Natural Capital and Economic Growth*

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Abstract

This paper examines the complex relationship between natural capital and long-term economic growth. Specifically, we review resource-based growth theories and various modeling approaches. In most frameworks, natural capital is considered an additional production factor that supplements traditional inputs. However, we highlight a common conceptual confusion between economic wealth (a stock) and economic growth (a flow). This distinction is often overlooked in discussions about the role of natural assets in development. Using World Bank data from 1995 to 2020, we empirically estimate a Cobb-Douglas production function that incorporates produced (physical) capital, labor (human capital), renewable resources, and non-renewable resources. We then classify countries according to their resource endowment and assess the elasticity of natural capital with respect to GDP. To address uncertainty and downside risk, we propose a stress-testing framework that integrates historical worst-case analysis, parametric methods, and extreme value theory. Our results reveal significant heterogeneity in the impact of natural capital on growth. Over the past 25 years, non-renewable resources appear to have had little influence on economic growth. Conversely, growth has been more responsive to renewable resources. Notably, countries such as Iran, Australia, South Korea, and Nicaragua experienced a negative contribution of natural capital to growth, while Vietnam, Indonesia, Mozambique, and Egypt experienced a positive contribution. The stress-testing analysis further underscores wide cross-country variation. Over a 25-year horizon, the countries that are potentially most affected by adverse natural capital scenarios include Ethiopia, Chile, New Zealand, Brazil, Iran, and Poland. An additional insight comes from decomposing the stress test results into the sum of the worst-performing years. This reveals that, in some countries, stress outcomes are driven by one or two severe events. In contrast, in other countries, a prolonged decline in natural capital leads to multiple moderately bad years without any single catastrophic event.

Keywords: Natural capital, production, economic growth, natural resources, wealth, stress testing, worst-case scenario, historical method, parametric method, extreme value theory, skew normal and t distributions, order statistics.

JEL Classification: E01, C52, O11.

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1 Introduction

Concerns about finite resources and their implications for long-term economic growth date back to Malthus (1798). He was one of the first to argue that the limited availability of arable land would constrain economic and population growth. He warned that population growth is geometric while food supply growth is arithmetic, which would inevitably lead to shortages and widespread poverty. More than a century later, Hotelling (1931) formalized the economics of non-renewable resource use in a classic model. According to the Hotelling rule, the price of a finite resource should increase over time at the interest rate. This increase reflects the resource's scarcity and the opportunity cost of extracting it now versus later. Hotelling's framework highlights the inter-temporal allocation problem posed by finite resources and the need for efficient management to ensure long-term economic viability. His work paved the way for understanding how market forces might or might not guide the sustainable use of depleting resources.

Building on this line of reasoning, modern ecological economists have challenged the assumption that economic growth can continue indefinitely. For example, Daly (1974) questions the idea that economic growth can continue indefinitely in a world with finite resources. Therefore, he proposes the concept of a steady-state economy, and distinguishes between growth, which is a quantitative increase, and development, which is a qualitative improvement. Daly argues that economic development should replace economic growth. In related research, Daly (1997) supports Georgescu-Roegen's thermodynamic perspective that economic processes are constrained by the entropy law (second law of thermodynamics). He challenges the more optimistic view of Solow (1974b) and Stiglitz (1974), who suggested that capital accumulation, technological progress and innovation, and input substitutability can offset resource scarcity:

> "*[...] If it is very easy to substitute other factors for natural resources, then there is in principle 'no problem'. The world can, in effect, get along without natural resources, so exhaustion is just an event, not a catastrophe.*" (Solow, 1974a, page 11).

> "*[...] The fact that there is a limited amount of natural resources and natural resources are necessary for production does not necessarily imply that the economy must eventually stagnate and then decline. Two offsetting forces have been identified: technical change and capital accumulation. Even with no technical change, capital accumulation can offset the effects of the declining inputs of natural resources, so long as capital is 'more important' than natural resources,* i.e. *the share of capital is greater than that of natural resources. With technical change, at any positive rate, we can easily find paths along which aggregate output does not decline.*" Stiglitz (1974, pages 130-131).

