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How is human well-being shaped? A global cross-national empirical analysis from the sustainable-development-system perspective

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Abstract

Sustainable development is a complex coupled system of ecology, technology, institutions and human well-being. Clarifying the synergistic mechanisms of multiple factors is key to advancing the global sustainability transition. Existing sustainable development frameworks mostly focus on the enumeration of development goals, lacking a systematic deconstruction of the logical hierarchy, transmission pathways and conditional dependencies among factors, which makes it difficult to explain the marked divergence in sustainability outcomes across countries. To this end, this paper constructs a logical analytical framework for a human-well-being-oriented sustainable development system, selects proxy indicators, and quantitatively examines the empirical associations between core factors and human well-being, together with their country-specific differentiated characteristics. The core scientific contributions of this study are twofold: at the theoretical level, it reconstructs the hierarchical logical system of sustainable development factors, proposes a logical transmission chain linking natural capital, technological capacity and institutional equity to human well-being, and establishes a systematic analytical paradigm of "base constraints–instrumental conditions–institutional adjustment–ultimate goal"; at the empirical level, it identifies the comprehensive patterns of association between core factors and human well-being, as well as cross-country heterogeneity.The study provides a theoretical analytical framework and cross-national empirical support for countries at different development stages to advance well-being-oriented sustainable development and improve the global sustainable development governance system.

Keywords: sustainable development; human well-being; economic complexity; distributive justice; natural capital; threshold effect; cross-national empirical analysis

Introduction

One of the intellectual origins of modern sustainable development thought can be traced back to the ecological-critical perspective of Marx, which dissected the rupture in the material exchange between humanity and nature under the logic of capital and laid the ideological foundation of ecological Marxism (Marx & Engels, 1932; Marx, 1983). In the following century, neoclassical growth theory remained dominant, assuming an unconstrained supply of natural resources and taking aggregate economic expansion as the sole objective of development (Solow, 1956), with environmental governance treated as a remedial measure applied once growth reached a certain level (Grossman & Krueger, 1991, 1995). A turning point came in 1972, when *The Limits to Growth* revealed the carrying-capacity boundaries of the Earth system (Meadows et al., 1972) and Leiss's *The Domination of Nature* offered a critique of "dominating nature" (Leiss, 1972). The 1973–1974 oil crisis pushed economists to incorporate resource constraints into growth theory (Dasgupta & Heal, 1974, 1979), emphasizing the substitution of man-made capital (Solow, 1974) and technological progress (Stiglitz, 1974), while Daly advocated keeping material-energy throughput within ecological limits (Daly, 1973, 1977). In the 21st century, green growth theory (OECD, 2011), planetary boundaries (Rockström et al., 2009) and degrowth theory (D'Alisa et al., 2014) emerged, and research diverged into weak- and strong-sustainability paradigms over whether "critical natural capital" is substitutable (Neumayer, 1999).

Beyond these theoretical debates, sustainable development, as a complex multidimensional practical issue, has also generated systematic frameworks for organizing diverse topics and measuring development practice. The 1987 Brundtland Commission's *Our Common Future* and the 1992 Rio Summit's *Agenda 21* established the principle of economic–social–environmental synergy (WCED, 1987; United Nations, 1992); the Millennium Development Goals (MDGs) of 2000 focused on poverty reduction, education and health in developing countries (United Nations, 2000); and the *2030 Agenda* established the SDG framework built on the 5P concept of People, Planet, Prosperity, Peace and Partnership, comprising 17 goals and 169 sub-targets (United Nations, 2015). Yet the system analytical framework still has deficiencies. First, it

emphasizes the listing and stacking of factors but lacks logical judgments about the mechanisms of interaction among different factors, making it difficult to distinguish core driving factors from secondary phenomena (United Nations, 2019). Second, universal standards are misaligned with national development stages: advocating the same targets for all countries ignores differences in resource endowments and development stages and fails to specify priority ordering across contexts. It is therefore necessary to consolidate more than a hundred targets into several logically related core factors and to identify differentiated sustainable-development pathways for countries at different development levels. We attempt to summarize the core factors of sustainable development into the following four aspects:

First, sustainable development prioritizes development. Early research, deeply influenced by traditional economics, treated aggregate economic expansion as the core subject of development (Solow, 1956), but the primary cognitive breakthrough of sustainable development theory was to distinguish growth from development, emphasizing that development does not necessarily entail physical scale expansion (Daly, 1973, 1977; Jackson, 2017). A consensus has since emerged that the ultimate subject of development is human beings (WCED, 1987) and that improving human well-being is the key objective of global sustainable development (Dietz et al., 2012; Gao, 2021); the economy is an instrument for achieving well-being rather than an end in itself (Daly & Cobb, 1994). Later research specifies the minimum floors and maximum ceilings of well-being (Raworth, 2017), and identifies consumerism as the key socio-cultural source of "material expansion with stagnant well-being" (Durning, 1992; Easterlin, 2004; Leonard, 2010).

Second, natural capital plays a foundational role. Traditional neoclassical economics treated the economy as an isolated system and long neglected the value of natural capital; Daly conceptualized it as an open subsystem of the Earth's ecological system (Daly, 1977), and Neumayer (1999) distinguished general from critical natural capital, emphasizing the non-substitutability of the latter. Scenario simulations confirm the severe consequences for human systems when natural-capital degradation crosses planetary boundaries (Randers, 2012; Dixson-Decleve et al., 2022), and ecosystem-services valuation estimates its importance (Costanza et al., 1997). Natural capital is the

preconditioning constraint for all development, but it does not directly translate into human well-being; it is mediated by property-rights institutions, technological level, distributional institutions and social governance (Thomas et al., 2000; Haines-Young & Potschin, 2010; Li et al., 2025). Wackernagel and Rees (1996) reveal the north–south imbalance in global ecological appropriation and the ecological-footprint displacement induced by trade, confirming that the realization of natural-capital value depends on international institutions as a mediating variable.

Third, the role of technology and efficiency is a focal point of debate, giving rise to two sharply contrasting judgments. The weak-sustainability paradigm, rooted in neoclassical economics, assumes that natural and man-made capital can be substituted for each other and takes improved resource-use efficiency as the core solution (Stern, 2009; von Weizsäcker et al., 2009; Nordhaus, 2013). However, a large body of literature warns of the Jevons paradox (Jevons, 1865): efficiency gains lower unit costs and stimulate the expansion of aggregate demand, so total resource consumption may rise rather than fall. Many scholars therefore argue that unless a ceiling is set on the aggregate material scale of the economy, improving efficiency alone cannot prevent ecological overshoot (Meadows et al., 1972; Daly, 1977, 1996; Leonard, 2010; Raworth, 2017). The relationship among ecology, technology and well-being is not a simple positive linear one; industrial structure and consumption patterns mediate the final outcome, and technology must be used within the framework of ecological scale constraints and fair distribution (Jackson, 2017).

Fourth, sustainable development is not merely a technical–material relationship between humanity and nature; it is also a matter of distributive justice. *Our Common Future* established the dual principles of intergenerational and intragenerational equity (WCED, 1987), and Daly's steady-state economics ranks distributional fairness alongside scale and efficiency as the three core dimensions (Daly, 1996), arguing that if distribution is severely unjust and efficiency gains are concentrated in a minority, sustainable development still cannot be achieved (Daly & Cobb, 1994; Thomas et al., 2000). Studies further reveal the phenomenon of ecologically unequal exchange: under the global "center–periphery" system, developed countries shift the ecological burden of resource extraction and pollution emissions onto developing countries while enjoying the

consumption benefits of resource products (Bunker, 1984; Common & Stagl, 2005; Dorninger et al., 2021; Dixson-Decleve et al., 2022). Scholarship also reflects on the practical dilemmas of realizing fairness, including the lack of operable, quantifiable institutional tools, the sovereign-constraint dilemma of global governance institutions, and the divergence in global ecological-justice values (Shue, 1980; Martínez-Alier, 2002; Dryzek, 2013).

