic complexity means less demand for primary materials per unit of Gross Domestic Product (GDP).

The results indicate that during the study period, there is a strong relationship between economic complexity and resource efficiency and that growing economic complexity can be associated with the improvements in a country's resource efficiency in the future. This relationship is highly non-linear, however, the resource efficiency of countries with already high economic complexity benefits greater. The positive impact of economic complexity on resource efficiency is stronger in countries reliant on imports of primary resources compared to countries whose economic development is resource- and export-driven. It is also stronger in countries with stable institutions. Economic complexity has a strong long-term effect on resource efficiency and is a good predictor of resource efficiency in the future different from other variables, such as the unit price of traded goods and the share of the service sector in added value, which only have a short-term effect. We find that the overall economic complexity of a country is strongly related to its range of core products with a high product complexity index, high resource efficiency (unit price), and high expansibility (core number), which explains why ECI has a long-term impact on future growth of resource efficiency.

In summary, we find that economic complexity is not only correlated with prosperity (measured by GDP growth) but also linked to sustainability (measured by resource efficiency improvements). These findings imply that improving economic complexity by increasing the proportion of core products seems to be a priority for achieving the Sustainable Development Goals targets 8.4 'resource efficiency' and 12.2 'sustainable materials management'.

Credit author statement

F.M., H.W., and H.S. designed the research, F.M. and H.W. performed the analysis, T.F. and X.T. advised the statistical analysis, L.S., W.C and P.W advised the policy implications, Y.L. advised the method and discussion on ECI. All authors contributed to the writing.

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.

Data Availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106530.

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