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Green growth assessment across 203 economies: Trends and insights

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ABSTRACT

Green growth underpins the achievement of sustainable transition through continued economic development while addressing threats to environmental sustainability and socially inclusive well-being. Yet, decoupling economic growth from natural resource depletion and environmental degradation while achieving long-term sustainable development remains complex. Here, we present a comprehensive evaluation of green growth across 203 economies using our novel dataset (i.e., Data descriptor titled, "*Comprehensive green growth indicators across countries and territories*" published in *Scientific Data*) to examine the determinants and indicators of green growth and their variations across diverse countries and regions. We further analyze the long-term trends and patterns of green growth performance, drawing insights from historical data for future policy-making. Finally, we examine the policy implications of β-convergence in green growth while addressing regional disparities. We use the constructed global measures of green growth to rank (winners and losers) countries with environmentally sustainable economic development. The top ten economies with high performance in green growth include Monaco, Singapore, New Zealand, New Caledonia, American Samoa, the US, Japan, Bangladesh, Sri Lanka, and Australia. In contrast, the bottom ten economies ranked by their low green growth performance include Saint Martin, Faeroe Islands, Turkmenistan, Sint Maarten, Palau, Guinea-Bissau, Sierra Leone, Bermuda, Suriname, and Curacao in a bottom-up fashion. Our empirical results show that green growth policies that internalize the negative effects of sustainable development improve a country's socioeconomic dynamics, environmental quality of life, natural asset base, policy responses, and emission productivity.

1. Introduction

The impact of climate change coupled with the rapid depletion of global environmental resources has heightened calls for climate change adaptation solutions—including a greener and more socially inclusive form of economic growth (Ofori et al., 2022; Sarkodie et al., 2022; UNEP, 2011). This global threat underpins the importance of transitioning from a carbon-intensive economy to green growth. Green growth advocates for the proactive pursuit of complete synergy among the economy, environment, and society, aiming to secure an unceasing provision of essential services and resources from nature to sustain life on earth (Acosta et al., 2019; OECD, 2014). Thus, regional bodies such as the OECD, African Development Bank (AfDB), and the Asian Development Bank (ADB), as well as the UNEP, have all introduced programs to promote the inclusion of green growth into the national development plans of member countries (African Development Bank, 2019; Jha et al., 2018; OECD, 2014; UNEP, 2011). The pursuit of green growth strongly complements, and even sometimes replaces multilateral development initiatives including the Sustainable Development Goals (SDGs), Paris Climate Accord, and Aichi Biodiversity Targets (Acosta et al., 2019; OECD, 2014).

In response, researchers have recently focused on the empirical assessment and comparison of the status of green growth among countries and regions (See: Houssini et al., 2022; Kim et al., 2014; Leth, 2022; Stoknes et al., 2018). However, despite the growing interest in comparing the level of green growth among countries, the extant literature is still beset with two fundamental challenges. First, no two studies (or even multilateral institutions) have a common theoretical understanding of the concept of green growth, much less an agreeable measure for it (Leth, 2022). Consequently, different authors have piloted varied measures of the concept, through which they have assessed various countries and advanced various conclusions and policy recommendations. For instance, after computing a new measure of green growth based on two new self-advanced definitions of the concept, Stoknes and Rockström (2018) proceeded to assess the levels of green growth among the Nordic countries and concluded that "excluding

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Norway, other Nordic countries namely Sweden, Finland, and Denmark have achieved genuine green growth" (Stoknes et al., 2018, p. 1). However, Kim et al. (2014) described their measure as being broader and appropriate for country-specific and global comparisons. They maintained that on average green growth performance, Sweden (7th), Denmark (11th), and Norway (11th) rank higher while Finland (21st) ranks lower than the majority of OECD countries on the same index. Unfortunately, despite these contrasting conclusions, attempts to compare the two studies would be erroneous. This is because the two studies approach the concept of green growth from entirely different theoretical understandings and empirical measures (Leth, 2022).

The second constraint of the extant literature is the limited number of studies assessing the status of green growth on a global scale. Only two identified studies have attempted to assess the status of green growth across multiple global economies (see: Acosta et al., 2019; Leth, 2022). First, using data from 115 countries across multiple continents, Acosta et al. (2019) computed the Green Growth Index which was used to rank countries on global green growth performance. However, the measure only relied on data for one year, making it nothing more than a snapshot of countries' green growth conditions in 2019. Second, Leth (2022) developed the Green Growth Score based on data from 72 countries over 30 years. However, the measure lacks discernible theoretical separations among the dimensions. For instance, while the economic dimension maintains variables such as age dependency and adjusted net savings, the social dimension is fed with similar variables such as the Gini coefficient, unemployment ratio, and poverty gap at $3.2.

This paper aims to bridge the existing gaps in the literature by formulating three distinct research questions: Firstly, it explores the essential determinants and indicators of green growth and their variations across diverse countries and regions. Secondly, it analyzes the long-term trends and patterns of green growth performance, drawing insights from historical data for future policy-making. Lastly, it examines the policy implications of β-convergence in green growth to promote sustainable development and address regional disparities. The research questions are addressed through a comprehensive global assessment of green growth, utilizing a new dataset [developed by Sarkodie et al. (2023b)] that encompasses 203 global economies, spanning across all continents and regions. The new dataset distinguishes itself not only by the extensive number of sample units but also, by the temporal coverage (32 years). Sarkodie et al. (2023b) also offers an extensive measure of green growth and its dimensions from 152 variables relying on a novel estimation technique that controls for arbitrary weights and missing data across countries and territories, making it a more promising and stable measure of green growth. The dataset further allows for comparing levels of green growth both between and within countries over a longer period of time. As expressed by Leth (2022), a more informative green growth measure should be one that "enables a better understanding of a country's achievement of green growth while aligning with a stronger comprehension of sustainability".

Our contribution to the existing literature is multifaceted: first, this study represents the largest cross-country ranking of green growth performances to date. The study covers several countries and territories spreading over 32 years (i.e., 1990–2021). The extensive coverage eliminates the generalizability problem faced by other studies since data from all countries are utilized. Second, we examine the concept of β-convergence for the global green growth dataset for the first time. Third, we use novel panel estimation methods to investigate common shocks, heterogeneous effects, and club convergence across economies. These estimation methods ensure the robustness of our empirical assessment. Our analysis indicates that green growth policies that internalize the negative effects of sustainable development improve a country's socioeconomic dynamics, environmental quality of life, natural asset base, policy responses, and emission productivity.

For the remaining sections of the study, we conduct a literature review, describe our methodology, present our findings, and conclude.

2. Literature review

A reliable green growth measure is a valuable tool for tracking progress, comparing performances, and informing policy developments across multiple entities. Yet, while prior studies have explored the concept of β-convergence for economic growth (Furceri, 2005; Sala-i-Martin, 1996), typically brown growth—there remains a noticeable scarcity of studies focusing on green growth, representing a gap in the current literature. The concept of β-convergence examines the tendency of countries with initially lower levels of economic development to catch up with initially advanced economies (Sala-i-Martin, 1996). Thus, the assessment of this concept for green growth has policy implications for promoting sustainable development while addressing environmental challenges.

Most studies assessing the status of green growth around the world have focused on individual countries or groups within a region (e.g., Baniya et al., 2021; Houssini et al., 2022; Kim et al., 2014; Stoknes et al., 2018). Other organizations and regional bodies have also conducted green growth assessments for their member countries (African Development Bank, 2019; Jha et al., 2018; OECD, 2014). Despite the variations in focus, two key emerging strings, as well as two enduring challenges, can be observed. Firstly, there is an emerging consciousness of efforts to establish, both theoretically and empirically, a clear separation between green growth and traditional economic growth. Secondly, there is also an increasing awareness of efforts to achieve social inclusivity in green growth, a dimension that had been ignored by some of the earlier studies on green growth. Nonetheless, a common challenge in most studies is the disjointed application of indicators by various authors, a phenomenon that only exacerbates the confusion surrounding the definition of green growth. Additionally, the paucity of data required to establish a global standard for green growth has led to the issue of generalizability. This issue undermines the applicability of most existing studies. In the following section, we discuss the state of emerging strings of research on green growth and the identified challenges.

The lack of a standard definition or a definitive theoretical understanding of the concept of green growth has inspired numerous studies to establish one. In 2009, the OECD defined green growth as striving for economic growth and development while simultaneously mitigating expensive environmental damage, addressing climate change, averting biodiversity loss, and promoting sustainable use of natural resources (OECD, 2009). Its measurement framework then categorized green growth indicators into four thematic areas namely: (1) Productivity of environment and resources, (2) assets of the economy and environment, (3) quality of life in the environment, and (4) economic opportunities and policy reactions. These four thematic areas, together, were fed with 25 to 30 indicators that the OECD identified as flexible enough to be tailored to diverse national contexts and periods of development. In related studies, the AfDB insisted on a simple theoretical understanding that describes green growth as simply "ensuring the quality and sustainability of growth". The Bank thus proposed the African Green Growth Index (AGGI) to facilitate the mainstreaming of green growth as a key and strategic development policy agenda. In response, Kararach et al. (2018) argued that "although simplicity is a key attribute in developing green growth indicators, it is equally important that these indicators capture the imagination of their users and stakeholders—specifically, African governments, development agencies (including banks), industries, labor, and other various entities." Nevertheless, although the AfDB highlights simplicity as a tenet of the AGGI, the inclusion of as many as 48 indicators in calibrating the measure signals anything but simplicity. In addition, the AfDB's intention to measure and capture, among others, factors such as regulatory reforms, policy development, capacity development, knowledge management, political commitment, public support, financing, and research and development signals a substantial deviation from the idea of simplicity. Unsatisfied with the existing theoretical conceptions of green growth, Stoknes and Rockstrom (2018) proposed two distinct definitions, which they referred to as "weak" and "strong." They assert that “whereas the weak definition requires absolute decoupling, the strong or “genuine green growth" requires sufficient decoupling to achieve science-based targets for planetary boundaries" (Stoknes and Rockstrom, 2018, p. 1). The authors validate their approach by assessing the state of green growth in Nordic countries since 2000, concluding that Sweden, Finland, and Denmark have achieved genuine green growth, adhering to the principles of strong decoupling. However, Norway, on the other hand, did not attain genuine or strong green growth.

In adjacent studies, the rising consciousness to make green growth inclusive has inspired a new string of research. Several of these studies are largely premised on questioning the widely held assumption that green growth is a win-win approach to development. For instance, UNRISD (2012) in questioning this assumption, expressed that different groups may be affected differently by efforts implemented to achieve green growth, which has the risk of producing winners and losers simultaneously. For instance, green growth can contribute to widening economic inequalities through incentive programs implemented for payment for environmental services or through market-based pricing or allocation of environmental assets that disproportionately benefit rich polluters to the detriment of the indigent. The World Bank (2012) also warned that green growth is not inherently inclusive and that the plight of groups such as children, women, and the youth must be specifically addressed by specific provisions to achieve green growth. In agreement, Kararach et al. (2018) also acknowledged that green growth should focus on achieving a “green and fair economy.” Thus, the inclusion of the gender dimension became a distinctive feature of Kararach et al.’s framework, a dimension rarely found in the hitherto literature. Nonetheless, questions remain regarding the set of variables needed to ensure that a green growth measure is inclusive. For instance, without any theoretical justification, Kararach et al. (2018) adopted variables such as female HIV rates, the female labor force, and the proportion of seats held by women to make the AGGI inclusive. It is unclear how these variables are related to economic growth. In a response to concerns that existing green growth measures failed to properly incorporate the social inclusivity element of green growth, Jha et al. (2018) also developed the inclusive green growth index (IGGI) for ADB. Interestingly, they also adopt a set of variables markedly different from those of Kararach et al. For instance, for the social equity dimension, the authors settle on, among others, variables such as infant mortality rate, political participation gap, and primary enrolment gender gap.