We integrate the four core factors above to construct a logical analytical framework for a human-well-being-oriented sustainable development system, clarifying the functional positioning and action logic of each factor by distinguishing the base constraints, instrumental conditions, institutional adjustment and ultimate goal: natural capital provides the objective material-base constraint, technology and efficiency provide the instruments for transforming and utilizing resources, and the development gains are reallocated through distributive justice as an institutional-adjustment mechanism, ultimately yielding human well-being. On this basis, we select proxy indicators of the core factors to conduct cross-national quantitative empirical tests. The contributions of this study are twofold: first, it builds a logical analytical framework for a human-well-being-oriented sustainable development system, clarifying the logical relationships among sustainable development factors; second, it uses proxy indicators for cross-national quantitative empirical tests, examining the associations between multiple factors of the sustainable development system and human well-being and identifying the differentiated associations of each factor across countries at different development levels. The remainder of this paper is organized as follows. The methodology section elaborates on data sources, variable definitions and quantitative analytical strategies; the results section presents the empirical findings, including baseline regression, heterogeneity analysis and panel time-series analysis; and the discussion section addresses the main insights derived from the empirical analysis, implications for sustainable development governance, and research limitations.

Methods

This paper constructs a three-tier progressive quantitative analytical framework of "overall baseline verification—development-tier heterogeneity analysis—long time-

series panel mechanism identification", combining cross-sectional and panel data and integrating parametric regression, interpretable machine learning, threshold testing and spatial visualization to cross-validate the empirical conclusions.

Variable definitions and data pre-processing

On the basis of the sustainable development system analytical framework, we select proxy indicators of core factors to conduct cross-national quantitative empirical tests:

1. Human well-being (ultimate-goal tier). We select the Inequality-adjusted Human Development Index (IHDI) measured by the United Nations Development Programme as the proxy indicator of human well-being (UNDP, 2024).

2. Natural capital (base-constraint tier). We adopt the World Bank's natural resource rent (RENT; we convert the original percentage data into total resource rent) as the proxy indicator of natural-capital returns (World Bank, 2021). Our basic assumption is that natural-capital returns are a potential part of what is transformed into human well-being.

3. Technology and efficiency (instrumental-condition tier). We select the Economic Complexity Index (ECI) of the Harvard Growth Lab as the proxy indicator of technology and efficiency (The Growth Lab at Harvard University, 2026). Our basic assumption is that improvements in technology and efficiency can enhance human well-being.

4. Distributive justice (institutional-adjustment tier). We select the World Bank's net barter terms of trade index (NTT) and the standardized disposable-income Gini coefficient (GINI) from the Standardized World Income Inequality Database (SWIID) as proxy indicators of international and domestic distributive justice (Solt, 2020; World Bank, 2026). Our basic assumption is that fair and reasonable international and domestic distribution can enhance human well-being.

We construct two sets of observational samples. The first is a cross-sectional sample for all variables. For each variable, we compute five-year averages using the latest valid observations from each dataset (missing values are filled by carrying forward observations from the previous period) to build the cross-sectional sample. A five-year

average is calculated and retained only if a country has no fewer than three valid observations. After missing-value filtering and threshold constraints on valid observations for the original 169 countries, the final cross-sectional sample includes 119 countries. The second is a panel sample for IHDI and ECI. We build a balanced panel dataset covering these two indicators from 2010 to 2023, which contains 133 countries with a total of 1,629 observations.

Quantitative method design

Overall baseline verification: baseline OLS regression, Kernel-SHAP decomposition and global spatial visualization

For the 119-country cross-sectional sample, we use standardized OLS regression with HC-3 heteroskedasticity-robust standard errors to conduct baseline estimation. Model diagnostics include the variance inflation factor (VIF) for multicollinearity, the Durbin–Watson statistic for first-order serial autocorrelation, and the Omnibus and Jarque–Bera tests for the normality of residuals; adjusted R^2, F statistic, standardized coefficients, z values and p values are output to obtain the global average marginal effects of each variable on IHDI.

We introduce the Kernel-SHAP interpretable machine-learning algorithm to calculate the global average absolute SHAP contribution shares of each variable, and combine SHAP-value box plots to observe the sample distribution of variable contributions, providing supplementary verification of the marginal-effect estimates of the OLS regression.

Based on the five-year-average dataset of each country, we carry out global spatial visualization of the five indicators IHDI, ECI, NTT, GINI and RENT, intuitively comparing the cross-national spatial differentiation patterns of each indicator and forming cross-evidence with the econometric regression and SHAP decomposition results.

Development-tier heterogeneity analysis: IHDI tertile-group regression, group SHAP and classification of country-dominant factors

Based on the IHDI tertiles, we divide the cross-sectional sample of 119 countries into low-, middle- and high-human-development subgroups, with sample sizes of 40, 39 and 40 countries respectively. For each group, we separately run standardized OLS regression with HC-3 heteroskedasticity-robust standard errors; we complete model diagnostics for each group, including residual-normality tests and multicollinearity condition-number tests, and output the overall significance, adjusted R^2, standardized coefficients, z-statistics and p-values of each group's regression equation, comparing the differences in marginal effects of each explanatory variable across development tiers.

We simultaneously conduct group-level Kernel-SHAP analysis, calculating the mean SHAP value of variables within each group, to distinguish the marginal-variation effects captured by OLS regression from the stock-level contribution effects reflected by SHAP, and to analyze the divergent characteristics of variable contributions across groups.

Based on the maximum of each country's absolute SHAP contribution share, we classify countries by dominant factor, identifying categories such as economic-complexity-led, income-inequality-constrained and terms-of-trade-led, and count the sample size, share and corresponding mean IHDI of each category.

Long time-series panel mechanism identification: two-way fixed effects, threshold identification, tiered fitting and evolution analysis

To overcome the static limitations of cross-sectional data and to identify the net time-series effect of economic complexity (ECI) on the Inequality-adjusted Human Development Index (IHDI), as well as the two-way causality problem, this study constructs a balanced panel dataset covering 133 countries and 1,629 observations over 2010–2023. We first calculate the value ranges of variables, the Pearson correlation coefficient between contemporaneous ECI and IHDI, and the correlation coefficient between contemporaneous and one-period-lagged ECI, to describe the basic statistical characteristics of the sample and the temporal-dependence properties of variables.

We adopt a country–year two-way fixed-effects PanelOLS model, which strips country-specific inherent endowments that do not vary over time and global common time shocks through within-group mean-differencing, relying only on the within-country

time-series variation of ECI and IHDI to identify the relationship between variables. To test lagged spillover effects, we re-run the two-way fixed-effects regression with one-period-lagged ECI as the core explanatory variable; we perform 1%–99% percentile winsorization to complete sensitivity robustness tests on extreme samples.

According to the ECI tertiles, we divide the panel sample into low-, middle- and high-industrial-complexity groups, and respectively run country–year two-way fixed-effects regressions to compare the regression coefficients, significance, within R^2 and F-test results of ECI across different industrial bases, testing the tiered heterogeneity of the effects.

We use the interaction-term scanning method to conduct threshold identification, setting finely spaced ECI candidate thresholds in the range −0.3 to 0.3, successively constructing interaction terms between group dummy variables and ECI and incorporating them into the two-way fixed-effects model, and selecting the optimal threshold value according to the magnitude and significance of the interaction-term coefficients; we further use segmented quadratic fitting with a fixed inflection point to depict the nonlinear relationship between ECI and IHDI. We note that this scanning procedure identifies a threshold descriptively rather than through an endogenous threshold estimator; the value ECI = 0 should therefore be interpreted as indicating a conditional pattern rather than a precisely estimated structural break.

Grouping the panel sample by ECI, we calculate the annual mean IHDI, absolute increment and relative growth rate of each group over 2010–2023, plot time-series trend charts, and analyze the long-run evolution paths of well-being across industrial-complexity groups. Using violin–box plots, we output the sample size, IHDI median and interquartile range of each group, depicting the distributional dispersion of IHDI across ECI groups.