Indeed, Solow (1974b) and Stiglitz (1974) argue that natural resource scarcity does not necessarily pose a limit to long-term economic growth, as long as capital, technology and labor can serve as substitutes for depleting resources. This is a cornerstone of what is later called *weak sustainability*, which contrasts with the notion of *strong sustainability*. While natural capital are largely substitutable in weak sustainability, strong sustainability argues that natural capital provides essential and non-substitutable functions — such as climate regulation, biodiversity, water purification, and ecosystem services — that cannot be replaced by other forms of capital. Therefore, natural capital must be preserved intact to ensure ecological stability, economic growth and long-term human well-being[1].

[1] Aristotle's distinction between *oikonomia*, or natural resource management, and *chrematistics*, or the pursuit of unlimited wealth, anticipated modern debates about sustainability.

For several reasons, measuring the impact of natural capital on economic output is far from straightforward. First, natural capital is not inherently comparable to physical or human capital as a production factor. While physical and human capital can theoretically grow indefinitely, natural capital is limited by its very nature. Its growth is inherently capped, which makes it qualitatively different from the other production inputs. Second, the timeframe over which the effects of changes in production factors become visible varies significantly. The impact of changes in human capital, such as improvements in workforce skills, can be immediate. For physical capital, however, the effect takes longer due to the lag between investment and increased output. The relationship is more complex in the case of natural capital. In some sectors, such as agriculture, fisheries, and oil extraction, the effect can be immediate because sudden resource depletion directly reduces gross income. For other types of natural capital, such as forests or mineral reserves, however, the effects may take years or even decades to materialize. This long-term horizon makes it difficult to capture the full economic consequences of resource depletion or mismanagement. Consequently, there is often a trade-off between short-term economic gains and long-term sustainability. Third, the economic roles of physical and human capital are well understood in terms of economic wealth (a stock measure) and economic growth (a flow measure). However, this is not yet the case for natural capital. A country may possess significant natural capital, making it wealthy in terms of resources, but this does not necessarily translate into high economic growth. Conversely, a resource-rich country may be economically poor yet experience rapid growth. Alternatively, it may enjoy both high wealth and strong growth. These varying outcomes illustrate that the relationship between natural capital endowment and management and economic wealth and growth is neither linear nor well-established. This ambiguity may explain why many empirical studies find only a limited impact of natural capital on economic development. Often, this is due to a conceptual confusion between wealth and growth, two fundamentally different dimensions of economic performance. These challenges ultimately reflect a deeper theoretical question: Does natural capital fundamentally constrain economic possibilities, or does it enable sustainable prosperity?

This paper is organized as follows. Section Two provides background on the relationship between natural capital and economic growth. First, we define natural capital, distinguishing between finite and renewable resources, as well as ecosystem services and pressures on biodiversity. Next, we present the main modeling approaches. The first is the production function method, which incorporates natural capital as an additional factor in a Cobb-Douglas or CES production function. The second approach considers the influence of natural capital on total factor productivity, often captured in the Solow residual. A third modeling strategy incorporates damage functions into the output function to illustrate the effects of biodiversity pressures. Air pollution is a common example of this approach. Section Three presents the empirical analysis. First, we review the existing literature, particularly studies conducted by the OECD. This includes a review of studies that estimate the contributions of factors to GDP growth and the output elasticity of natural capital. We also discuss negative externalities and the ongoing debate surrounding the resource curse, which examines the complex relationship between natural capital, economic wealth, and long-term economic growth. The second part of Section Three is dedicated to our empirical study. Using World Bank data, we estimate a Cobb-Douglas production function with four inputs: produced (physical) capital, labor (human capital), non-renewable (finite) resources, and renewable resources. Next, we categorize countries into different groups and evaluate the impact of natural capital on their economic growth. The final part of Section Three introduces a stress-testing exercise. We explore three approaches: the historical worst-case method, a parametric method using skew distributions, and extreme value theory, including the use of order statistics. Section Four concludes with our final remarks.