In subsequent studies, other authors have incorporated several variations of variables to make green growth more inclusive. For example, Awan and Nawaz (2022) designed a green growth index which they used to track the determinants of green growth and monitored its progress from 1990 to 2021 for Bangladesh, India, and Pakistan. They utilized a set of 19 indicators spread over three dimensions namely productivity of resources, quality of environment, and economic and social aspects. They reported that urbanization and forest area are the primary contributors to green growth in Bangladesh whereas trade openness acts as the major factor disrupting this growth. In India, green growth faces hindrances due to socioeconomic conditions but benefits from forest areas and urbanization. Conversely, in Pakistan, trade openness, urbanization, and law and order promote green growth while impeded by socioeconomic conditions. The authors demonstrated that, on average, countries have experienced shifts in their positions concerning the overall best performer on green growth. For example, Pakistan was the overall best performer among the three countries from 2003 to 2011 but declined to the worst performer between 2012 and 2020, while India and Bangladesh exchanged positions between first and second during the same period.

The stark differences in the choice of variables among these studies spell a growing problem for policymakers seeking guidance on how to implement green growth. Also, these varied and disjointed conceptions and applications of green growth present a challenge for scholars seeking to compare countries’ performances. Earlier, the World Bank decried these disjointed adaptations and examinations of the status of green growth with varied sets of indicators. The Bank lamented that presenting only successful examples resulted in a biased sample (Toman, 2012, p. 8). Additionally, the paucity of data to develop a truly grounded and widely representative measure of green growth undermined previous attempts to achieve a global measure of green growth. For example, though the African Development Bank piloted the AGGI over an impressive set of 48 indicators, the index was constructed using only 22 of Africa’s 54 countries. The Bank stated that “one of the main limitations of the AGGI was the lack of data.” A similar problem was faced by Jha et al. (2018) who developed the Inclusive Green Growth Index for the Asian Development Bank. Similarly, although the OECD (2009) identified 30 indicators that it described as flexible enough to be tailored to diverse national contexts and periods of development, the dataset is still mostly limited to only member countries, making it unsuitable for global assessments of green growth performances across different continents.

Recently, three known studies have attempted to remedy the issue of disjointed conceptions and applications of green growth, as well as, the challenge of an inexistent global measure of green growth (see: Acosta et al., 2019; Leth, 2022; Sarkodie et al., 2023b). In an attempt to establish a global measure of green growth, Acosta et al. (2019) developed the Green Growth Index based on data from 115 countries across multiple continents. They defined green growth as:

“a development approach that aims to achieve economic development that is environmentally sustainable and socially inclusive. This approach seeks opportunities for economic development that are low-carbon and climate-resilient, while also addressing pollution, maintaining healthy and productive ecosystems, creating green jobs, reducing poverty, and enhancing social inclusion” (Acosta et al., 2019).

Their index relied upon 36 indicators organized into four key dimensions namely: (1) efficient and sustainable use of resources, (2) protection of natural assets, (3) economic opportunities, and (4) social inclusion. The index included a critical gender equality component that allows for the assessment of the impact of green policies on women, signaling an attempt to incorporate a key emerging trend in the measurement of green growth. However, despite gaining valuable insights through a new measure, the authors acknowledged that 33 % of the 36 indicators used to construct the index lacked the “desired data”. To compensate, they resorted to using proxy variables, inadvertently giving certain indicators more weight than others. The authors acknowledged that regions like Oceania and Africa had significant missing values (83 % and 61 % respectively), leading to some uncertainty in the results of the constructed index (Acosta et al., 2019). Additionally, it’s crucial to note that the indicator was only developed and tested for the year 2019, providing only a snapshot of countries’ green growth conditions during that period. Thus, a more comprehensive and informative green growth measure should improve existing information on a country’s attainment of green growth and its commitment to a more robust understanding of sustainability (Leth, 2022, p. 48).

Leth (2022) utilized a composite index measurement strategy to evaluate the green growth performance of 72 countries based on 27 indicators distributed over three key dimensions namely: (1) Economic, (2) Environmental, and (3) Social. This approach, unlike Acosta et al. (2019) and Jha et al. (2018) covered a broader period from 1990 to 2019. The author argued that this measurement strategy aligns better with the theoretical conception of green growth by avoiding some compensatory approaches and excessive proxy variables found in other studies. However, it’s important to note some limitations of the study. First, the analysis only covers 72 countries, with a significant proportion (40 %) being European or OECD countries. This narrow sample raises concerns about the generalizability of the findings (challenges found in other studies). Additionally, the measure was standardized using data from only five European countries (Denmark, Ireland, Spain, Sweden, and Switzerland), which may limit its applicability to other regions. Moreover, the lack of clear theoretical distinctions among some of the dimensions poses another concern. The economic and social dimensions for instance seem to overlap on some variables. Thus, while Leth (2022) provides valuable insights into green growth performance, its limited country selection, and potential applicability issues, along with the lack of distinct theoretical separations among dimensions, calls for a cautious interpretation of the results.

Finally, Sarkodie et al. (2023b), represent by far, the most current and extensive attempt to develop a green growth measure on a global scale. The study covers 203 countries and territories over 32 years (from 1990 to 2021). It offers both country-specific and global-context models, making it suitable for multiple settings. Also, unlike Acosta et. al. (2019) (which has four dimensions) and Leth (2022) (which has three dimensions), Sarkodie et al. (2023b) offered five dimensions of green growth, making it the most multidimensional of the three. Their study indicated that its innovative approach is based on the theoretical concept of transitioning from brown to green growth and involves strategic multifaceted actions influenced by economic endowments, socioeconomic capabilities, political decisions, and environmental outcomes (Sarkodie et al., 2023b). Hence, their definition of green growth entails "a continuous economic development approach that is dissociated from adverse environmental impacts while relying on eco-technological efficiency, decreasing poverty, and enhancing social inclusion" (Sarkodie et al., 2023b).

Our study relies on the dataset developed by Sarkodie et al. (2023b) to assess the status of green growth in 203 countries. While we outline our key empirical and theoretical contributions in the introduction, the use of Sarkodie et al. (2023b) implies that our study represents, by far, the largest cross-country ranking of green growth performances.

3. Methods

This study presents a follow-up analysis of our "*Comprehensive green growth indicators across countries and territories*" published as a Data descriptor in *Scientific Data.*[1] In this Data descriptor, we presented the description of variables and their characteristics, in addition to the systematic panel methods used in constructing the numerous datasets on green growth indicators and dimensions of green growth (environmental policy responses, environmental productivity, quality of life, socioeconomic outputs, and natural resources). For brevity, the description of datasets used and detailed estimation models for the construction of green growth indicators are presented extensively in Sarkodie et al. (2023a, 2023b).

3.1. *Empirical models*

After constructing the green growth indicators (Sarkodie et al., 2023b), we employed diagnostic tools including a cross-section dependence (CD-test) (Pesaran, 2004) and CADF test (Im et al., 2003) to confirm the global common shock/spillover effect and stationarity of green growth. Cross-section dependence may arise due to spatial and economic interactions, common external shocks (for example, global crises and /or economic crises), spillover effects, common unobserved factors, and time-varying heterogeneity (Hsiao, 2022; Phillips and Sul, 2003). Investigating potential cross-section dependence is crucial in panel modeling because of its reflection of the real-world interdependencies and interconnectedness across global economies. Similarly, panel stationarity underpins the validity and reliability of the panel modeling process, by ensuring the consistency of the panel estimators (Baltagi and Kao, 2001). Hence, neglecting these challenges could lead to biased estimates, reduced statistical efficiency, incorrect statistical inferences, and misleading policy implications (Baltagi, 2008). We further used the panel kernel-smoothing technique to examine green growth heterogeneity across economies. The selection of the panel kernel-smoothing technique is due to its versatility in panel modeling and robustness to outliers, offering non-parametric flexibility and spatiotemporal smoothing while handling nonlinearity and capturing heterogeneous effects and patterns within panel data (Li and Racine, 2023; Linton and Nielsen, 1995). This panel technique incorporates a split (half)-panel jackknife bias-corrected method that reduces biases of kernel-smoothing, problems with incidental parameters, and non-linearity of kernel-smoothing functions in the existing literature while computing the mean, autocorrelation, and autocovariance density functions (Okui and Yanagi, 2019, 2020). Thus, this approach produces robust estimates and confidence intervals even in a small sample size. The computed mean [$\mu_i = E(y_{i,t} \mid i)$], autocorrelation [$\rho_{k,i} = \gamma_{k,i}/\gamma_{o,i}$], and autocovariance [$\gamma_{k,i} = E((y_{i,t} - \mu_i)(y_{i,t-k} - \mu_i) \mid i]$ density functions can be expressed as (Okui and Yanagi, 2020):

$$\widehat{f}_{\hat{\xi}}(x) = \frac{1}{N_h} \sum_{i=1}^{N} K\left(\frac{x - \widehat{\xi}_i}{h}\right)$$

Where $\widehat{f}_{\hat{\xi}}(x)$ is the kernel density estimator; $\widehat{\xi}_i$ denotes either mean (μ_i), autocorrelation ($\rho_{k,i}$), or autocovariance ($\gamma_{k,i}$); country i=1, …, N; $h > 0$ represents the bandwidth fulfilling $h \to 0$; $x \in \mathbb{R}$ and $K : \mathbb{R} \to \mathbb{R}$ are the fixed point and kernel function, respectively. For specification, the panel density of moments was estimated using a Gaussian kernel with an equally-spaced grid of size 100 bandwidth, and a split (half)-panel jackknife bias-corrected method, hence, revealing strong evidence of heterogeneous effects in green growth dynamics (Fig. 7; Supplementary Table 7). Subsequently, we examined the global effect of individual dimensions on green growth using a fixed-effects model while applying simultaneous hypotheses testing of global green growth on individual dimensions and vice versa. To prevent rejection of false null hypotheses, we used Romano-Wolf (Clarke et al., 2020) step-down adjusted p-values based on 100 resamples at 95 % significance level to compare with the Uncorrected (Model) p-values (Fig. 9, Supplementary Fig. 19; Supplementary Tables 8, 10). The estimated model is validated by both Kernel Regularized least squares (i.e., a machine learning approach) and heterogeneous panel regression models (Supplementary Tables 8–9). The standard errors and confidence intervals were estimated with 1000 non-parametric bootstrap replications.

We further examined the concept of β-convergence in green growth by using the simplified expression viz. $GrowthRate_{i,t} = \beta \times lnGreenGrowth_{i,t} + \gamma \times Control_{i,t} + \varepsilon_{i,t}$ (Furceri, 2005). Where *GrowthRate* is the estimated growth rate of green growth across economies *i* and time periods *t*, β is the estimated coefficient of green growth, γ is the estimated coefficient of controls (i.e., lag-dependent variable for dynamic models, otherwise, excluded), *lnGreenGrowth* is the natural log (*ln*) of the initial values of green growth and ε is the error term. We estimated this concept using both a baseline model (i.e., panel fixed effects model) and complex models from several methods [i.e., Mean Group Common Correlated Effects Estimator (CEMG), Pooled Common Correlated Effects Estimator (CCEP) (Ditzen, 2018), Bootstrap Corrected Dynamic FE Regression (BCFE) (De Vos et al., 2015), Kernel Regularized Least Squares (KRLS) (Hainmueller and Hazlett, 2014), Mean Group Defactored Instrumental Variable approach with Common Factors (MGIV), and 2-Stage Instrumental Variable approach with Common Factors (2SIV) (Kripfganz and Sarafidis, 2020)].