Results

Based on cross-national cross-sectional and long time-series panel data, this paper explores the effects of natural capital, technology and efficiency, and distributive justice

on human well-being, identifying global effects, development-tier heterogeneity, threshold gradients and spatiotemporal evolution patterns.

Baseline regression of overall effects and global SHAP decomposition

The adjusted R^2 of the OLS baseline regression is 0.777, indicating that the core variables selected in this paper can account for 77.7% of the cross-sectional variation in IHDI across the sample countries, indicating sufficient explanatory power of the model. The F statistic is 147.4 and $P = 4.26\times10^{-44}$, and the model as a whole is significant at the 1% level. The VIFs of all explanatory variables are far below the critical value of 10, indicating no serious multicollinearity; the Durbin–Watson statistic is 1.880, indicating no first-order serial autocorrelation; the Omnibus test P = 0.310 and the Jarque–Bera test P = 0.368, indicating that residuals follow a normal distribution. Model diagnostics are generally satisfactory, and the coefficient estimates are reliable in the context of this cross-sectional specification. As discussed in the limitations section, however, these estimates capture cross-country associations rather than causal effects.

The standardized cross-sectional regression results show that ECI has the strongest positive association with IHDI among the four explanatory variables, with a standardized coefficient of 0.1506, z = 14.122 and $p < 0.001$, meaning that for each one-standard-deviation increase in ECI, IHDI increases by 0.1506 standard deviations; GINI has the strongest negative association with IHDI, with a standardized coefficient of −0.0518, z = −5.172 and $p < 0.001$, meaning that for each one-standard-deviation increase in GINI, IHDI decreases by 0.0518 standard deviations. The standardized coefficient of NTT is 0.0213, z = 1.811 and p = 0.070, marginally significant at the 10% level; for each one-standard-deviation increase in NTT, IHDI increases by 0.0213 standard deviations, with a relatively small effect. The standardized coefficient of RENT is 0.0028, z = 0.256 and p = 0.798, not statistically significant, indicating that under this model specification RENT has no significant linear effect on IHDI.

The global average absolute SHAP contribution shares show that ECI accounts for 68.19%, ranking first; GINI accounts for 22.01%, the second-largest factor; NTT accounts for 8.99%; and RENT accounts for only 0.81%. The box plots (Fig. 1) show that ECI has the widest range of SHAP values, GINI's values span positive and negative

ranges, NTT's values are mostly concentrated near 0, and RENT's values are highly concentrated near the 0 baseline, consistent with the respective contribution shares. The SHAP contribution structure is broadly consistent with the OLS results: ECI accounts for the largest share of predicted variation in IHDI, GINI the second largest, NTT a limited share, and RENT extremely little. As SHAP is a model-based decomposition rather than causal evidence, these shares should not be interpreted as causal contributions.

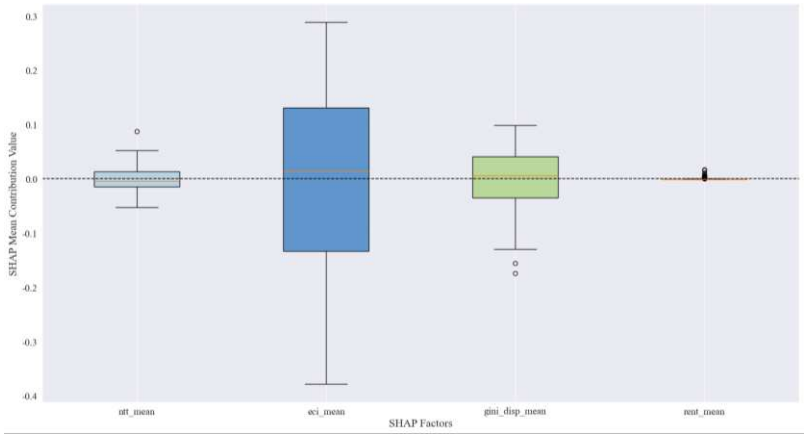


Fig. 1 Global Distribution of Four SHAP Contribution Indicators

Based on the five-year-average data of multiple countries, we carry out global spatial visualization of the five indicators: IHDI (Fig. 2a), ECI (Fig. 2b), GINI (Fig. 2c), NTT (Fig. 2d) and RENT (Fig. 2e). The spatial pattern shows that IHDI and ECI are highly synergistic, while the explanatory power of the other indicators at the macro-spatial level is weak, corroborating the regression and other results.

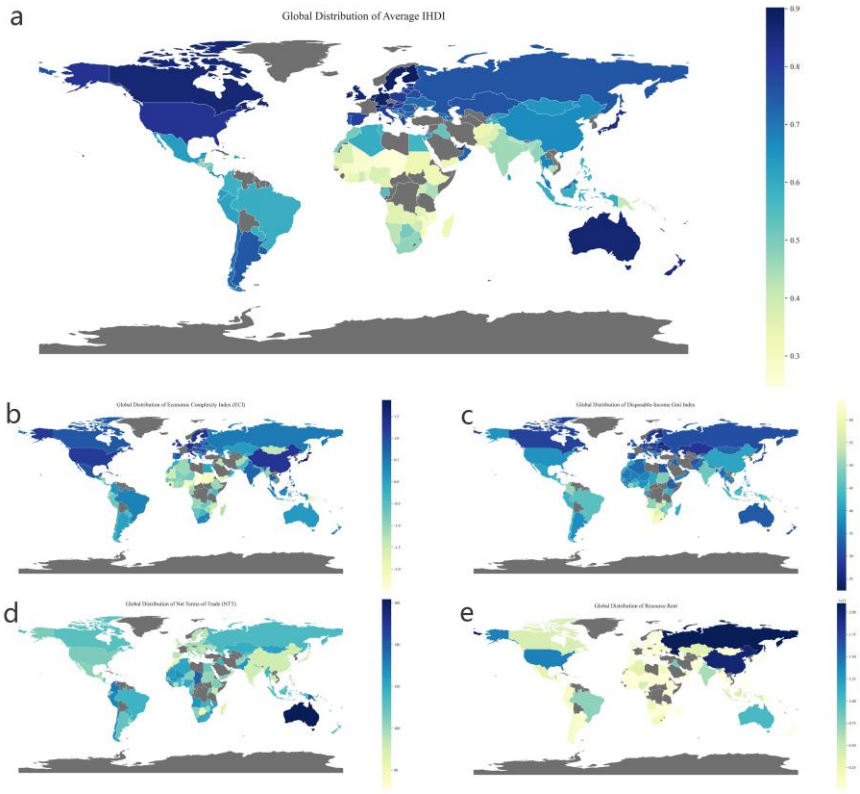


Fig. 2 Global spatial distribution of five-year averages for IHDI, ECI, GINI, NTT and RENT

Heterogeneous effects across development tiers

According to the IHDI tertiles, we divide the 119 samples into the low-development group (40 countries), the middle-development group (39 countries) and the high-development group (40 countries), and respectively conduct standardized OLS regression and global Kernel-SHAP analysis. All three group regressions are overall significant, the residual-normality tests of each group pass, there is no multicollinearity, and the basic assumptions of the models hold.