2 Background

2.1 Natural capital

Natural capital refers to the world's stock of natural assets, including air, water, soil, geology, and living organisms, which provide essential goods and services to humans and ecosystems. David Pearce notably formalized the term in 1988, defining it as the stock of all environmental assets. According to Pearce (1988), "*sustainable development is categorized by economic change subject to constancy of the natural capital stock*". The idea gained broader attention in 1997 through the work of Robert Costanza, who estimated the annual global value of ecosystem services at $33 trillion (in 1995 dollars), a figure that exceeded the world GDP at the time, highlighting the immense, often overlooked economic significance of nature. Since the publication of Costanza *et al.* (1997), economists have refined the boundaries of natural capital, emphasizing distinctions between stocks and flows, and clarifying the roles of natural resources, ecosystem services, and environmental pressures within this framework. In line with this evolving literature, we adopt the following definition:

> "*Natural capital encompasses the stock of natural resources and the goods and services they provide. This includes both renewable and non-renewable resources, as well as ecosystem functions and the ecological integrity necessary for human well-being and economic productivity.*"

2.1.1 Finite vs. renewable resources

Natural capital is divided into two categories: finite and renewable. Finite resources, such as fossil fuels and minerals, are exhaustible and do not regenerate within a human lifetime. In contrast, renewable resources, such as forests and fisheries, can be replenished through sustainable management. Understanding this distinction is crucial for grasping economic limits because overusing finite resources can lead to irreversible depletion, while mismanaging renewable resources can cause them to collapse.

2.1.2 Ecosystem services

Natural capital encompasses not only tangible resources but also the ecosystem services generated by ecological processes. These services are commonly classified into four categories: aesthetic and cultural, provisioning, regulating, and supporting (Roncalli, 2025b). These services are essential for human well-being and the productivity of economic systems. Importantly, these services represent flows derived from underlying stocks of natural capital. When ecosystems degrade due to land-use changes, pollution, or overexploitation, their capacity to sustain these flows diminishes. This erosion can lead to significant long-term economic and social costs, highlighting the importance of preserving ecological integrity.

2.1.3 Biodiversity pressures

An increasing number of threats to ecosystems undermines their resilience and function, endangering biodiversity. Pollution degrades air, water, and soil quality, harming plants and animals. Overexploitation, such as overfishing and unsustainable hunting, reduces population sizes and disrupts the balance of ecosystems. Introduced invasive species outcompete native organisms, altering ecosystems and reducing biodiversity. These pressures weaken ecosystems' ability to regenerate and adapt, thereby destabilizing vital services. The resulting biodiversity loss threatens natural capital and economic growth. For example, the high costs of air pollution are evident (Roncalli, 2025b).

2.2 Modeling approach

Several approaches exist for incorporating natural capital into economic growth models. These approaches can be classified into three categories:

1. Extended production functions
   This approach modifies traditional production functions by explicitly including natural capital as an additional input alongside physical capital and labor.

2. Productivity-linked models
   In these models, natural capital indirectly influences economic output by affecting total factor productivity (TFP). The degradation or improvement of natural capital is assumed to enhance or hinder the efficiency of other inputs.

3. Damage function frameworks
   This approach focuses on the economic consequences of environmental degradation, such as biodiversity loss and pollution. It models natural capital depletion as causing damage to output via explicitly defined economic damage functions.

The following paragraphs provide a detailed discussion of each of these three approaches.

2.2.1 Production function

We follow Döhring *et al.* (2023), who provides an excellent overview of the role of natural capital in economic modeling.

Cobb-Douglas function The Cobb-Douglas function is a mathematical formula widely used in economics to represent how output is generated from input factors such as physical capital and labor. It captures the relationship between total production and the quantities of inputs used. In its standard form, the function is written as:

$$Y = AK^{\alpha}L^{\beta}$$

where Y is the total production, A is the factor productivity, K is the input of physical capital, and L is the input of labor. The coefficients α and β are the elasticities of capital and labor, respectively[2]. The previous function can be extended to several inputs. A first approach is to include the natural capital N. We have[3]:

$$Y = AK^{\alpha}L^{\beta}N^{\gamma}$$

If $\alpha + \beta + \gamma = 1$, the production function has constant returns to scale and can be written in per capita terms[4]:

$$y = Ak^{\alpha}n^{1-\alpha-\beta}$$

where $y = Y/L$, $k = K/L$ and $n = N/L$. Some authors define natural capital with greater granularity by distinguishing between different types of natural resources. For example, they

[2] To achieve constant returns to scale, it is generally assumed that $\alpha + \beta = 1$. Moreover, in a perfectly competitive market, α and β represent the proportion of income paid to physical capital (capital owners) and human capital/labor (workers), respectively. This is because each input is paid according to its marginal product in equilibrium.

[3] This formulation is used by Solow (1974a) and Stiglitz (1974), where $A = e^{\lambda t}$ and λ is the constant rate of technological progress.