4. Results

4.1. *Ranking category indices*

We estimated the average category indices while accounting for time-frequency dynamics to identify winners and losers. We further normalized the resultant average indices between 0 and 1. The five hotspot economies with high emission productivity include Nauru, Vanuatu, Seychelles, Fiji, and Cabo Verde whereas five countries with

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[1] https://www.nature.com/articles/s41597-023-02319-4

low emission productivity comprise Turkmenistan, Uganda, Mali, Somalia, and Burkina Faso (Supplementary Figure 1). The emission productivity index identifies economies with high or low demand-based CO_2 emissions, production-based CO_2 emissions, and CO_2 intensity. The energy productivity index classifies economies with historically high or low energy consumption in other sectors, industries, transport, and services. Five top-down ranked economies with high energy consumption include Jamaica, Sudan, Benin, Panama, and Togo while five bottom-up countries with low energy consumption consist of Equatorial Guinea, Ethiopia, Suriname, Yemen, and South Sudan (Supplementary Figure 2). The non-energy material productivity top-down ranking encompasses economies with high consumption of biomass, non-metallic minerals, and metals, but low municipal waste generation. The top five countries with high non-energy material productivity index include South Sudan, Timor-Leste, Norway, Equatorial Guinea, and Luxembourg while Bahamas, Tuvalu, Peru, Guyana, and Guinea-Bissau represent five bottom-up economies with a low index (Supplementary Figure 3). The multifactor productivity index shows countries with high or low adjustments for pollution abatement, environmentally-adjusted multifactor productivity growth, and the level of contribution of natural capital. Russia, Chile, Romania, Germany, and Lithuania top the list of countries with high multifactor productivity whereas the five bottom-up countries capture Mexico, Croatia, India, Korea, and Costa Rica (Supplementary Figure 4).

The environmental risk exposure index features economies with high mortality rates from exposure to ambient $PM_{2.5}$ and lead, and welfare costs of premature mortalities from exposure to ambient ozone and residential radon. Economies with high exposure to environmental risks consist of Syria, Cuba, Aruba, Turks & Caicos Islands, and Faeroe Islands while economies with low-risk exposure include Andorra, Northern Mariana Islands, American Samoa, South Sudan, and Somalia (Supplementary Figure 5). The index for access to drinking water and sewage treatment capture countries with high population connected to sewerage with primary, secondary, and tertiary treatment. These countries with high accessibility include Monaco, Kuwait, Singapore, Liechtenstein, and Malta, whereas economies with low access to sewage treatment comprise Tuvalu, Madagascar, Togo, Guinea-Bissau, and Ghana (Supplementary Figure 6).

The water resource index shows a top-down ranking of economies with high seasonal surface water, conversion of seasonal to permanent water surface, water stress, and conversion of permanent to seasonal water surface. Some of these economies with high water resources comprise the Turks & Caicos Islands, Marshall Islands, Bahamas, Estonia, and the United States. In contrast, economies with low water resources include the Netherlands, Timor-Leste, Malawi, Somalia, and Iran (Supplementary Figure 7). The land resource index covers the total built-up area, irrigated land, cropland, artificial surfaces, water, and natural & semi-natural vegetated land across economies. The top five countries with high land resources comprise Japan, Korea, Israel, Greece, and China, whereas Faeroe Islands, Somalia, Cabo Verde, Peru, and Tonga are the five bottom-up countries with low land resources (Supplementary Figure 8). The top five countries with high forest resources include Croatia, Ireland, Poland, Estonia, and Latvia whereas economies with relatively low forest resources comprise Vanuatu, Albania, Cabo Verde, Burundi, and Israel (Supplementary Figure 9). The forest resource index incorporates historical changes in naturally regenerating forests, forests under sustainable management certification fsc, forests with long-term management plans, and intact forest landscapes.

To develop a sustainable index for wildlife resources, indicators with high values were incorporated negatively into the final index—implying that low values depict sustained wildlife resources. The index covers the sustainable sales of pesticides per unit of agricultural land alongside low levels of threatened bird, mammal, and vascular plant species. Countries with high wildlife resources include Indonesia, Kazakhstan, Russia, South Africa, and India whereas Japan, Korea, Malta, Curacao, and the Netherlands are five economies with low wildlife resources (Supplementary Figure 10). The temperature index shows a considerable increase in average annual surface temperature from 1951 to 1980 specifically in Guinea-Bissau, Slovenia, Finland, Mongolia, and Estonia—but a relatively low change in temperature was observed in Micronesia, Solomon Islands, Chile, Marshall Islands, New Zealand (Supplementary Figure 11).

Development and relative advantage in environment-related technologies have experienced historically high growth typically in high-income economies including Japan, Germany, Liechtenstein, the United States, and Monaco, but slow historic growth in developing countries such as Nicaragua, Uganda, Marshall Islands, Haiti, and Côte d'Ivoire (Supplementary Figure 12). Lack of data across several economies, typically in developing countries makes it difficult to assess the global status of research & development, regulation & management, and official development assistance. However, the few available data show increasing interest in research & development through energy [i.e., renewable energy and fossil fuel (excluding Ccs)] public RD&D budget, and environmentally-related Government R&D budget and expenditure. While research & development is historically high in Colombia, Norway, Australia, Denmark, and Finland—responses to RD&D are relatively low in Chile, Russia, Mexico, Lithuania, and Turkey (Supplementary Figure 13). The International Union for Conservation of Nature's management categorized marine and terrestrial protected areas are crucial to policy regulation & management of the ecosystem and are dominant in high-income countries including Germany, Luxembourg, New Caledonia, France, and Poland. However, attention to similar policy responses is fairly low in Bermuda, Moldova, Faeroe Islands, India, and China (Supplementary Figure 14). Similarly, total allocable official development assistance is very high in developed countries including Liechtenstein, Denmark, Germany, Norway, and the Netherlands but relatively low in Kazakhstan, Russia, Latvia, Azerbaijan, and Israel (Supplementary Figure 15). The country-specific official development assistance is mostly allocated to the environmental sector, renewable energy sector, and water supply & sanitation sector while targeting desertification, and climate change adaptation. Global environmental taxes & transfers have observed historical growth, specifically in developing economies (such as Bangladesh, Sri Lanka, Lao, Madagascar, and Afghanistan). Historic increases in energy-related taxes (i.e., diesel and petrol tax), fossil fuel producer and consumer support, electricity support, residential electricity price, and environmental tax including carbon pricing underpin the observed surge in environmental taxes & transfers. While energy-related taxes such as diesel and petrol tax appear higher in developing economies (excluding some oil-producing countries), environmental tax such as carbon pricing is relatively high in developed economies (Supplementary Figure 16).

A transition towards green growth requires financial investments, hence, sustained economic development is crucial to achieving a low-carbon and resource-efficient future. The sustainable economic index captures purchasing power parity, real GDP per capita, labor tax revenue, and value-added in agriculture, services, and industry whereas high values of GDP deflator and nominal exchange rate were incorporated negatively into the final index (i.e., a high GDP deflator and nominal exchange rate worsen sustained economic management) (Supplementary Figure 17). The social management index allows the understanding of the social dynamics that underpin the social inclusivity of green growth. The social management index ranks economies based on life expectancy at birth, total fertility rate, population density, population, and net migration. These indicators further determine the social capital of an economy, which may be advantageous or hamper green growth. The top five economies with high social management include Monaco, Singapore, Nauru, Bahrain, and San Marino whereas Saint Martin, Faeroe Islands, Liechtenstein, Palau, and Bermuda have low social management (Supplementary Figure 18).

4.2. Dimensions of green growth

The environmental productivity dimension was constructed using 56.39 % weight of emission productivity, 19.03 % weight of multifactor productivity, 14.45 % weight of non-energy material productivity, and 10.13 % weight of energy productivity while altering the sign (i.e., because an increase in emissions denotes worse outcome, the sign is altered to move in the opposite direction in the summary index) of emission productivity. The top-down ranking of the environmental productivity dimension represents economies with sustainable emission productivity (i.e., reduced demand-based CO_2 emissions, production-based CO_2 emissions, and CO_2 intensity), multifactor productivity (i.e., high adjustment for pollution abatement, environmentally adjusted multifactor productivity growth, and contribution of natural capital), non-energy material productivity (sustainable consumption of biomass, non-metallic minerals, and metals, but a low municipal waste generated), and energy productivity (energy consumption in other sectors, industries, transport, and services). The top five economies with high environmental productivity comprise Saint Lucia, Saint Kitts & Nevis, Somalia, Monaco, and Saint Vincent & the Grenadines. Five hotspots with low environmental productivity include Turkmenistan, Vanuatu, Equatorial Guinea, Ethiopia, and Palau (Fig. 1).

We constructed the natural asset dimension using 28.29 % weight of wildlife resources, 22.73 % weight of water resources, 16.96 % weight of land resources, 16.28 % weight of forest resources, and 15.74 % weight of temperature while altering the sign (i.e., an increase in temperature denotes a worse outcome for global warming, thus, the sign is altered to move in the opposite direction in the summary index) of temperature. Countries with sustainable natural asset base include Estonia, New Zealand, Turkey, Greece, and Ireland whereas the top 5 economies with limited natural assets comprise Guinea-Bissau, Curacao, Saint Martin, Hungary, and Mongolia (Fig. 2). The high natural asset dimension denotes economies with improved wildlife (sustainable sales of pesticides per unit of agricultural land, with low levels of threatened bird, mammal, and vascular plant species), water (low water stress, seasonal surface water, conversion of seasonal to permanent water surface, and conversion of permanent to seasonal water surface), land (built-up area, irrigated land, cropland, artificial surfaces, water, and natural & semi-

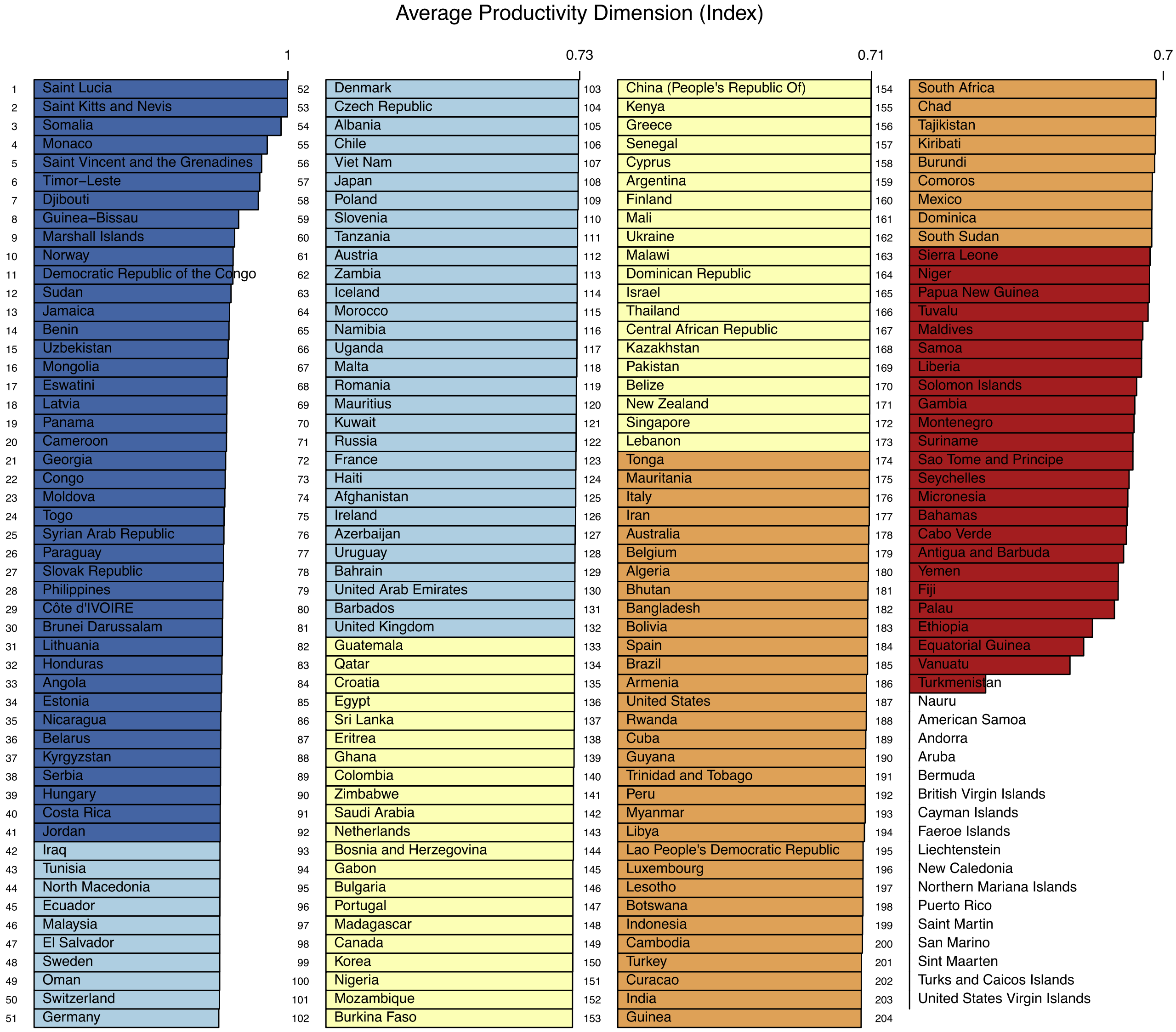

Fig. 1. Average environmental productivity dimension (index) of the constructed index across economies. Note: Countries with missing values are presented last in ranking without colored bar plots. Legend: Top-down/bottom-up ranking denotes high/low emission productivity (demand-based CO_2 emissions, production-based CO_2 emissions, and CO_2 intensity), multifactor productivity (adjustment for pollution abatement, environmentally adjusted multifactor productivity growth, and contribution of natural capital), non-energy material productivity (consumption of biomass, non-metallic minerals, and metals, but a low municipal waste generated), and energy productivity (energy consumption in other sectors, industries, transport, and services).