Table 1 Comparison of regression coefficients of core variables across human-development groups

Variable	High human-development group (n=40)	Middle human-development group (n=39)	Low human-development group (n=40)
ECI	**0.0270, z=4.049, P<0.001**	**0.0318, z=2.917, P=0.004**	**0.0320, z=2.945, P=0.003**
GINI	**−0.0153, z=−2.229, P=0.026**	**−0.0208, z=−2.332, P=0.020**	+0.0089, z=0.980, P=0.327
NTT	+0.0143, z=0.993, P=0.321	+0.0087, z=0.634, P=0.526	−0.0123, z=−1.104, P=0.270
RENT	≈0, z=−0.003, P=0.998	−0.0096, z=−0.459, P=0.646	+0.0062, z=0.302, P=0.763
Intercept	0.8279	0.6334	0.3697

ECI is the only variable that is significantly positive at the 1% level in all three groups, and its positive promotion effect is universal across development stages, with the marginal effect relatively higher in the low-human-development group. GINI shows marked development-stage heterogeneity: it is significantly negative in the high- and middle-human-development economies but positive and insignificant in the low-human-development group, indicating that the negative constraint of income inequality on well-being emerges only at the middle and high development stages. NTT and RENT do not pass the significance test in any of the three groups. The three group intercepts exhibit a declining gradient, indicating systematic differences among human-development groups independent of the core explanatory variables (Table 1).

The group SHAP analysis reveals the stage-divergence characteristics of the stock contributions of variables: a positive value indicates the current variable values on average raise the predicted IHDI, while a negative value indicates they depress it. Overall, the SHAP contributions of ECI and GINI shift from negative to positive as the human-development level rises, NTT shifts gradually from positive to negative, and RENT shows a negative contribution only in the low-development group and a small positive contribution in the middle and high groups; all four variables exhibit marked stage heterogeneity (Fig. 3). Note that the mean SHAP of GINI reflects the contribution of the stock GINI level of each group relative to the global mean, which differs in meaning from the marginal effect of OLS: the negative mean SHAP of GINI in the low-development group reflects its relatively high overall inequality dragging down IHDI, whereas its insignificant OLS coefficient represents that small within-group changes in GINI bring no significant penalty; the positive SHAP of GINI in the high-development group stems from generally lower Gini coefficients, meaning an equitable income pattern supports a higher IHDI (Fig. 4).

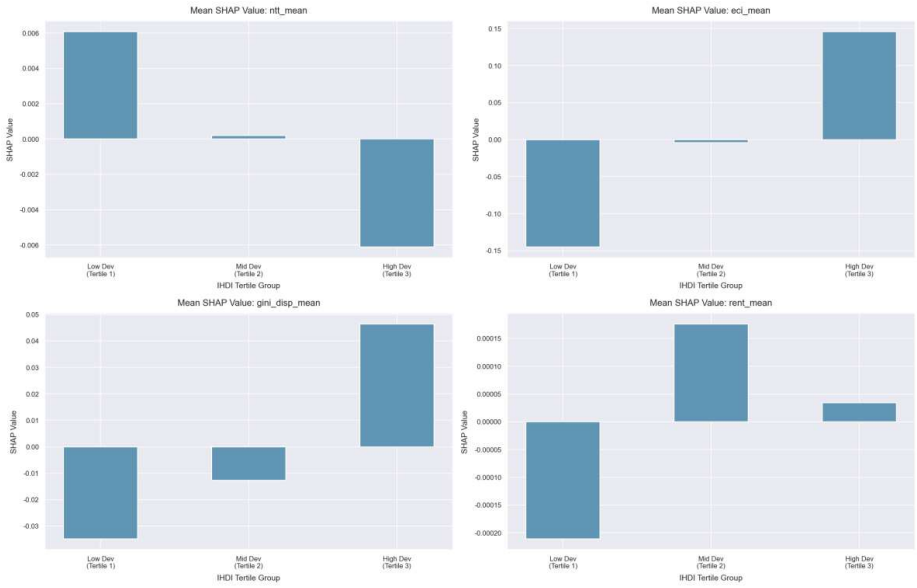


Fig. 3 Group-averaged SHAP values across IHDI tertile groups

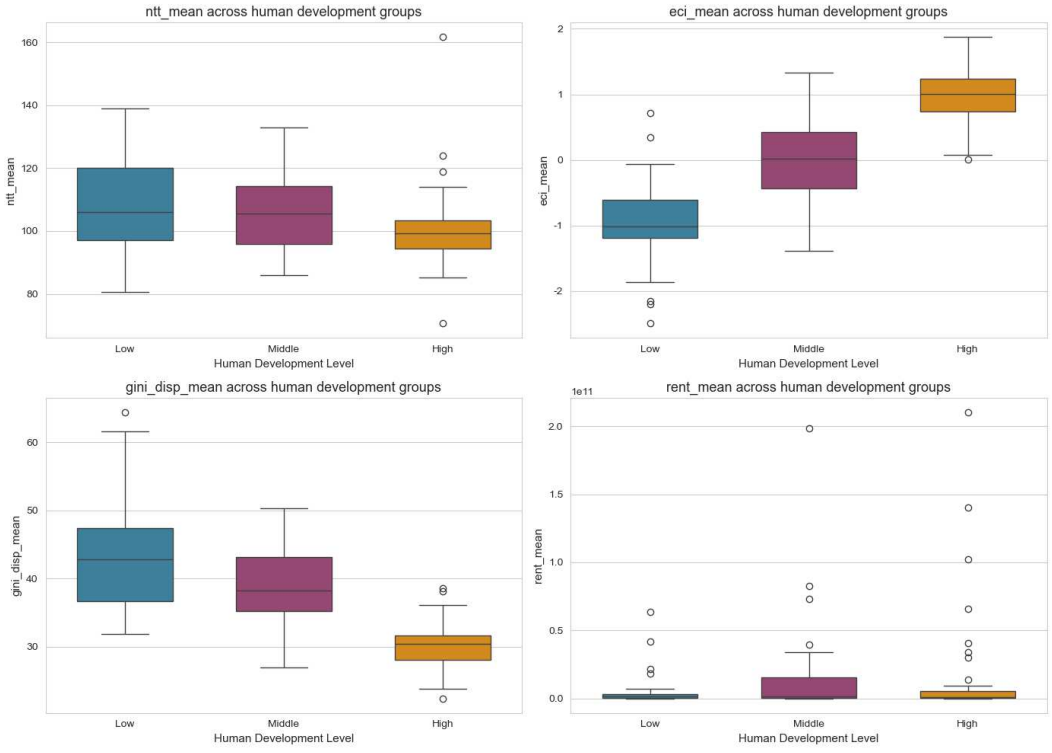


Fig. 4 Boxplots of mean values for NTT, ECI, GINI and RENT across human development tiers

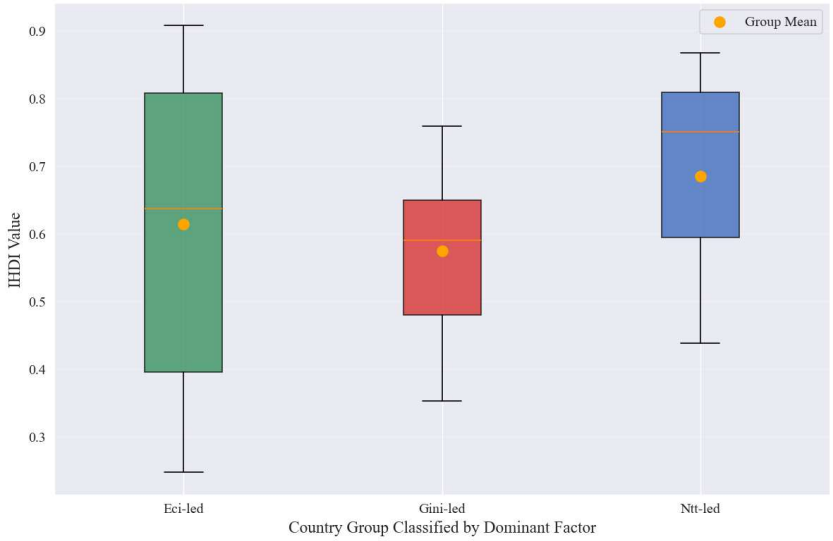


Fig. 5 IHDI Distribution under Different Dominant-Factor Types

Classifying the dominant-factor types according to the maximum absolute SHAP contribution share of each country, there are 102 ECI-led countries (85.71%) with a mean IHDI of 0.6130; 14 GINI-constrained countries (11.76%) with a mean IHDI of 0.5737, the lowest among the three types; only 3 NTT-led countries (2.52%), which, despite a mean IHDI of 0.6845, have too small a sample to be representative; and no RENT-led countries (Fig. 5). These results indicate that ECI shows the largest absolute SHAP contribution for the vast majority of countries, whereas for a small number of countries, generally at lower human-development levels, IHDI is most strongly associated with GINI. Given the descriptive nature of the SHAP-based classification, these labels are statistical summaries rather than causal drivers.