[4] We have:

$$y = \frac{Y}{L} = A\frac{K^{\alpha}L^{\beta}N^{\gamma}}{L} = A\frac{K^{\alpha}L^{\beta}N^{\gamma}}{L^{\alpha+\beta+\gamma}} = Ak^{\alpha}n^{\gamma} = Ak^{\alpha}n^{1-\alpha-\beta}$$

may separate finite (non-renewable) resources N from renewable resources R, leading to an extended Cobb-Douglas production function of the form:

$$Y = AK^{\alpha}L^{\beta}N^{\gamma}R^{\delta}$$

More generally, natural capital can be modeled as a composite of several different resources. In this case, non-renewable resources are expressed as a sum $N = \sum_{j=1}^{m} N_j$, and the production function becomes $Y = AK^{\alpha}L^{\beta}\prod_{j=1}^{m} N_j^{\gamma_j}$, where m is the number of individual natural resource types.

Solow and Stiglitz used this extended Cobb-Douglas model to establish several important results. First, Solow (1974b) demonstrated that maintaining a constant level of consumption in the absence of technical progress requires the elasticity of output with respect to physical capital to be greater than that of natural capital:

$$g_C = \frac{\mathrm{d}\ln C(t)}{\mathrm{d}t} = 0 \Leftrightarrow \alpha > \gamma$$

This implies that, at equilibrium, the income paid to physical capital must exceed the income paid to natural capital. On his side, Stiglitz (1974) showed that any path along which consumption grows at a constant rate must asymptotically exhibit a constant savings rate, a constant decline rate of natural capital — $g_N = \dfrac{\mathrm{d}\ln N(t)}{\mathrm{d}t} < 0$ — and a constant flow-stock ratio $\dfrac{N}{S}$, where S denotes the stock of natural capital. Stiglitz also proved that if the population growth rate is positive, then maintaining constant per capita consumption implies the following condition:

$$\lambda > \gamma g_L$$

where $g_L = \dfrac{\mathrm{d}\ln L(t)}{\mathrm{d}t}$ is the demographic (labor) growth rate. This equation highlight the importance of technical progress in the relationship between natural capital and economic growth. These results have inspired numerous extensions and reformulations. Among them, the most well-known is certainly the Hartwick Rule, which states that if all resource rents (*i.e.*, the income generated from depleting natural capital) are reinvested in reproducible capital, then it is possible to maintain a constant level of consumption over time (Hartwick, 1977).

CES function Following Arrow *et al.* (1961), another approach is to use the constant elasticity of substitution (CES) production function:

$$Y = A\left(\alpha K^{\rho} + (1-\alpha)L^{\rho}\right)^{1/\rho}$$

where $\alpha \in [0,1]$ is the share parameter, $\rho = 1 - \sigma^{-1} \leq 1$ is the substitution parameter and σ is the elasticity of substitution:

$$\sigma = -\frac{\mathrm{d}\ln\left(K/L\right)}{\mathrm{d}\ln\left(\dfrac{\partial_K Y}{\partial_L Y}\right)}$$

This last parameter measures the percentage change in the capital-labor ratio resulting from a 1% change in the marginal rate of technical substitution of labor for capital[5]. We

[5]For the Cobb-Douglas function, we have $Y = AK^{\alpha}L^{\beta}$, $\partial_K Y = \alpha AK^{\alpha-1}L^{\beta}$, $\partial_L Y = \beta AK^{\alpha}L^{\beta-1}$, and:

$$\mathrm{MRTS} = \frac{\partial_L Y}{\partial_K Y} = \frac{\beta K}{\alpha L} = \frac{\beta}{\alpha}k$$

obtain three special cases. When $\rho = 1$, $Y = A\left(\alpha K + (1-\alpha)L\right)$ and the two factors are perfectly substitutable. When $\rho = -\infty$, the two factors are used in fixed proportions[6]: $Y = A\min(K, L)$. Finally, when $\rho \to 0$, we obtain the Cobb-Douglas function[7]: $Y = AK^{\alpha}L^{1-\alpha}$. The traditional CES production function can be extended in various ways to include natural capital. The simplest extension adds natural capital as a third input alongside physical capital and labor:

$$Y = A\left(\alpha_K K^{\rho} + \alpha_L L^{\rho} + \alpha_N N^{\rho}\right)^{1/\rho}$$