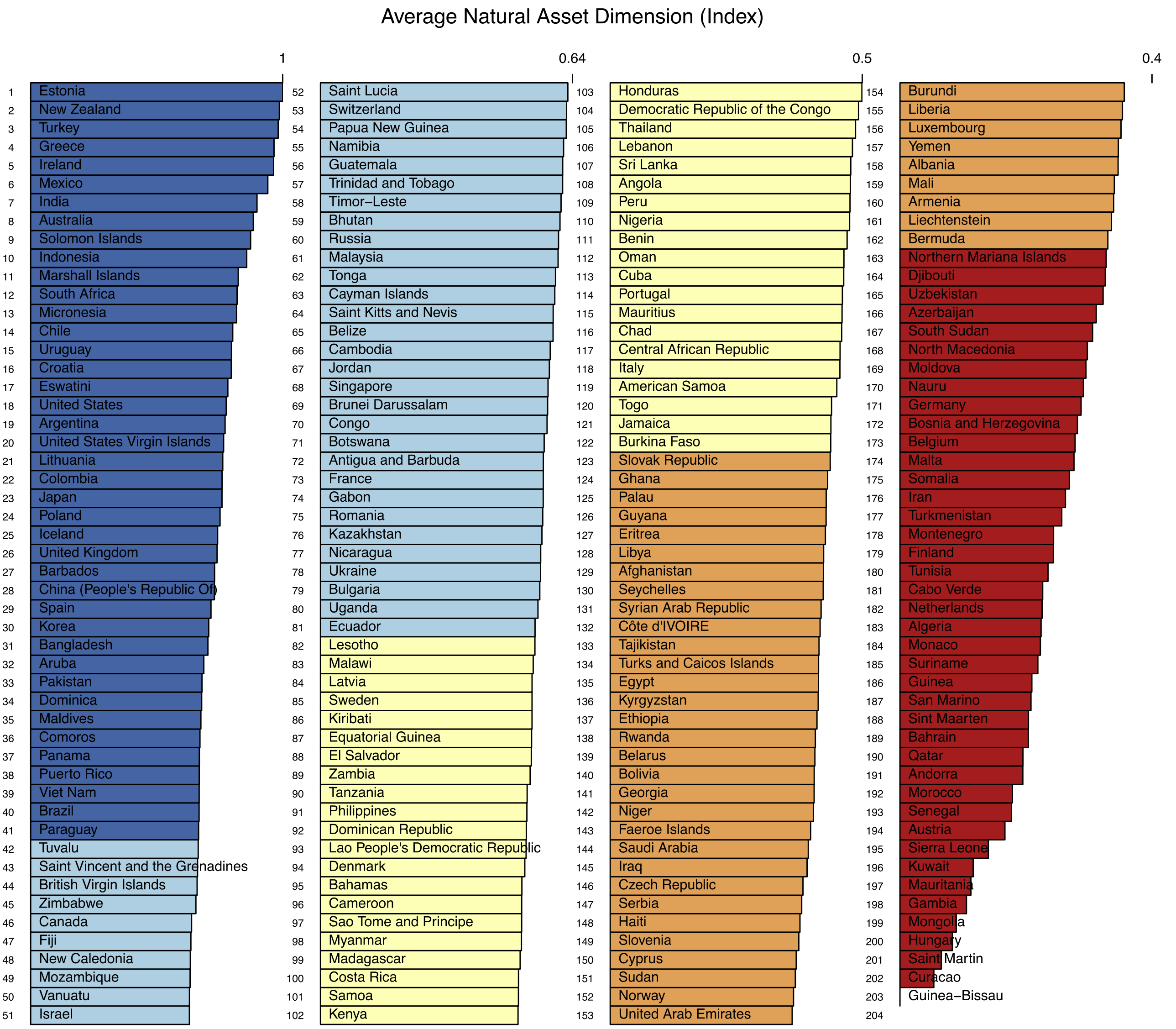

Fig. 2. Average natural asset dimension (index) of the constructed index across economies. Note: Countries with missing values are presented last in ranking without colored bar plots. Legend: Top-down/bottom-up ranking denotes high/low Wildlife (sustainable sales of pesticides per unit of agricultural land, with low/high levels of threatened bird, mammal, and vascular plant species), Water (water stress, seasonal surface water, conversion of seasonal to permanent water surface, and conversion of permanent to seasonal water surface), Land (built-up area, irrigated land, cropland, artificial surfaces, water, and natural & semi-natural vegetated land), Forest (naturally regenerating forests, forests under sustainable management certification fsc, forests with long-term management plans, and intact forest landscapes), and Temperature (annual surface temperature since 1951–1980).

natural vegetated land), and forest (naturally regenerating forests, forests under sustainable management certification fsc, forests with long-term management plans, and intact forest landscapes) resources but optimal annual surface temperature.

The environmental quality dimension was constructed using 53.44 % weight of access to water & sanitation quality, and 46.56 % weight of environmental risks while altering the sign (i.e., an increased environmental risk worsens the environmental quality of life, hence, the sign is altered to move in the opposite direction in the summary index) of environmental risks. The top-down ranking represents economies with high access to water & sanitation quality (i.e., population connected to sewerage with primary, secondary, and tertiary treatment), and low environmental risks (i.e., low mortality from exposure to ambient $PM_{2.5}$ and lead, and low welfare costs of premature deaths from exposure to ambient ozone, and residential radon). The top 5 economies with high environmental quality comprise Andorra, Northern Mariana Islands, Monaco, American Samoa, and South Sudan whereas economies with poor environmental quality include Syria, Cuba, Aruba, Turks and Caicos Islands, and Faeroe Islands (Fig. 3).

We constructed the policy response dimension using 33.72 % weight of environmental taxes & transfers, 32.99 % weight of R&D, 14.10 % weight of regulation & management, 11.83 % weight of patents, and 7.36 % weight of official development assistance. The top 5 economies with high environmentally-related policy responses include Sri Lanka, Monaco, Liechtenstein, New Caledonia, and Saint Martin whilst Bermuda, Solomon Islands, Iran, Bahrain, and Turkmenistan are the 5 bottom-up ranked economies with lax policy responses (Fig. 4). The top-down ranking represents countries and territories with high environmental taxes & transfers (i.e., energy-related taxes such as diesel and petrol tax, fossil fuel producer and consumer support, electricity support, residential electricity price, and environmental tax including carbon pricing), R&D investment (i.e., increased energy public RD&D budget as% of GDP, renewable energy public RD&D budget, fossil fuel public RD&D budget, excluding Ccs, environmentally-related Government R&D budget, and expenditure), environmental regulation & management (marine and terrestrial protected areas), patents (i.e.,

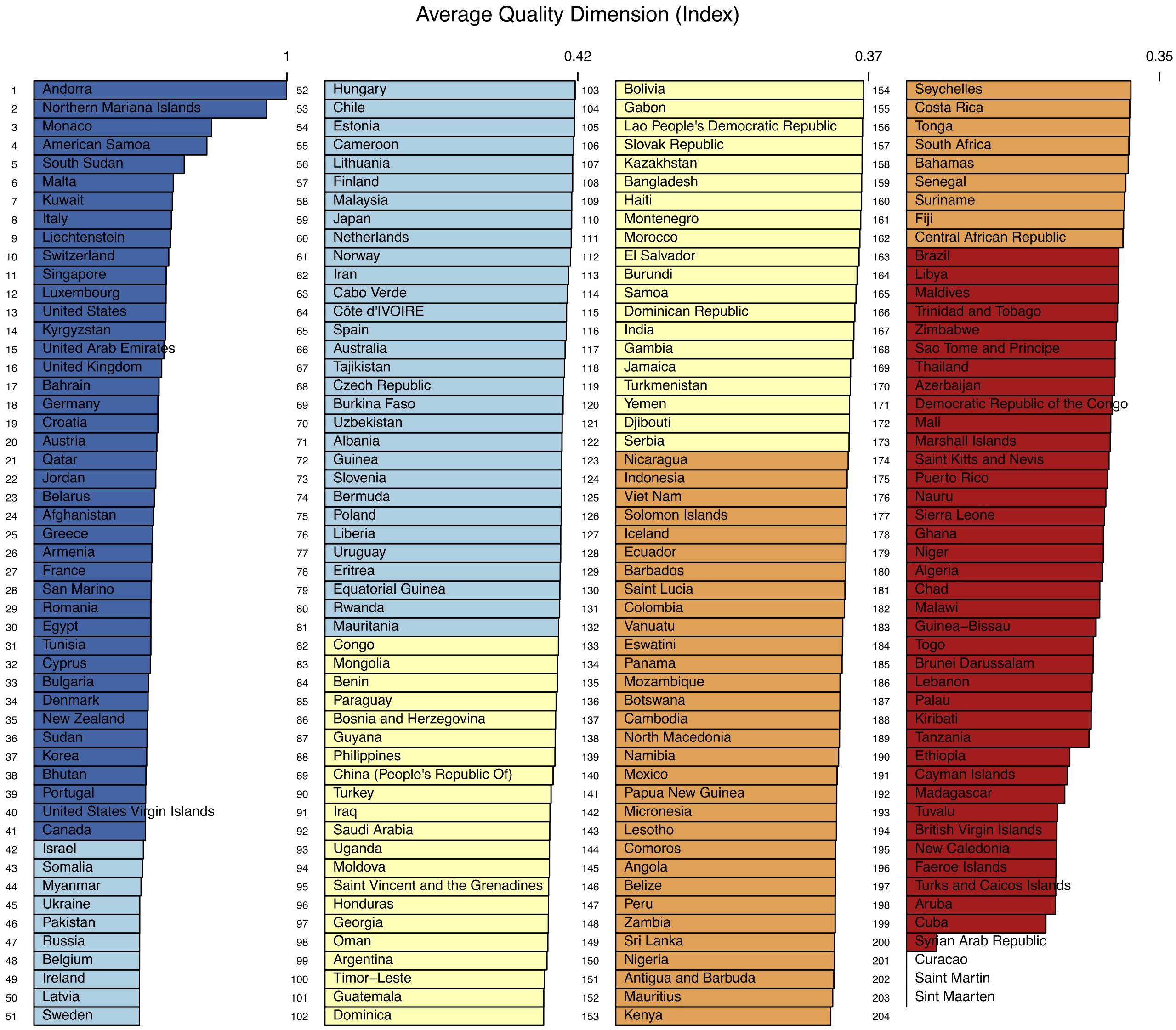

Fig. 3. Average environmental quality dimension (index) of the constructed index across economies. Note: Countries with missing values are presented last in ranking without colored bar plots. Legend: Top-down/bottom-up ranking denotes high/low access to water & sanitation quality (population connected to sewerage with primary, secondary, and tertiary treatment), and environmental risks (mortality from exposure to ambient $PM_{2.5}$, welfare costs of premature deaths from exposure to ambient ozone, welfare costs of premature mortalities from exposure to residential radon, and mortality from exposure to lead).

increased development of environment-related technologies and relative advantage in environment-related technology), and official development assistance (total allocable official development assistance to the environmental sector, renewable energy sector, water supply & sanitation sector, desertification, and climate change adaptation).