Panel time-series analysis and threshold-gradient effects

To overcome the limitations of static cross-sectional analysis and to identify the net time-series effect of ECI on IHDI and the two-way causal relationship, this paper constructs a balanced panel dataset covering 133 countries and 1,629 observations over 2010–2023. In the sample, IHDI ranges 0.216–0.91 and ECI ranges −2.85–2.1; the Pearson correlation between contemporaneous ECI and IHDI is 0.83, indicating a strong positive linear association, while that between contemporaneous and one-period-lagged ECI is

0.987, reflecting the strong time persistence and path dependence of economic complexity.

To exclude the interference of country-specific fixed endowments and global common shocks, this paper adopts a country–year two-way fixed-effects model, stripping out the above factors through double within-group mean-differencing and relying only on the within-country time-series variation of ECI and IHDI to identify their relationship. The regression results show that the contemporaneous ECI coefficient is 0.0091, significant at the 5% level. The results indicate that after excluding country-specific fixed endowments, annual small industrial iterations have a weak pull on a country's IHDI, and IHDI improvement relies more on long-term accumulation. To test whether ECI has a lagged effect on IHDI, we construct a country–year two-way fixed-effects model with one-period-lagged ECI. The regression results show that the lagged ECI coefficient is 0.0097, P = 0.0102, significantly positive at the 5% level, confirming that the IHDI dividends brought by ECI upgrading exhibit time-series accumulation and lagged spillover effects. To test the sensitivity of the results to extreme samples, we conduct a 1%–99% winsorization robustness test; the ECI coefficient is 0.0098, still significant at the 5% level, with essentially unchanged coefficient magnitude and significance, indicating that the core conclusions are not disturbed by extreme samples. The marginal effect is relatively small in magnitude, because the two-way fixed-effects model strips country-specific fixed differences and identifies only the effect of small within-country time-series fluctuations of ECI on IHDI. ECI is a slow variable whose single-year improvement is limited, so the annual marginal effect is low; but the effect accumulates persistently and will bring significant IHDI improvement over the long run.

Dividing the panel sample into low-, middle- and high-industrial-complexity groups according to the ECI tertiles, we respectively run country–year two-way fixed-effects regressions. The results show that the ECI coefficient of the low-industrial-complexity group is 0.0075 (not significant); that of the middle-industrial-complexity group is 0.0186 (significant at the 5% level); and that of the high-industrial-complexity group is 0.0436 (significant at the 5% level). The F tests of all three groups are significant, and the models are overall valid. These results indicate that the effect of ECI on IHDI exhibits tiered heterogeneity: at the low-industrial-complexity stage, ECI improvements are

difficult to translate significantly into IHDI dividends; once ECI reaches a certain level, the positive effect of ECI improvement on IHDI gradually emerges and continues to amplify.

To identify the critical threshold of the effect of ECI on IHDI, we set finely spaced ECI candidate thresholds in the range −0.3 to 0.3, successively construct interaction terms between group dummy variables and ECI, incorporate them into the two-way fixed-effects model, and select the optimal cut-off point according to the coefficient magnitude and significance of the interaction terms. The results show that when the threshold is set at ECI = 0 (the global average of this standardized index), the interaction-term coefficient peaks at 0.0206 with a p-value approaching 0 and the segmented effect difference is largest. The smooth segmented quadratic fitting (with the inflection point fixed at ECI = 0) further depicts the nonlinear relationship: in the range ECI < 0 the fitted curve is convex downward with marginal effects growing slowly; after crossing ECI = 0 the curve turns convex upward, with the marginal effect peaking at ECI = 0 and then gradually declining (Fig. 6). These results suggest a threshold-like association: the positive association between ECI and IHDI becomes more pronounced after crossing the critical value and then gradually weakens at higher levels. As described in the Methods, this threshold is identified descriptively and should be interpreted cautiously rather than as a precisely estimated structural break.



Fig. 6 Scatter plot and smooth segmented quadratic fit of IHDI against ECI

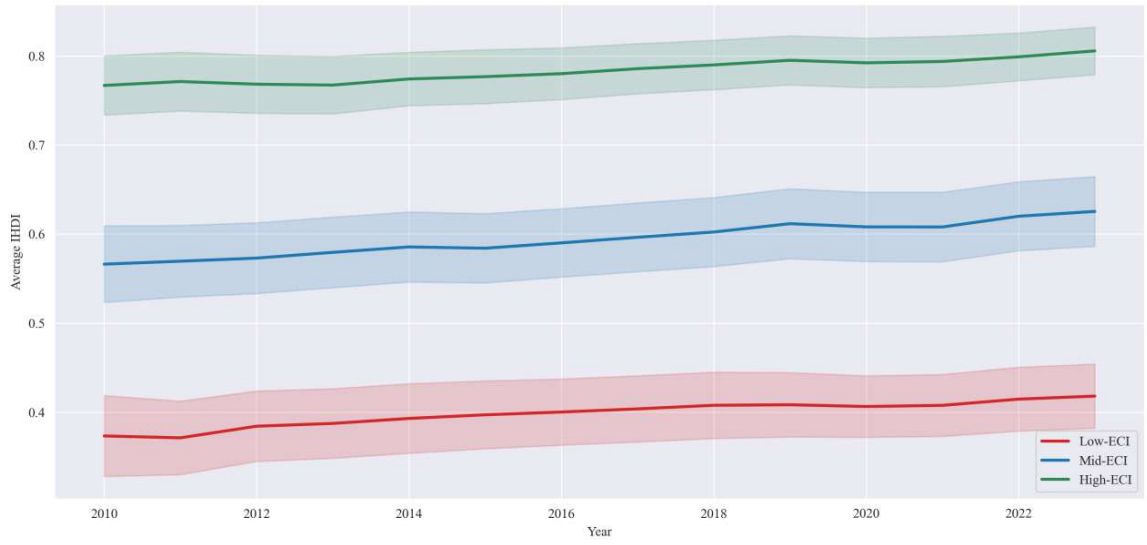


Fig. 7 Time-Trend of IHDI by Long-Run ECI Groups (95% Confidence Interval)

To depict the long-run evolution paths of IHDI across ECI groups, this paper plots the time-series charts of the mean IHDI of the low-, middle- and high-ECI groups over 2010–2023 (Fig. 7). The results show that the IHDI of the three groups generally maintains an upward trend over the sample period, and the tier ranking among groups remains stably high-ECI group > middle-ECI group > low-ECI group, indicating that the tier pattern has statistical rigidity. The IHDI of the low-ECI group increases from 0.3732 to 0.4180, an absolute increment of 0.0448 and a growth rate of 11.99%; that of the middle-ECI group increases from 0.5662 to 0.6254, an absolute increment of 0.0592 and a growth rate of 10.46%; that of the high-ECI group increases from 0.7669 to 0.8058, an absolute increment of 0.0388 and a growth rate of 5.06%. The low- and middle-ECI groups have higher relative growth rates, but the high-ECI group maintains a sustained lead in absolute development level, indicating that the global IHDI tier gap shaped by ECI differentiation persists over the long run.