where $\alpha_K + \alpha_L + \alpha_N = 1$. However, authors usually prefer a more flexible structure with two-level nested CES production functions, which allow for different substitution elasticities between input groups. A general form is:

$$Y = F_{\text{CES}}\left(F_{\text{KL}}(K, L), N\right)$$

where $F_{\text{KL}}(K, L)$ can be specified as either a Cobb-Douglas or another CES function depending on the modeling assumptions. For example, Markandya and Pedroso-Galinato (2007) use the following nested CES specification:

$$\begin{cases} X = A_1\left(\alpha_1 K^{\rho_1} + (1-\alpha_1)L^{\rho_1}\right)^{1/\rho_1} \\ Y = A_2\left(\alpha_2 X^{\rho_2} + (1-\alpha_2)N^{\rho_2}\right)^{1/\rho_2} \end{cases}$$

Hassler *et al.* (2021) propose a different functional form, where production depends on a CES aggregation of a capital-labor Cobb-Douglas composite and natural capital, each with its own productivity term:

$$Y = \left(\alpha\left(AK^{1-\beta}L^{\beta}\right)^{\rho} + (1-\alpha)\left(A_N N\right)^{\rho}\right)^{1/\rho}$$

Using the simplest CES production function, Dasgupta and Heal (1979) were able to reproduce many of the results previously derived by Solow (1974b). In particular, they highlighted a necessary condition under which natural capital is not essential for sustained economic growth. The output elasticity of physical capital must exceed that of natural capital: $\alpha_K > \alpha_N$. This inequality implies that the economy can continue to grow even as natural resources are depleted, provided that physical capital plays a sufficiently dominant role in production (Neumayer, 2000).

We deduce that:

$$\sigma = \frac{\mathrm{d}\ln(k)}{\mathrm{d}\ln\left(\dfrac{\beta}{\alpha}k\right)} = 1$$

[6] We have $\lim_{\rho\to-\infty} Y = \lim_{\rho\to-\infty} A\max\left(\alpha K^{\rho}, (1-\alpha)L^{\rho}\right)^{1/\rho} = A\min(K, L)$.

[7] We have:

$$\ln Y = \ln A + \frac{\ln\left(\alpha K^{\rho} + (1-\alpha)L^{\rho}\right)}{\rho}$$

It follows that $\lim_{\rho\to 0}\ln\left(\alpha K^{\rho} + (1-\alpha)L^{\rho}\right) = 0$ and $\lim_{\rho\to 0}\rho = 0$. We notice that:

$$\partial_{\rho}\left(\ln\left(\alpha K^{\rho} + (1-\alpha)L^{\rho}\right)\right) = \frac{\alpha K^{\rho}\ln K + (1-\alpha)L^{\rho}\ln L}{\alpha K^{\rho} + (1-\alpha)L^{\rho}}$$

Applying L'Hôpital's rule gives:

$$\lim_{\rho\to 0}\frac{\ln\left(\alpha K^{\rho} + (1-\alpha)L^{\rho}\right)}{\rho} = \frac{\alpha K^{\rho}\ln K + (1-\alpha)L^{\rho}\ln L}{\alpha K^{\rho} + (1-\alpha)L^{\rho}} = \alpha\ln K + (1-\alpha)\ln L$$

Therefore, we get $\lim_{\rho\to 0}\ln Y = \ln A + \alpha\ln K + (1-\alpha)\ln L$.

2.2.2 Measuring productivity and Solow residual

Consider a dynamic version of the Cobb-Douglas function:

$$Y_t = A_t K_t^{\alpha} L_t^{\beta}$$

The Solow residual A_t is the portion of output growth that cannot be explained by the growth of capital and labor. It captures how much of output growth is due to something else and is usually interpreted as technological progress, but also includes factors such as improvements in efficiency, better organization or institutions, education, infrastructure or knowledge and innovation. Today, the Solow residual is also called total factor productivity (TFP) or multi-factor productivity (MFP). For the Cobb-Douglas function, we have $\ln Y_t = \ln A_t + \alpha \ln K_t + \beta \ln L_t$. We deduce that $\mathrm{d} \ln A_t = \mathrm{d} \ln Y_t - \alpha \,\mathrm{d} \ln K_t - \beta \,\mathrm{d} \ln L_t$ or:

$$\frac{\mathrm{d}A_t}{A_t} = \frac{\mathrm{d}Y_t}{Y_t} - \alpha \frac{\mathrm{d}K_t}{K_t} - \beta \frac{\mathrm{d}L_t}{L_t}$$