The socioeconomic dimension was constructed using 50.75 % weight of social context, and 49.25 % weight of economic context. The high socioeconomic index denotes economies with high social management (i.e., high life expectancy at birth, total fertility rate, population density, population, and low net migration) and sustained economic development (i.e., high purchasing power parity, high value-added in agriculture, high-income level (GDP per capita), high value-added in services, and industry, and labor tax revenue but low GDP deflator, and nominal exchange rate). The top 5 economies with high socioeconomic performance comprise Monaco, Nauru, Singapore, Bahrain, and Malta whereas the 5 bottom-up economies with low socioeconomic performance include Faeroe Islands, Liechtenstein, Andorra, Palau, and Northern Mariana Islands (Fig. 5).

4.3. *Ranking green growth indicators*

We developed 10 green growth indicators (Models 1–10) with diverse input characteristics. Our optimal indicator (Model 2) for green growth was derived from sustainable attributed dimensions (Supplementary Table 5). This infers the top-down ranking of green growth indicators shows economies with high performance in green growth accounted by socioeconomic opportunities, environmentally-attributed quality of life, sustainable natural resource base, stringent policy responses, and environmental productivity (Fig. 6). The top 10 economies with high performance in green growth include Monaco, Singapore, New Zealand, New Caledonia, American Samoa, the US, Japan, Bangladesh, Sri Lanka, and Australia. In contrast, low green growth performance comprises countries and territories with one or more attributes including reduced and unequal socioeconomic prospects, poor quality of life, high ecological footprint, lax policy responses, and poor environmental productivity. Bottom-up ranked economies with low green growth performance include Saint Martin, Faeroe Islands, Turkmenistan, Sint Maarten, Palau, Guinea-Bissau, Sierra Leone, Bermuda, Suriname, and Curacao. The statistical distribution shows that

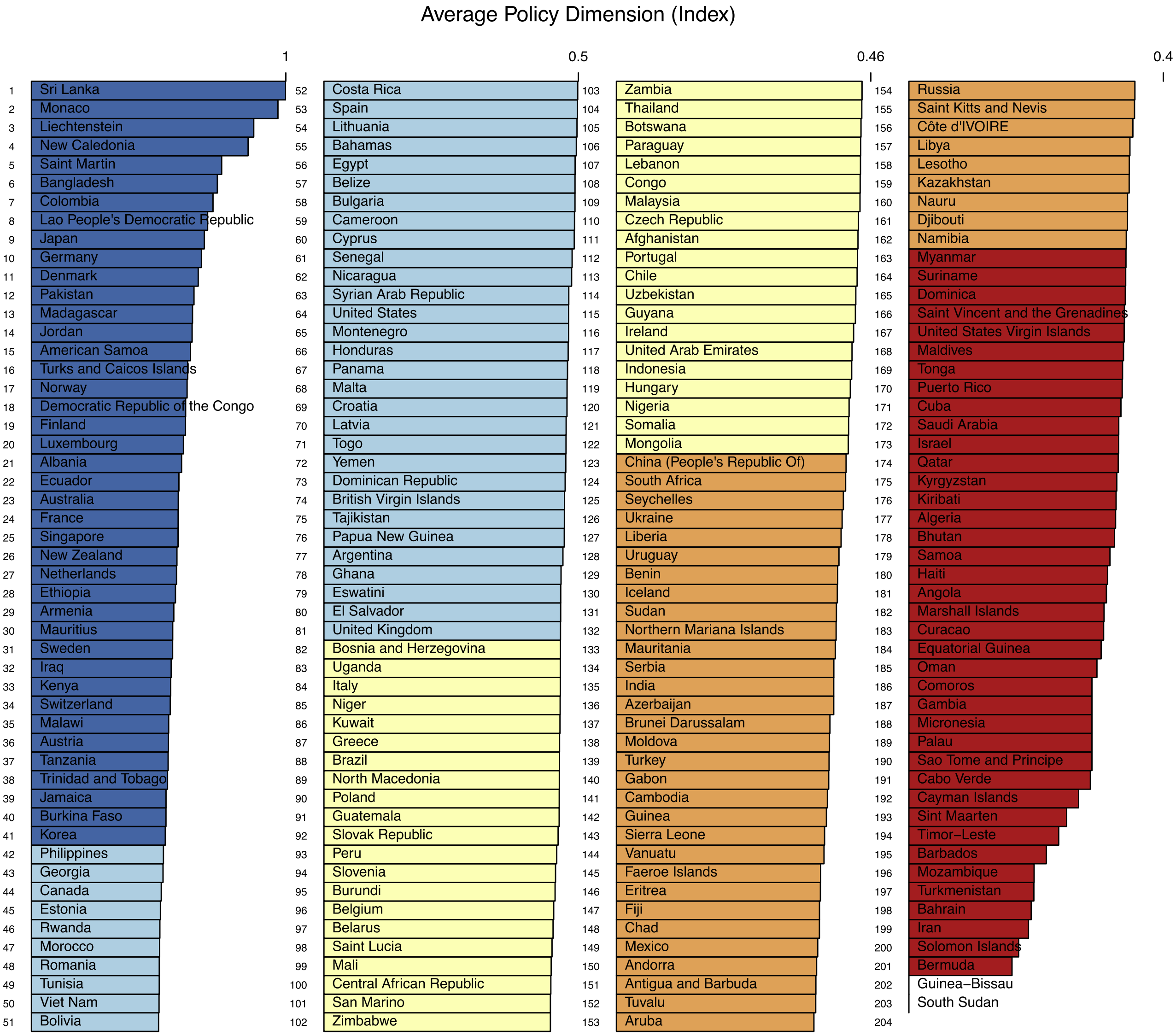

Fig. 4. Average policy dimension (index) of the constructed index across economies. Note: Countries with missing values are presented last in ranking without colored bar plots. Legend: Top-down/bottom-up ranking denotes high/low environmental taxes & transfers (energy-related taxes such as diesel and petrol tax, fossil fuel producer and consumer support, electricity support, residential electricity price, and environmental tax including carbon pricing), R&D (energy public RD&D budget,% GDP, renewable energy public RD&D budget, fossil fuel public RD&D budget, excluding Ccs, environmentally-related Government R&D budget, and expenditure), regulation & management (marine and terrestrial protected areas), patents (development of environment-related technologies and relative advantage in environment-related technology), and official development assistance (total allocable official development assistance to the environmental sector, renewable energy sector, water supply & sanitation sector, desertification, and climate change adaptation).

the mean of green growth across income groups is relatively high (0.53) in high-income economies but low (0.49) in low-income economies. The degree of green growth heterogeneity across economies was estimated using the sample average of indicators with further application of kernel smoothing to compute the corresponding density functions. Using the half-panel jackknife bias-corrected technique for both density functions and confidence intervals, the kernel density estimation for mean green growth indicators is presented in Fig. 7. The green growth indicators show significant (95 % CI) heterogeneous characteristics but varying distribution across economies (Supplementary Table 7). The mode of heterogeneity of Models 4, and 6 of the green growth indices is unimodal and negatively skewed (the majority of economies are clustered at the right with a long-left tail), however, Models 1, 5, and 7 show unimodal and positively skewed distribution (the green growth index of the majority of economies are clustered at the left with a long-right tail). In contrast, Models 2–3, and 8–9 illustrate a bell-shaped curve with nearly zero skewness that fulfills the normality assumption, hence, shows a symmetrical distribution. This illustration highlights that future research that utilizes our green growth indicators should control for unobserved heterogeneity across economies.

4.4. Dimensions vs green growth

We modeled the effect of individual dimensions on green growth (Model 2) by accounting for country-specific and unobserved heterogeneous effects across countries (Fig. 8). We captured the inertial effects of green growth by incorporating a lagged-dependent variable, which is an essential proxy for controlling omitted variable bias. We find that the level of green growth increases (i.e., by 0.12 % at $p < 0.001$) in countries with a sustained economic strategy that prioritizes resource efficiency, technological innovation, environmental policy stringency, and sustainability (Fig. 8a). Improving global CO_2 productivity spurs green growth (i.e., by 0.29 % at $p < 0.001$) by reducing both production-based and demand-based emission intensity while decoupling economic

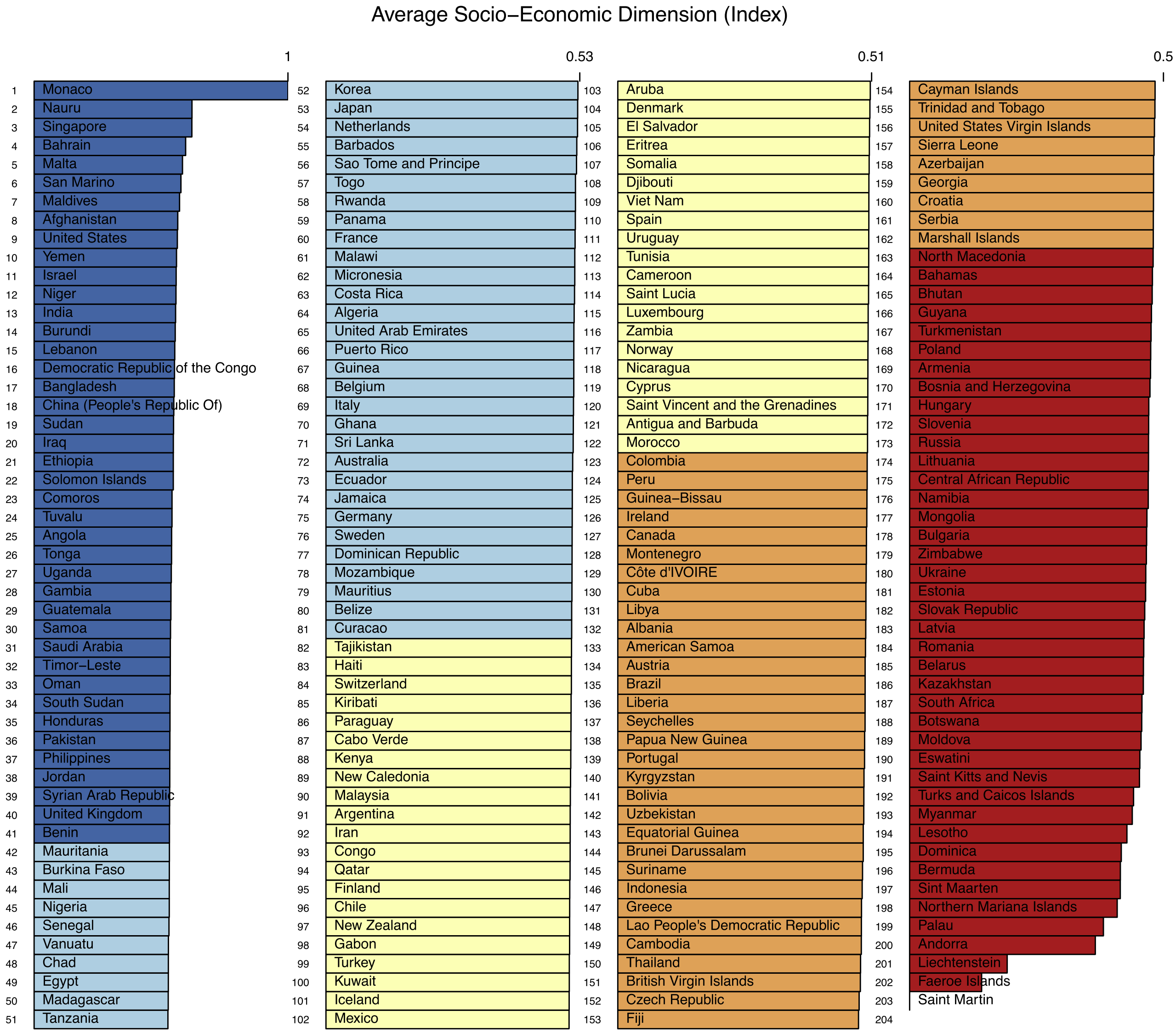

Fig. 5. Average socioeconomic dimension (index) of the constructed index across economies. Note: Countries with missing values are presented last in ranking without colored bar plots. Legend: Top-down/bottom-up ranking denotes high/low social (life expectancy at birth, total fertility rate, population density, population, and net migration) and economic management (purchasing power parity, value added in agriculture, real GDP per capita, value added in services, and industry, and labor tax revenue. Here, a high GDP deflator, and nominal exchange rate worsen sustained economic management).