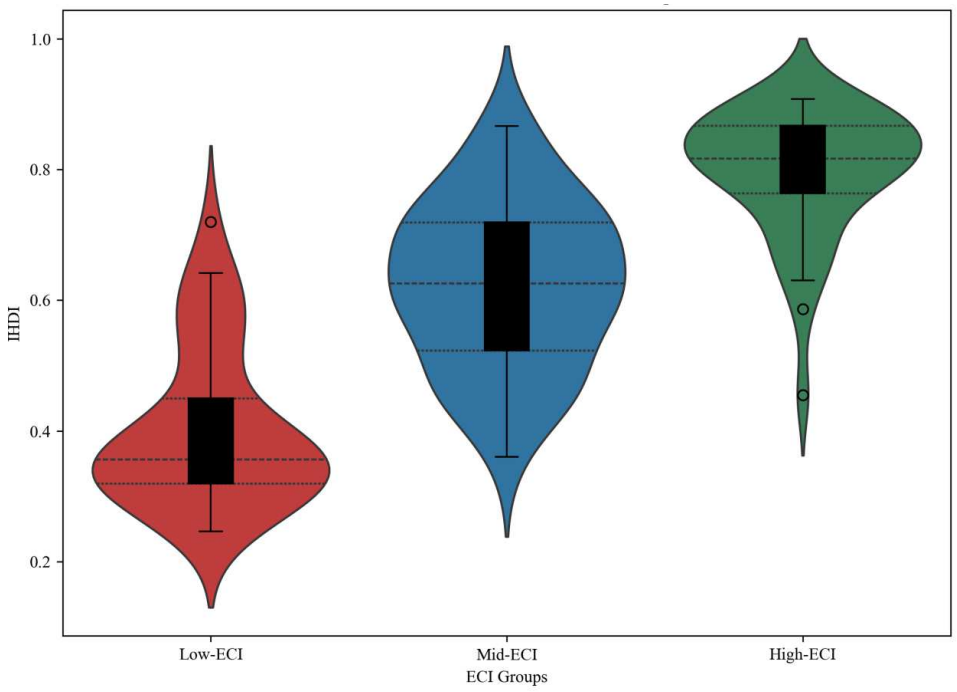


Fig. 8 Violin-box plots of IHDI distribution across ECI tiers

The violin–box plots depict the distributional characteristics of IHDI across ECI groups (Fig. 8). The low-ECI group has 39 samples with an IHDI median of 0.3564, with samples concentrated in the 0.3196–0.4496 range (interquartile range); the middle-ECI group has 39 samples with an IHDI median of 0.6260 and an interquartile range of 0.5234–0.7191, with a relatively large within-group value span and the highest internal development divergence; the high-ECI group has 40 samples with an IHDI median of 0.8169 and an interquartile range of 0.7636–0.8672.

Discussion

Based on the empirical findings, we systematically analyze the effects of ECI, GINI, NTT and RENT on IHDI, distinguishing global effects, development-tier heterogeneity and long time-series evolution characteristics, identifying the structural patterns and persistent gaps of global sustainable development, and elaborating the research limitations and corresponding governance implications.

Mechanisms of the four core indicators

This study divides the core factors of sustainable development into human well-being (ultimate-goal tier), natural capital (base-constraint tier), technology and efficiency (instrumental-condition tier), and distributive justice (institutional-adjustment tier). The realization of human well-being is a sustainable-development-system process in which the natural-capital base is transformed through technology and efficiency and the returns are then allocated through domestic–international distribution, with the effects of different links on ultimate well-being differing markedly.

The cross-sectional results show that ECI has the strongest positive association with IHDI among the four indicators, with a standardized coefficient of 0.1506 ($p < 0.001$) and a global Kernel-SHAP contribution share of 68.19%, the highest among all explanatory variables. According to the country classification based on SHAP contribution shares, 85.71% of sample countries are ECI-led, indicating that the well-being level of the vast majority of countries is closely associated with their domestic industrial capacity; the global spatial visualization also shows that the geographical patterns of ECI and IHDI are highly synergistic, cross-validating this association from the spatial dimension. From the system logic of action, ECI is not a mere technical indicator; behind it lies a composite process of industrial diversification, accumulation of production knowledge and improvement of the labor-employment structure. Higher economic complexity enables a country to build a more diversified production system, which can activate the local natural-capital endowment and expand universal employment opportunities through production division, transmitting resource endowments and capital inputs to residents' health, education, income and other livelihood dimensions, completing the mediating transmission of the system chain of "natural capital–technological transformation–human well-being" (Hidalgo & Hausmann, 2009; Balland et al., 2022).

However, the transformation of industrial technology into well-being is not a simple linear relationship. Our threshold test identifies ECI = 0 (the global mean of industrial complexity) as the key critical threshold, revealing that industrial enabling is subject to significant conditional constraints: when ECI < 0, economies mostly maintain resource-dependent and structurally homogeneous industrial forms with insufficient production-knowledge accumulation, so even small industrial improvements are difficult to spill over into universal well-being gains; only after crossing the threshold, when a diversified

industrial system takes shape, can the well-being dividends of industrial upgrading be fully released; and as ECI continues to rise, its marginal promotion effect gradually declines. As Hartmann et al. (2017) reveal, industrial-capacity structure delimits the base range of income inequality; after industrial complexity reaches a relatively high level, institutional adjustment factors such as distributive justice and redistribution mechanisms significantly increase their shaping effect on IHDI. The long time-series two-way fixed-effects panel regression further shows that ECI is a slow variable with strong path dependence: because production knowledge, industrial support and human capital cannot be iterated in the short run, the immediate pull of small single-year industrial changes on IHDI is very limited, and the gains of industrial progress for inclusive well-being are manifested more as lagged spillover effects revealed through long-term continuous accumulation. This also explains the rigidity of the global well-being pattern at the empirical level: the IHDI tier gap across countries is rooted in the long-accumulated industrial-capacity gap, so latecomer countries cannot rely on short-term policies to achieve leapfrog well-being catch-up; industrial diversification must be a long-cycle evolutionary process.

The Gini coefficient shows the second-strongest association with IHDI, with a standardized coefficient of -0.0518 ($p < 0.001$) and a global Kernel-SHAP contribution share of 22.01%, second only to ECI, indicating that the domestic income-distribution pattern is an important correlate of inclusive human well-being. The higher the income inequality, the more the development gains from industrial progress and resource development are concentrated in a minority, making it difficult to translate into education, health and livelihood security accessible to all citizens; this is consistent with the steady-state-economics view that distributional fairness is one of the three core dimensions of sustainable development (Daly, 1992, 1996). Under country classification, 11.76% of sample countries are GINI-constrained, and the mean IHDI of this group is the lowest among the three dominant-factor types, indicating that higher domestic income polarization is associated with lower human-development outcomes.

The baseline regression shows that NTT is only marginally significant at the 10% level, with a global Kernel-SHAP contribution share of 8.99%, indicating that the net barter terms of trade has only a very limited positive effect on inclusive human well-

being and no stable universal linear driving effect. Although a favorable external trade price ratio should in principle bring more trade gains, its transformation into residents' well-being is subject to real constraints such as the global division-of-labor pattern and the operating behavior of multinational capital, especially in the low-human-development group. Box plots show that low-human-development countries have the highest NTT mean and median, yet the trade price-ratio advantage has not been converted into a higher IHDI. The internal constraints operate at two levels. First, gains from the trade price ratio are difficult to transform into domestic resource-capital returns: some resource-exporting countries exhibit an indicator mismatch of "high NTT, low RENT", confirmed by the spatial visualization, because when resource-extraction industries are monopolized by multinational capital, mining groups can build overseas low-tax structures and transfer excess returns through related-party transfer pricing and cross-border profit remittance, while insufficient tax-collection capacity aggravates the loss of domestic resource returns (Guj et al., 2017). Second, even if part of the trade gains flows into the country, it is difficult to transform into universal well-being: when domestic distributional institutions are weak, the small retained trade gains tend to concentrate in a few interest groups rather than reaching health, education and other well-being improvements through public services and social security. The country-dominant-factor classification identifies only 3 NTT-led economies (2.52%), too small a sample for cross-national significance. Taken together, relying solely on improving the external trade price ratio cannot be a core pathway for raising a country's Inequality-adjusted Human Development Index; releasing trade dividends depends on domestic resource-return retention mechanisms and domestic distributional institutions.