Brandt *et al.* (2017) and Cárdenas *et al.* (2018) extended the earlier framework to account for additional factors of production, including natural capital, providing an enhancement of the OECD model for measuring productivity (OECD, 2001). These authors assume a production function that is homogeneous of degree one in all inputs:

$$Y_t = F\left(A_t, K_t, L_t, N_t\right)$$

It follows that the growth rate of total factor productivity can be expressed as:

$$\frac{\mathrm{d} \ln A_t}{\mathrm{d}t} = \frac{\partial \ln Y_t}{\partial t} - \varepsilon_K \frac{\partial \ln K_t}{\partial t} - \varepsilon_L \frac{\partial \ln L_t}{\partial t} - \varepsilon_N \frac{\partial \ln N_t}{\partial t}$$

where ε_K, ε_L and ε_N are the output elasticities with respect to physical, human, and natural capital, respectively. Assuming market equilibrium, the producer's optimization problem is:

$$\max pY_t - \left(r_K K_t + r_L L_t + r_N N_t\right) \qquad \text{s.t.} \qquad Y_t = F\left(A_t, K_t, L_t, N_t\right)$$

where r_K, r_L, and r_N are the unit costs of physical, human, and natural capital, respectively. Let λ be the Lagrange multiplier. The first-order conditions give $r_K = \lambda \frac{\partial Y_t}{\partial K_t} \Leftrightarrow \frac{r_K K_t}{\lambda Y_t} = \varepsilon_K$, $\frac{r_L L_t}{\lambda Y_t} = \varepsilon_L$, $\frac{r_N N_t}{\lambda Y_t} = \varepsilon_N$ and $\lambda = p$. We deduce that:

$$\frac{\mathrm{d} \ln A_t}{\mathrm{d}t} = \frac{\partial \ln Y_t}{\partial t} - \omega_K \frac{\partial \ln K_t}{\partial t} - \omega_L \frac{\partial \ln L_t}{\partial t} - \omega_N \frac{\partial \ln N_t}{\partial t} \tag{1}$$

where ω_K, ω_L and ω_N are the income shares of physical, human, and natural capital, respectively[8]:

$$\omega_K + \omega_L + \omega_N = \frac{r_K K_t}{pY_t} + \frac{r_L L_t}{pY_t} + \frac{r_N N_t}{pY_t} = 1$$

Equation (1) can be generalized to account for multiple forms of natural capital. In this case, the expression for TFP growth becomes:

$$\frac{\mathrm{d} \ln A_t}{\mathrm{d}t} = \frac{\partial \ln Y_t}{\partial t} - \left(\omega_K \frac{\partial \ln K_t}{\partial t} + \omega_L \frac{\partial \ln L_t}{\partial t} + \sum_{j=1}^{m} \omega_{N_j} \frac{\partial \ln N_{j,t}}{\partial t}\right)$$

[8]Under the assumption of perfect competition and equilibrium, profits are zero.

2.2.3 Damage function

The previous two approaches generally assume that natural capital positively contributes to the economy. While a reduction in certain components of natural capital can lower economic growth in relative terms, its absolute contribution is still considered positive. However, some biodiversity risks could result in an overall negative contribution. For instance, the productivity approach was used by Cárdenas *et al.* (2023) to calculate the contribution of the different factors to GDP growth. In particular, they estimated the decomposition of pollution-adjusted GDP growth:

$$g_Y^\star = g_Y + a_P = c_K + c_L + c_N + r_{Solow} \tag{2}$$

where g_Y is GDP growth, a_P is the adjustment for pollution abatement, c_K, c_L, and c_N are the contributions of physical, human and natural capital and r_{Solow} is the Solow residual. In this model, air pollution is shown to have a negative contribution.

The impact of air pollution on economic growth has led to a substantial body of empirical research. Some of the most notable studies include Myllyvirta (2020), World Bank (2022), Mejino-López and Oliu-Barton (2024), and EEA (2024a,b). The global economic cost of air pollution is estimated to range between 2% and 4% of GDP, with significant disparities between countries. Table 1 presents estimates from Myllyvirta (2020), which indicate that emerging economies such as China, India, and Bangladesh are among the most affected.