development from natural resources, (non) energy material utilization, and waste generation (Fig. 8b). The adoption of strategies to achieve natural capital efficiency while adjusting pollution abatement targets for sustainable transition facilitates the positive effect of environmentally adjusted multifactor productivity by reducing the negative consequences of economic development on the environment. Environmental externalities could impede green growth if producers and/or consumers are incentivized to pollute more. Thus, negative production and consumption externalities at the expense of environmental quality of life and well-being thwart sustainable economic development efforts. We observe that achieving green growth requires improvements in quality of life attributable to the environmental conditions of economic productivity—such as increasing access to safe drinking water and sewage treatment while reducing exposure to environmental risks (Fig. 8c). A country's natural asset provides the raw materials required to achieve economic productivity. However, unsustainable use or depletion of the natural asset base could hamper sustainable development and green growth. We find conscious efforts toward global sustainable management of wildlife, water, land, and forest resources while reducing the annual surface temperature enhances biocapacity while reducing both ecological deficit and ecological footprint—thus, leading to a long-term positive impact (i.e., by ~0.23 % at $p < 0.001$) on green growth (Fig. 8d). If well-coordinated, policy responses will fundamentally create economic opportunities and a conducive environment for sustainable development and green growth (i.e., by ~0.22 % at $p < 0.001$). The effectiveness of environmental taxes & transfers (fiscal measures and market-based mechanisms including carbon pricing), R&D budgets, environmental regulation & management, and external financing (through international cooperation) such as official development assistance—determine the political will, institutional quality and capacity, and social readiness (i.e., level of public support) to achieve green growth (Fig. 8e). socioeconomic outcomes are crucial in the design and implementation of green growth policies. This implies that green growth could have both positive and negative effects on social inclusion, inequality, poverty, and employment. We observe that improving the socioeconomic dimension enhances green growth policies (i.e., by ~0.51 % at $p < 0.001$) by reducing the negative effects on vulnerable groups and marginalized communities. This enables green growth policies to be sustainable, equitable, and socially inclusive (Fig. 8f).

We further used simultaneous equations via the Romano-Wolf

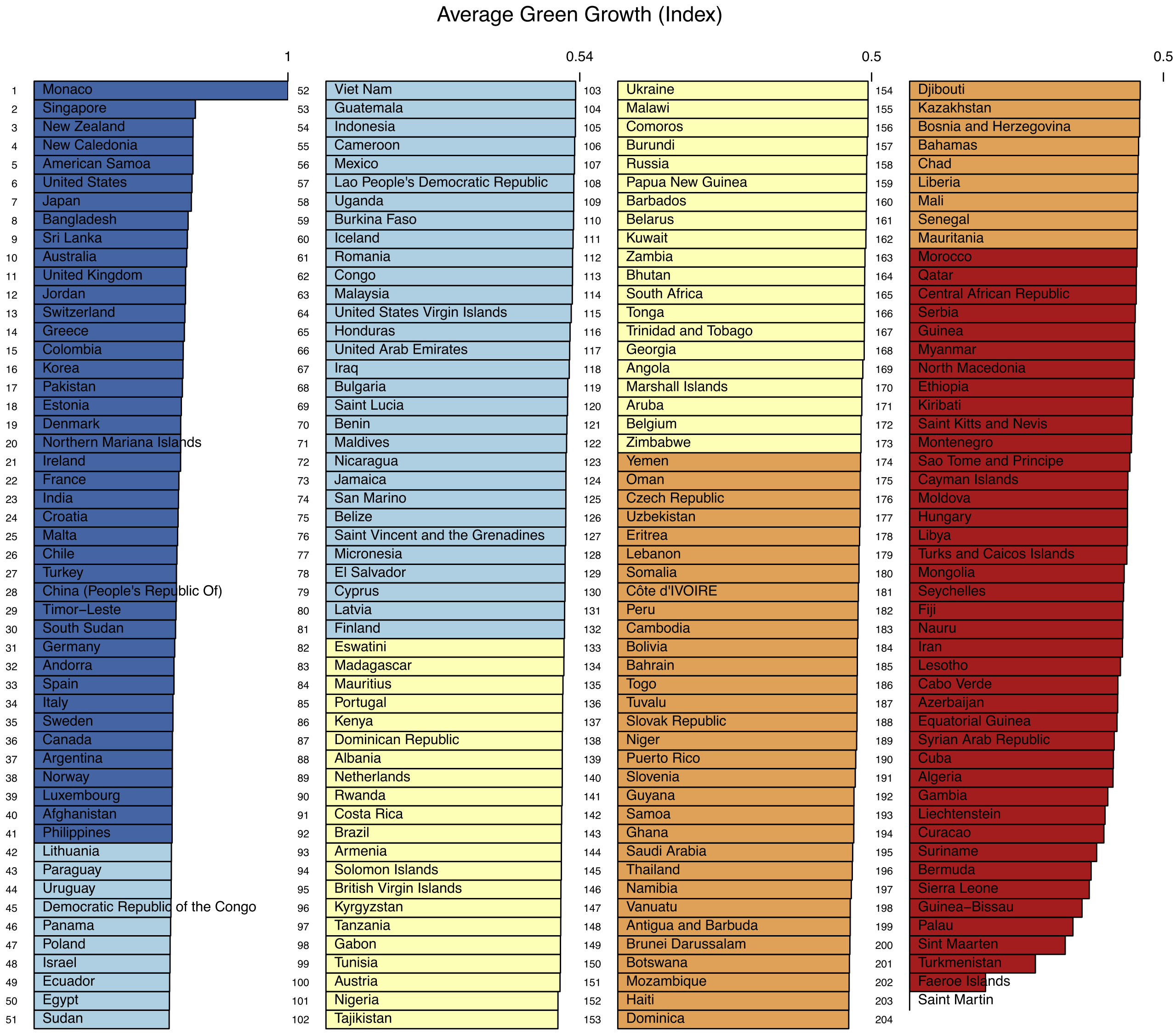

Fig. 6. Ranking green growth indicators (index) across economies. Note: Countries with missing values are presented last in ranking without colored bar plots. Legend: This indicator (Model 2) is derived from sustainable attributed dimensions of socioeconomics, policy response, natural asset base, environmental quality, and emission productivity. Top-down/bottom-up ranking denotes high/low performance in green growth accounted by socioeconomic opportunities (28.95 %), environmentally-attributed quality of life (19.74 %), sustainable natural resource base (18.87 %), stringent policy responses (16.25 %), and environmental productivity (16.18 %).

algorithm to validate the estimated model and further examine the nexus between green growth and individual dimensions at the same time period but across diverse economies. In this way, our model prioritizes dimensions for developing policies in achieving green growth amidst scarce resources. The estimated Romano-Wolf coefficients show similar signs but different magnitudes compared to estimates from Fig. 8 (Supplementary Table 8). To validate the estimated fixed-effects and heterogeneous model (we further used a machine learning technique to corroborate the estimated model, see Supplementary Table 9), the Romano-Wolf step-down adjusted p-values based on 100 resamples of uncorrected (model) p-values and Romano-Wolf adjusted p-values result in 1 model rejecting the null hypothesis at 95 % level (Supplementary Figure 19). The predictive power (overall R^2) of nearly 99 % confirms the positive effect of dimensions on green growth. The empirical model prioritizes the dimensions in the order of socio-economics $>$ quality of life $>$ natural asset $>$ policy responses $>$ productivity $>$ historical effects of green growth. In contrast, we estimated the effect of global green growth on individual dimensions using simultaneous hypotheses testing (Fig. 9). We observe that green growth policies that internalize the negative effects of sustainable development improve a country's socio-economic dynamics, environmental quality of life, natural asset base, policy responses, and emission productivity. Green growth policies have a significant positive influence on dimensions in the order natural asset $>$ socio-economics $>$ policy responses $>$ productivity $>$ quality of life $>$ historical effects of green growth (Supplementary Table 10).

4.5. Assessment of β-convergence

The estimated baseline model presented in Fig. 10a shows a statistically significant ($P\text{-}value < 0.01$) negative monotonic relationship (i.e., coef = 0.883) between growth rate and green growth. This directional relationship is further validated by multiple empirical methods in Fig. 10b, confirming the existence of β-convergence in green growth across economies. To further validate the β-convergence, we used the panel club convergence approach which entails the estimation of a log t-test across countries and initial country-specific club classification through the club clustering technique (Du, 2017). Thus, a convergence club with members is obtained if the estimated log t-test is greater than