In the sustainable development system analytical framework, the natural resource rent RENT serves as the proxy indicator of natural capital (base-constraint tier), representing the potential material returns that natural-capital development can bring. The empirical results show that, in this cross-sectional model, resource rent has no statistically significant direct association with inclusive human well-being: its coefficient is insignificant, its global Kernel-SHAP contribution share is only 0.81% (the lowest among the four core variables), and no RENT-led country exists among the 119 samples. This is consistent with the framework's presumption that natural capital is merely the

potential material base for realizing well-being: resource-rent returns do not automatically translate into universal human-development outcomes, and the transformation chain from natural-capital returns to IHDI must be jointly regulated by the technology-efficiency and distributive-justice mediating mechanisms, depending on the domestic industrial structure, resource fiscal-tax distributional institutions and the global division-of-labor environment. When an economy lacks the diversified industrial system represented by ECI, the institutional arrangements for redistribution of resource returns, and a favorable position in the global division of labor, even considerable resource rents are difficult to convert into residents' education, health and other livelihood gains. This finding also provides an explanatory perspective on the "resource curse" debate (Auty, 1993; Sachs & Warner, 1995; Lederman & Maloney, 2006), suggesting that the association between resource rents and development is condition-dependent rather than decisive: the advantage of natural capital is itself neutral, and whether it appears as a development impetus or a shackle depends on whether the instrumental conditions and institutional-adjustment mechanisms are in place.

Differentiated pathways for countries at different human-development tiers

According to the IHDI tertiles, we divide the 119 cross-sectional samples into high-, middle- and low-human-development groups, and the empirical results show that the core driving factors and constraints faced by the three groups present significant structural divergence. This indicates that there is no one-size-fits-all universal template for sustainable development; countries advancing a human-well-being-oriented sustainable development transformation need to identify the binding constraints of their own system based on their development tier and adopt differentiated strategies matching their development reality.

The regression results for the high-human-development group show that ECI is significantly positive and GINI is significantly negative, while NTT and RENT are both insignificant; the group SHAP also shows that the mean SHAP values of ECI and GINI in this group are both positive. Countries in this group have crossed the industrial threshold of ECI = 0, most belong to the ECI-led type, and the instrumental-condition tier is mature, having built a diversified industrial-knowledge system and freed themselves

from dependence on natural-resource rents and trade price ratios. Relying on a mature industrial system, they can transform natural capital and various capital inputs into employment, education and health gains, with industrial capacity constituting the core foundation of their well-being. At the same time, this group has generally established basic social security and redistribution institutions that buffer the negative shocks of income polarization, achieving basic smoothness of the system chain of "natural capital–technological transformation–distributive justice–human well-being". Even so, the within-group regression confirms that a marginal widening of income inequality still significantly erodes inclusive well-being. As industrial complexity reaches a high level, subject to the ECI threshold effect, the well-being dividends of industrial upgrading enter diminishing marginal returns, so the relative importance of institutional-adjustment factors rises. The insignificant NTT result only indicates that the trade price ratio no longer has a direct effect on domestic well-being, which does not mean that ecologically unequal exchange does not exist: under the global center–periphery division-of-labor pattern, high-human-development countries rely on their industrial and economic-trade advantages to shift ecological burdens such as resource extraction and pollution emissions outward, constituting a hidden external contradiction at the level of global sustainable governance (Prebisch, 1950; Emmanuel, 1972).

The regression results for the middle-human-development transitional economies show that ECI is significantly positive and GINI is significantly negative, with the negative inhibiting effect of the Gini coefficient reaching its peak among the three groups, while NTT and RENT have no significant linear effect. This group is mostly in the development stage of crossing or just having crossed the industrial threshold of ECI = 0: the well-being dividends of industrial diversification have begun to emerge, and they possess the material-technological base for a well-being leap, but there is a mismatch between the instrumental-condition tier and the institutional-adjustment tier—industrial capacity is expanding rapidly while domestic distributional institutions lag, which is the internal root of the strongest constraint of income inequality on this group. If the construction of distributive-justice institutions is neglected while single-mindedly pursuing industrial scale, the incremental gains will concentrate in a minority and the universal improvement of education, health and other livelihood outcomes will stagnate.

The regression results for the low-human-development economies show that ECI is significantly positive with the highest marginal return among the three groups, GINI is insignificant, and NTT and RENT also have no significant effect; in the group SHAP, the mean GINI is negative, and the box plots show that the NTT level of this group is the highest. Most countries in this group have ECI < 0, with a single industrial structure and an underdeveloped instrumental-condition tier, and have not yet established a complete industrial transformation channel. Although the marginal effect of ECI is high, representing substantial potential gains from industrial upgrading, constrained by the stock of human capital and industrial-support capacity, large-scale industrial transformation can trigger competitive crowding-out of scarce production factors, giving rise to transformation pains. The boom cycle of bulk commodities tends to solidify the regressive specialization pattern of primary products and erode the domestic manufacturing base; once production capacity is destroyed, the reconstruction of human capital and supporting industrial chains is far slower than their destruction (Gala & Nicolini Gabriel, 2026). For single-resource economies with ECI < 0, the probability of failure of leapfrog diversification is high; industrial-complexity upgrading can only proceed gradually along adjacent industries and belongs to long-term structural change, with outcomes highly dependent on human-capital reserves, industrial support and governance capacity (IMF, 2012). One must also distinguish the marginal effect from the stock effect of the Gini coefficient: the insignificant Gini regression only indicates that small within-group fluctuations have no statistical marginal penalty, whereas the group SHAP confirms that the generally high Gini levels in this group continuously suppress IHDI. At the external level, many countries in this group exhibit the indicator mismatch of “high NTT, low RENT”, deeply caught in the division-of-labor lock-in of primary-product exports, where multinational capital consumes resource dividends through monopolistic extraction, transfer pricing and outward profit flows, and even small retained gains are further intercepted by domestic distributional shortcomings.

Global development time-series characteristics and structural dilemmas

Based on the balanced panel dataset of 133 countries over 2010–2023, combined with time-series evolution, threshold regression and group time-trend analysis, we step beyond

single-country static cross-sections and, from a long-cycle systematic-evolution perspective, identify the inherent contradictions of global sustainable development. Such contradictions are rooted in human–environment coupling relationships, the international division-of-labor pattern and the path dependence of industrial capacity, and belong to deep-seated institutional–technological composite structural problems.

First, global human well-being over 2010–2023 presents an evolutionary pattern of "relative growth catch-up but absolute gap solidification", and inclusive well-being across countries has not achieved substantive convergence. The low- and middle-human-development groups have higher relative growth rates of IHDI, showing a catch-up trend of latecomer countries, but the high-human-development group always maintains an absolute-level advantage. Inclusive well-being is the result of long-term accumulation of multiple socioeconomic conditions, with marked lagged-accumulation characteristics, and cannot be raised in a leapfrog manner through short-term policies. This indicates that the persistence of global well-being inequality is associated not only with current development strategies but also with long-accumulated differences in human capital, institutional systems and social bases (Galor, 2011; Acemoglu & Robinson, 2012); these descriptive patterns suggest that convergence is unlikely to occur spontaneously through country-level development alone (UNDP, 2019).

Second, economic complexity, as the core carrier of the instrumental-condition tier, amplifies the unbalanced divergence of global development at the material-technological level through its threshold effect and path-dependence characteristics. The threshold regression identifies ECI = 0 as the key critical threshold, and the transformation of industrial capacity into well-being is not a smooth linear process but exhibits jump characteristics. Economies with ECI < 0 are mostly resource-dependent single-industrial structures with insufficient production-knowledge reserves, so local industrial improvements are difficult to transform into universal inclusive well-being, easily falling into a low-level equilibrium trap; only after crossing the threshold, when a diversified production system is established, can the well-being dividends of industrial upgrading be fully released. This pattern is consistent with a "Matthew effect"-like divergence in global development: countries that have crossed the threshold continue to accumulate industrial-related gains, whereas industrial investment below the threshold is less readily

reflected in livelihood outcomes, and the development gap tends to widen. At the same time, ECI is a typical slow variable whose industrial support, production knowledge and human capital all require long-term sedimentation, leaving no short-cut catch-up path and constituting an important constraint on the development of latecomer countries.