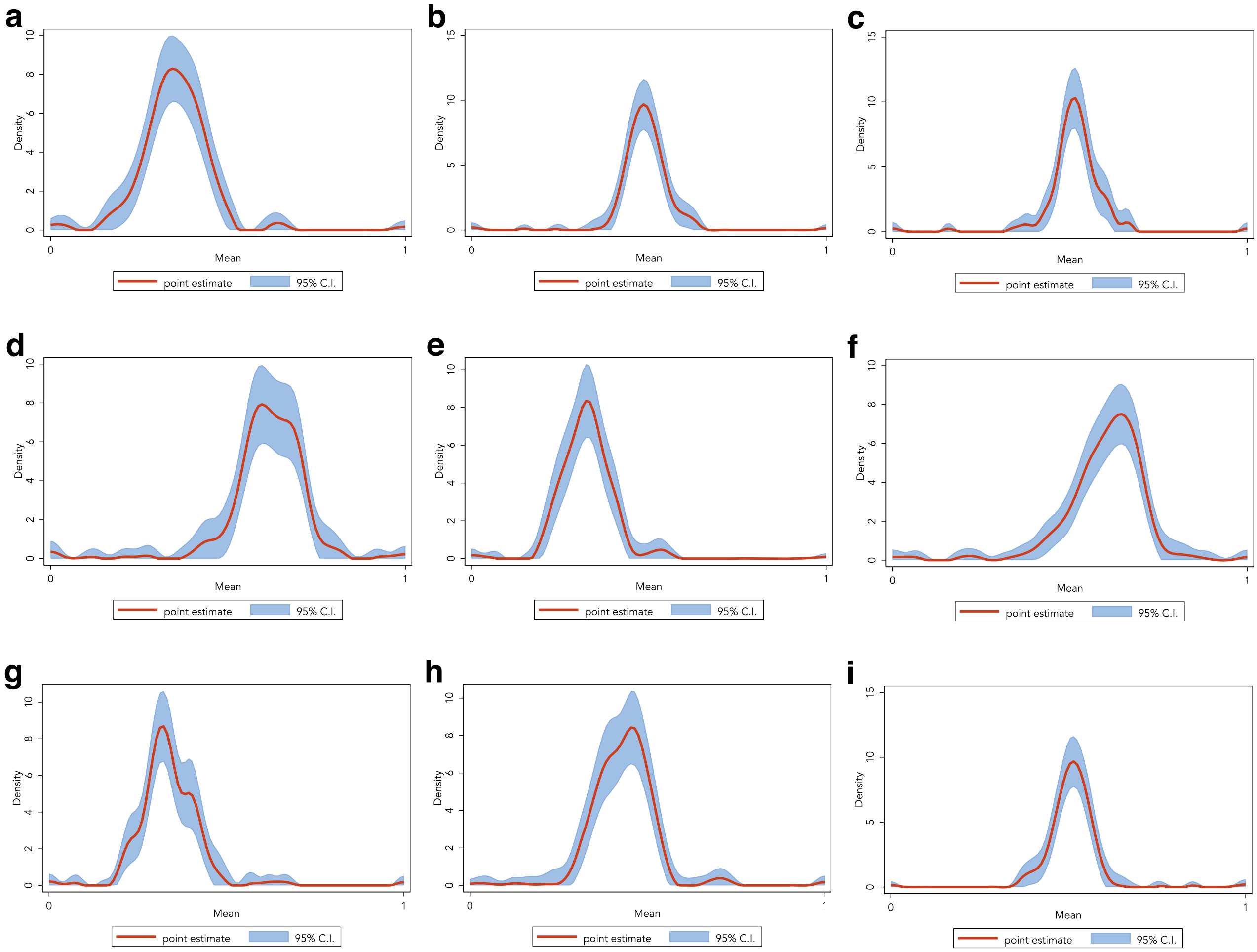

Fig. 7. Degree of panel heterogeneity using kernel density estimation for mean green growth (a) Model 1 (b) Model 2 (c) Model 3 (d) Model 4 (e) Model 5 (f) Model 6 (g) Model 7 (h) Model 8 (i) Model 9. Note: The panel density of moments was estimated using a Gaussian kernel with an equally-spaced grid of size 100 bandwidth, and a split (half)-panel jackknife bias-corrected method. Model 10 was disregarded due to missing values with the function returning as an error. Pesaran's CD-test: 422.13, *p-value*$<$0.05; and Pesaran's CADF-test: $-$11.39, *p-value*$<$0.05.

$-$1.65. The estimated panel club convergence presented in Supplementary Table 11 captures the initial country-specific club classification (Model 1), tests of adjacent club merging (Model 2), and final club classification (Model 3). The estimated log *t*-tests (see Supplementary Table 11) in Models 1–3 are greater than $-$1.65 [excluding Group 7 (Model 1), Club 6 + Group 7 (Model 2), and Group 5 (Model 3)], validating the existence of panel convergence, thus, corroborating the β-convergence.

Next, we scrutinized the initial country-specific club classifications for potential club merging. The tests of adjacent club merging involve the estimation of log *t*-test for all countries belonging to the initially designated clubs. The adjacent clubs are merged into one club if the paired clubs jointly fulfill the convergence hypothesis. The final club classification presented in Fig. 11 and Supplementary Table 12 shows 89.16 % (181) of countries (See Supplementary Table 12 for detailed country-specific classifications) in Club 1, 2.96 % (6) of countries (Belarus, Brunei Darussalam, Equatorial Guinea, North Macedonia, Saudi Arabia, and Serbia) in Club 2, 3.45 % (7) of countries (Azerbaijan, Cuba, Fiji, Gambia, Moldova, Qatar, and Somalia) in Club 3, 2.96 % (6) of countries (Curacao, Guinea-Bissau, Sierra Leone, Suriname, Syrian Arab Republic, and Turkmenistan) in Club 4 and 1.48 % (3) of countries in Group 5—which represents the cluster of economies (namely Bosnia & Herzegovina, Nauru, and Seychelles) that reject the null hypothesis of convergence, hence, exhibiting divergence in green growth. The panel convergence in Fig. 11 pictorially validates β-convergence irrespective of income classifications. This infers a catch-up effect in green growth—where economies in low-, lower-middle-, upper-middle- and higher-income groups with initially lower levels of green growth tend to increase at higher rates than countries with initially higher levels.

5. Discussion and conclusion

To contribute to the global debate on shifting from the traditional brown economy to a green economy, we used our constructed green growth measures whose pillars are anchored on 5 dimensions—namely natural resource base, socioeconomic outcomes, environmental productivity, environmental-related policy responses, and quality of life—to test the concept of β-convergence. Contrary to the aggregated methods used in constructing indices, our data descriptor employed a novel summary index technique with a GLS attributed-standardized-weighted index that controls for highly correlated variables and missing values (Sarkodie et al., 2023b). We further used the constructed global measures of green growth to rank (winners and losers) countries with environmentally sustainable economic development. We observed that green growth policies that internalize the negative effects of sustainable development improve a country's socioeconomic dynamics, environmental quality of life, natural asset base, policy responses, and emission productivity. Natural resources are essential to green growth or sustainable development initiatives under the SDGs, the Climate Accord, and the Aichi Biodiversity Targets (Acosta et al., 2019). This is because

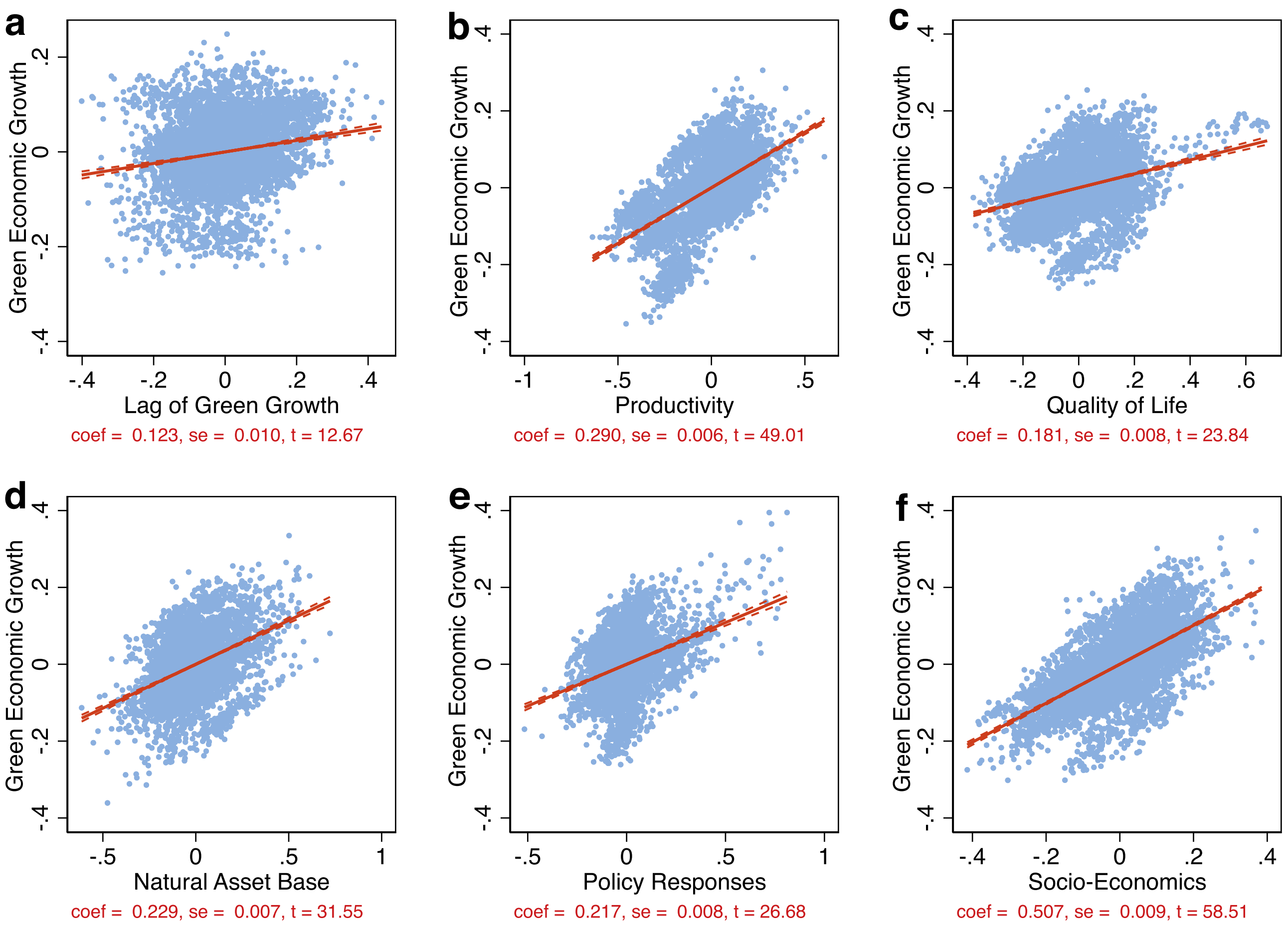

Fig. 8. Global effect of individual dimensions on green growth (a) lag of green growth (b) emissions productivity (c) quality of life (d) natural asset base (e) policy responses (f) socio-economics. Note: the estimated model is validated by both machine learning and heterogeneous panel regression models (Supplementary Tables 8–9). The standard errors and confidence intervals are estimated with 1000 non-parametric bootstrap replications.

natural resources constitute the very foundation of socioeconomic development (Acosta et al., 2019) and at least 80 % of countries generate a substantial amount of income from natural resources and their related services (Taden, 2021). Accordingly, most studies adopt to some extent (even if different), perspectives of the natural resource base that directly and/or indirectly constitute a country's natural capital. The indicators may reflect efforts ranging from the protection of natural capital or assets to their optimal utilization.

The environmental productivity dimension of green growth entails the efficient ways by which economic growth is decoupled from resource use. Acosta et al. (2019) defined a productivity dimension focusing on the efficient and sustainable use of resources. They argue that green growth mimics the definition of sustainability, which highlights meeting the current global demand without endangering the resource security of future generations. Environmental externalities could hamper green growth if producers and/or consumers are incentivized to pollute more. Thus, negative externalities of production and consumption at the expense of environmental quality of life and well-being thwart sustainable economic development efforts. The environmental quality-of-life dimension of green growth tracks individuals' social well-being as resources are extracted for economic growth. This well-being borders on their exposure to environmental risks, access to drinking water, and other health-related measures. socioeconomic dynamics are essential in designing and implementing green growth policies. However, green growth could have both positive and negative effects on social inclusion, inequality, poverty, and employment. This highlights the potential trade-offs in efforts toward achieving green growth amidst the positive effects on the environment. Our empirical assessment shows that improving socioeconomic outcomes enhances green growth policies significantly by reducing the negative effects on vulnerable groups and marginalized communities. The initial high costs of investing and transitions toward green growth may hinder developing countries, specifically poor countries from taking action. Thus, the emergence and expansion of new economic opportunities are crucial to the success of green growth strategies. New economic opportunities reinforce the motivations for sustainability by incentivizing policymakers to accelerate investments and innovations that support green policies (Bowen and Fankhauser, 2011). Studies argue that the generation of fair opportunities and respect for the rights of different groups are fundamental to the success of a sustainable development agenda (Li et al., 2021). These rights, they explain, must extend to education, employment, and healthcare programs.