Third, from a global-system perspective, the international division of labor and the rules of multinational capital give rise to a mismatch of multiple factors, fostering the dependent-development dilemma of resource-dependent countries. Peripheral resource-based countries are situated in the center–periphery division-of-labor pattern, resource-extraction activities are dominated by foreign capital, and through mechanisms such as transfer pricing and cross-border profit remittance the excess returns of resource development flow outward; coupled with the absence of a domestic deep-processing industrial system, natural-capital endowments cannot be transformed inward into domestic industrial-capacity accumulation, domestic manufacturing continues to shrink, and the economy is solidified into a peripheral division-of-labor position in primary-product output. These patterns are consistent with the core proposition of our framework: natural capital is merely the potential material base of development, and resource endowments do not automatically generate universal human well-being. When technological-instrumental conditions have shortcomings and domestic distributional institutions are incomplete, a country's resource endowments not only fail to transform into development momentum but further deepen its development dependence. The system-chain rupture in some resource countries is a structural result jointly shaped by the global division-of-labor system and the rules of multinational capital, not a purely internal problem of a single country; relying only on domestic reform may be insufficient to fully resolve such systemic imbalances.

Implications for sustainable development governance and research limitations

Based on the empirical results, global sustainable governance should abandon the globally unified standardized development-assessment template and set differentiated target priorities according to the industrial base. At the global-institutional level, it should promote systematic reform of trade and investment rules to break the division-of-labor

dilemma of outward loss of returns in resource economies, help economies cross the industrial-capacity threshold of ECI = 0, and alleviate the global human-well-being gap from the material-technological base. At the same time, one must face the objective law that economic complexity is a path-dependent slow variable, respect the accumulation cycle of industrial knowledge and human capital, abandon the short-term radical catch-up mindset, and rationally set policy expectations for livelihood-well-being improvement.

For high-human-development economies, it is necessary to dialectically view the advantages and shortcomings of their own system and step out of the development-path dependence of "industrial complexity only". At the domestic dimension, while consolidating the technological-innovation advantage and maintaining the competitiveness of the instrumental-condition tier, greater attention should be paid to the institutional-adjustment tier, restraining the concentration of incremental industrial gains in a minority through optimizing tax adjustment and social-security systems. At the global dimension, as the main beneficiaries of the existing international economic and trade system, whose development dividends partly rely on the existing global division-of-labor pattern, they need to assume global responsibilities commensurate with their development level, actively participate in reforming international economic and trade rules, constrain ecologically unequal exchange behavior, promote global-level distributive justice, and alleviate the cross-national human-well-being gap.

Middle-human-development economies are in a critical window period of system transition: the instrumental-condition tier is expanding rapidly, but the institutional-adjustment tier easily lags behind, and according to the system-coupling logic, industrial upgrading and income-distribution reform cannot be promoted in isolation. Such countries should, on the one hand, continue to promote industrial diversification and technological iteration to consolidate the material-technological base on which sustainable development depends; on the other hand, they must simultaneously improve redistribution institutions such as taxation, transfer payments and social security, strengthen the institutional-adjustment tier, and ensure that the achievements of industrial development are shared universally.

Low-human-development economies are subject to the threefold constraint of weak instrumental conditions, stock distributional contradictions and an unfavorable external division of labor; governance practice must distinguish long-term and short-term goals. At the long-term dimension, they should gradually promote industrial-diversification transformation, extricate themselves from the primary-product division-of-labor lock-in, make up the shortfall in technology-efficiency as the core instrumental shortcoming, and release the long-term development potential of industrial upgrading. In the short run, radical industrial-leap strategies should not be implemented, to avoid crowding out scarce capital and human capital; priority should be given to improving resource fiscal-tax and return-monitoring institutions, curbing the unreasonable outward profit flows of multinational capital, achieving domestic retention of resource returns, and accumulating capital for subsequent industrial transformation. At the same time, the continuous livelihood loss brought by the stock of high inequality should be squarely faced, and domestic distributional institutions should be improved gradually to reduce the excessive concentration of development gains in a minority, building the institutional-adjustment foundation for sustainable development.

This study has several limitations, and its findings should be interpreted accordingly. First, all indicators are proxies drawn from public databases; IHDI, ECI, NTT, RENT and GINI capture only partial aspects of the underlying concepts, and measurement error in these proxies may attenuate or distort the estimated associations. In particular, because the IHDI already adjusts the Human Development Index for inequality, our outcome and the GINI indicator are conceptually related, which warrants caution in interpreting their joint coefficients. Second, cross-national macro-empirical research cannot achieve strict causal identification. The baseline estimates are based on cross-sectional variation and control for only a limited set of covariates, so they remain vulnerable to omitted-variable bias, reverse causality and simultaneity; likewise, the country–year two-way fixed-effects panel estimates identify only short-run within-country co-movement between ECI and IHDI and should not be read as causal effects of the wider sustainable-development system. Accordingly, the conclusions of this paper rest on correlational and descriptive evidence rather than rigorous causal proof. Third, the threshold (ECI = 0) is identified through a descriptive interaction-scanning procedure with a fixed inflection point rather

than an endogenous threshold estimator, and the SHAP results are model-based decompositions rather than causal attribution. Fourth, macro cross-national analysis cannot capture the micro-transmission processes within countries. It cannot directly quantify local environmental pressures or the operational details of micro-level institutions, making it difficult to conduct fine-grained analysis of the specific pathways through which resource rents flow out, economic complexity improves, or distributional institutions are reformed within individual countries. Fifth, the sample is restricted to countries with sufficient valid observations, and the five-year averaging and forward-filling procedures smooth the data; consequently, the findings may not fully generalize to all countries or to year-to-year dynamics, and the cross-country associations we document do not necessarily hold within countries or at the subnational level. Future research can be extended in multiple directions: conduct country-case studies for different types of economies such as resource-dependent countries and countries with rising economic complexity; distinguish traditional industrial complexity from green industrial complexity to identify differentiated effects of various forms of industrial upgrading; further explore how reforms of global trade rules can assist low-ECI countries in breaking low-end division-of-labor lock-in; carry out more refined micro-level analysis of sustainable development systems at the subnational regional scale; and explore disparities in regional sustainable development models combined with geographical background characteristics.

Data availability

The datasets analysed in this study are publicly available and can be accessed directly from the following sources:

(i) The Inequality-adjusted Human Development Index (IHDI) data were obtained from the United Nations Development Programme, available at: https://hdr.undp.org/data-center/documentation-and-downloads. On this page, the IHDI-value for all countries can be retrieved using the built-in selection filters. The extracted dataset is also provided in the supplementary file `hdr-data.xlsx`.

(ii) Natural resource rent (RENT) data were retrieved from the World Bank, available at: https://data.worldbank.org/indicator/NY.GDP.TOTL.RT.ZS

(iii) The net barter terms of trade index (NTT) data are available from the World Bank, available at: https://data.worldbank.org/indicator/TT.PRI.MRCH.XD.WD

(iv) The Economic Complexity Index (ECI) is provided by the Growth Lab at Harvard University, available at: https://atlas.hks.harvard.edu/data-downloads. Users can download the source data by selecting the dataset titled 'Complexity Rankings & Growth Projections' on this webpage. We have additionally supplied the corresponding data as supplementary file `growth_proj_eci_rankings.csv`.

(v) Standardized disposable-income Gini coefficient (GINI) data come from the Standardized World Income Inequality Database (SWIID), available at: https://fsolt.org/swiid/

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