In contrast to this study, a key observation in the extant literature is the glaring omission of a policy response dimension in the assessment of green growth in a large number of studies (Tables 1–2 in Sarkodie et al. (2023b)). Imperatively, we might expect that the government's efforts at going green may be reflected in policies that spell out management procedures, regulatory mechanisms, the stringency of environmental taxes, the level of FDIs in green sectors, and the investments in environmental technology R&D. In practice, it should be noted that every aspect of green growth is controlled by strategic policy initiatives and a political will to shift scarce resources from traditional mechanisms of production to environmentally friendly systems (OECD, 2014). The amount of resource exploration that a country undertakes is subject to a political decision-making calculus that constantly makes trade-offs between expected political payoffs and economic costs as well as between

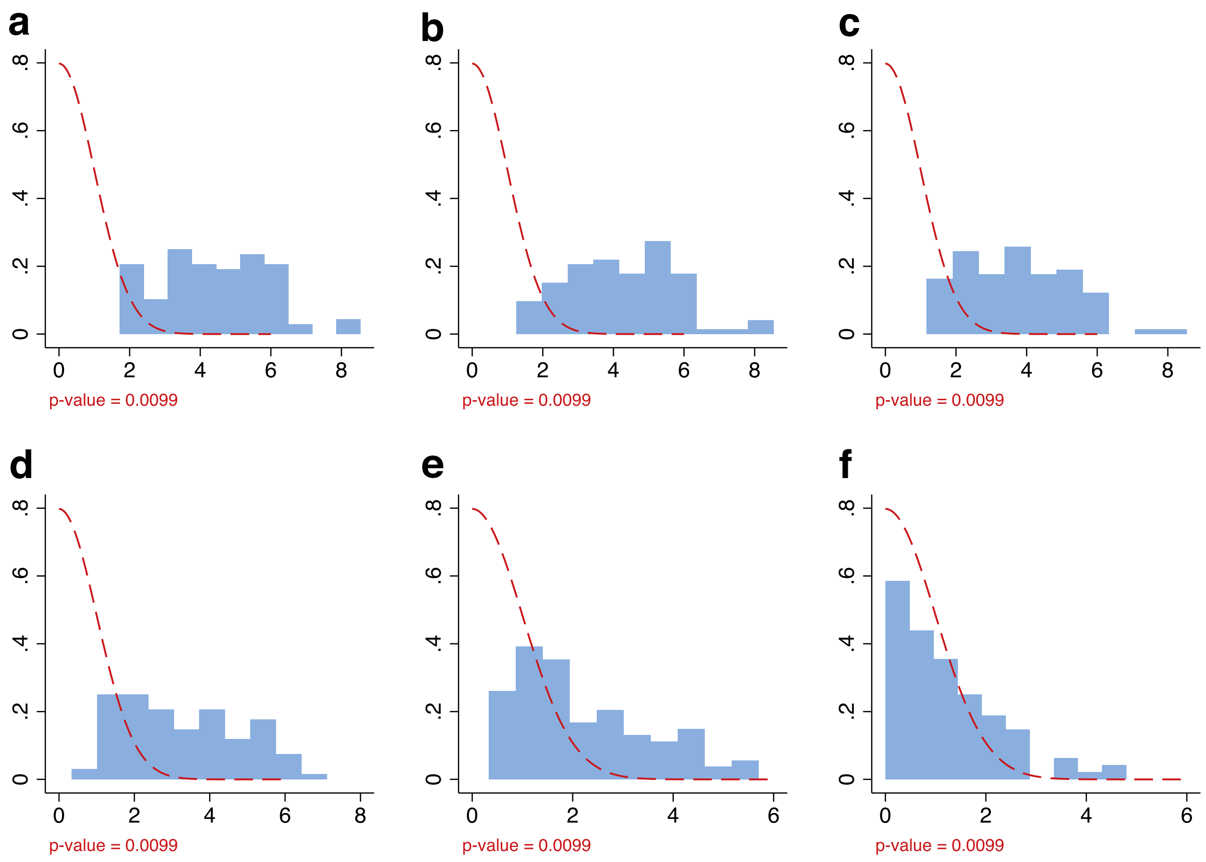

Fig. 9. Simultaneous hypotheses testing of global green growth on individual dimensions (a) emissions productivity (b) quality of life (c) natural asset base (d) policy responses (e) socio-economics (f) lag of green growth. Note: Romano-Wolf step-down adjusted *P-values* based on 100 resamples. The results of Uncorrected (model) *P-values* and Romano-Wolf adjusted *P-values* for the 6 models reject the null hypotheses at 95 % significance level.

expected economic benefits and political costs (Taden, 2021). Hence, political and social resistance could impede the sustainable transition to green growth regardless of the synergies—if stakeholders may lose from this process. Wang et al. (2019) argue strongly that systematically designing policies and institutional quality play a crucial role in achieving green growth in both developed and developing countries. Consequently, any measure of green growth that ignores the set of policy responses instituted by governments might omit half of the picture. The policy responses to achieve environmental productivity (typically reducing anthropogenic emissions) include the implementation of market-based mechanisms including carbon pricing, improvements in energy efficiency, and the displacement of fossils via clean energy technologies (such as renewables). Similarly, natural capital efficiency could be achieved by improving resource efficiency, increasing renewable resource utilization, adopting conservation and management options for protecting and conserving biodiversity, and investing in green technologies and innovations.

The validation of β-convergence of green growth implies that economies with initially lower levels of environmentally friendly practices, eco-technological efficiency, sustained economic development, and social inclusion are improving at a faster rate, converging toward higher levels of green growth over time. Specifically, the panel club convergence has policy implications for addressing environmental challenges and promoting sustainable development—by further demonstrating that at least 98.5 % (i.e., 200/203 economies) of countries across 4 club memberships are converging over time. The results highlight the prioritization of targeted investments including eco-technologies, renewable energy projects, and research & development (R&D), among others—in regions with lower levels of green growth to accelerate their progress while facilitating convergence. Besides, regional collaboration (international cooperation and partnerships) among economies could facilitate green technology transfer, and exchange of experience and knowledge (of best practices in green growth) from advanced countries to less developed regions, thus, promoting faster convergence. Finally, aligning environmental policies and regulations (such as environmental standards, financial incentives and subsidies, and sustainable practices) with policy initiatives across economies to ensure a level playing field encourages the adoption and diffusion of best (green) practices in sustainable development. This makes it attractive for businesses and industries to invest in green industries, and sustainable projects and technologies without relocating to countries with lower environmental standards, hence, leading to the creation of new green jobs and sustained economic development while reducing the global environmental impacts.

Due to limited studies in understanding and evolution of the concept of green growth, future studies could investigate this theory from an interdisciplinary perspective with more focus on low-carbon transitions, green finance, green (eco) technology, green infrastructure, sustainable natural asset management, and sustained economic development.

Data availability

The green growth datasets analyzed in this study are available in the Figshare repository, https://doi.org/10.6084/m9.figshare.22291069.v2.

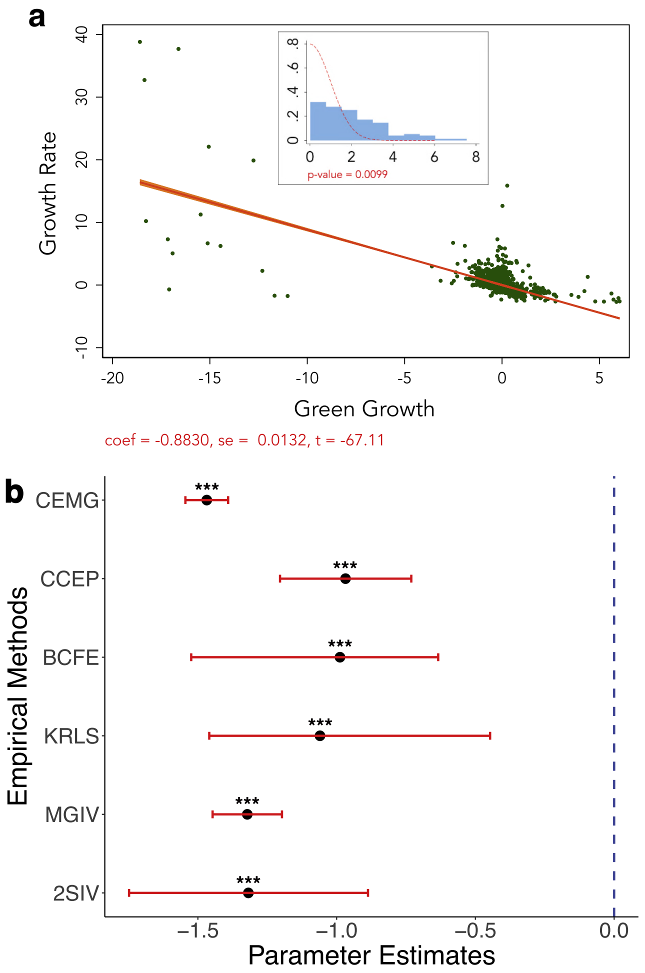

Fig. 10. Assessing β-convergence using multiple empirical techniques (a) Baseline model using panel fixed-effects (b) Complex models using several panel data methods. Legend: CEMG = Common Correlated Effects Estimator - Mean Group, CCEP = Common Correlated Effects Estimator - Pooled, BCFE = Bootstrap Corrected Dynamic FE Regression, KRLS = Kernel Regularized Least Squares, MGIV = Mean Group Defactored Instrumental Variable approach with Common Factors, 2SIV = Two-Stage Instrumental Variable approach with Common Factors. The black dot (●) represents the estimated coefficient whereas the red error bar (|——|) is the 95 % confidence interval. *** denotes statistical significance at *P-value* < *0.001*. Estimation Notes: (a) The baseline model was validated using Romano-Wolf hypothesis testing; (b) for CEMG — $n = 6018$, $P<0.001$ and $R^2=77$ %; for CCEP — $n = 6018$, $P<0.001$ and $R^2=58$ %; for BCFE —Bootstrapped standard errors, bootstrap 95 % (percentile-based) confidence intervals, Inference performed with non-parametric bootstrap. Resampling: Monte Carlo heterogeneous, Initialization: Analytical heterogeneous, Convergence: Yes, and $n = 5993$; for KRLS — $n = 6236$, tolerance=7.795, λ=10.65, σ=, 1, and R^2=29 %; for MGIV — $n = 6018$, Hansen test ($\chi 2 = 2.281$, $P>\chi 2 = 0.131$); and for 2SIV — $n = 6018$.

Code availability

No custom code was used to generate or process the data described in the manuscript, however, the steps used are detailed in the Methods section.

CRediT authorship contribution statement

Samuel Asumadu Sarkodie: Conceptualization, Formal analysis, Methodology, Software, Validation, Visualization, Writing – review & editing, Supervision. **Phebe Asantewaa Owusu:** Writing – original draft, Writing – review & editing. **John Taden:** Writing – original draft.

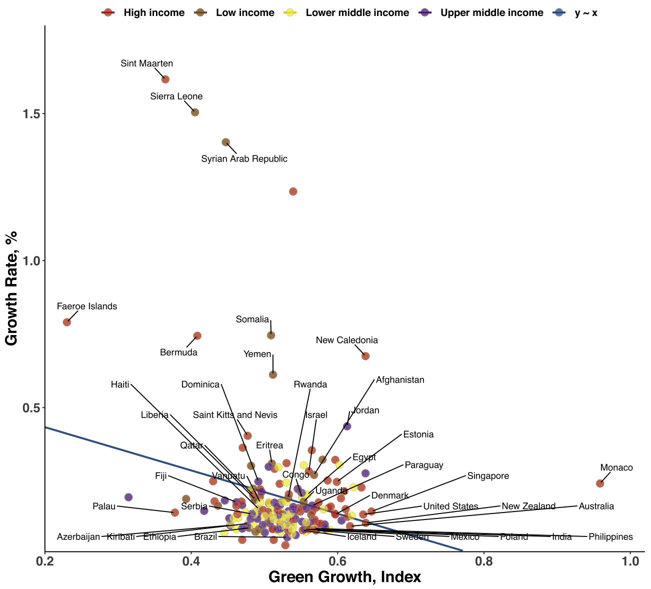

Fig. 11. Panel convergence showing club classifications. Legend: Club 1 = 181 economies [See Supplementary Table 12 for detailed country-specific classifications.], Club 2 = 6 economies [Belarus | Brunei Darussalam | Equatorial Guinea | North Macedonia | Saudi Arabia | Serbia], Club 3 = 7 economies [Azerbaijan | Cuba | Fiji | Gambia | Moldova | Qatar | Somalia], Club 4 = 6 economies [Curacao | Guinea-Bissau | Sierra Leone | Suriname | Syrian Arab Republic | Turkmenistan], Club 5 (Not convergent group) = 3 economies [Bosnia and Herzegovina | Nauru | Seychelles].

Declaration of interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.enpol.2020.112049.

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