Table 1: Economic costs of air pollution from fossil fuels (% of GDP, 2018)

Country	Cost	Country	Cost
China	6.6%	Bulgaria	6.0%
Hungary	6.0%	Ukraine	5.8%
Serbia	5.8%	Belarus	5.4%
India	5.4%	Romania	5.3%
Bangladesh	5.1%	Moldova	5.0%
Poland	4.9%	Russia	4.1%
Germany	3.5%	South Korea	3.4%
USA	3.0%	Japan	2.5%
UK	2.3%	France	2.0%
Spain	1.7%	Brazil	0.8%

Source: Myllyvirta (2020, page 6) & Centre for Research on Energy and Clean Air (CREA).

A basic economic model of pollution costs Dechezleprêtre *et al.* (2019) consider a classical output function that uses physical and human capital as factors of production, but also incorporates pollution as an additional variable: $Y = F(K, L, P)$, where Y is economic output, K is capital, L is labor, and P is pollution. The labor input L can be expressed as $L = S_L \cdot A_L \cdot T_L$ where S_L is the workforce size (or the population), A_L is labor productivity,

$T_L = \tau - \varsigma$ is the time individuals spend working, which is the difference between the total endowment of labor time τ and sick time ς. It is assumed that all three variables (S_L, A_L, and ς) depend on the pollution P. Consequently, the output function can be rewritten as:

$$Y = F\left(K, S_L(P)\, A_L(P)\left(\tau - \varsigma(P)\right), P\right)$$

From this, we deduce the derivative of the logarithm of output with respect to pollution:

$$\frac{\mathrm{d}\ln Y}{\mathrm{d}P} = \frac{\partial \ln Y}{\partial \ln L}\frac{\partial \ln L}{\partial P} + \frac{\partial \ln Y}{\partial P} = \epsilon_L \frac{\partial \ln L}{\partial P} + \frac{\partial \ln Y}{\partial P}$$

where $\varepsilon_L \geq 0$ is the elasticity of output with respect to labor. We deduce that:

$$\frac{\mathrm{d}\ln Y}{\mathrm{d}P} = \epsilon_L \left(\frac{\partial \ln S_L}{\partial P} + \frac{\partial \ln A_L}{\partial P} + \frac{\partial \ln\left(\tau - \varsigma(P)\right)}{\partial P}\right) + \frac{\partial \ln Y}{\partial P}$$

and:

$$\frac{\partial \ln\left(\tau - \varsigma(P)\right)}{\partial P} = -\frac{1}{\tau - \varsigma(P)}\frac{\partial \varsigma(P)}{\partial P} = -\frac{\varsigma(P)}{\tau - \varsigma(P)}\frac{\partial \ln \varsigma(P)}{\partial P}$$

Substituting this into the equation and introducing the notation $\theta = \dfrac{\varsigma}{\tau - \varsigma}$, which represents the ratio of sick time to effective labor time, we get:

$$\frac{\mathrm{d}\ln Y}{\mathrm{d}P} = \epsilon_L \underbrace{\left(\frac{\partial \ln S_L}{\partial P} + \frac{\partial \ln A_L}{\partial P} - \theta\frac{\partial \ln \varsigma(P)}{\partial P}\right)}_{\text{Pollution-related labor impact}} + \frac{\partial \ln Y}{\partial P}$$

This equation can be expressed in the following compact form:

$$\beta_P = \epsilon_L \beta_{L,P} + \beta_{L,P}$$

Therefore, pollution has an indirect impact on output through the labor factor, which operates through three dimensions:

1. Pollution increases mortality, reducing the size of labor force: $\dfrac{\partial \ln S_L}{\partial P} < 0$.
2. Pollution increases morbidity, decreasing labor productivity: $\dfrac{\partial \ln A_L}{\partial P} < 0$.
3. Pollution increases morbidity, leading to more work absences: $\dfrac{\partial \ln \varsigma(P)}{\partial P} > 0$.

The labor-related impact of pollution also depends on the labor-output elasticity. A higher value of ϵ results in a higher cost of pollution, especially in labor-intensive industries (Graff Zivin and Neidell, 2013). Consequently, the labor-related impact of pollution is always negative: $\epsilon_L \beta_{L,P} \leq 0$. In contrast, the direct impact of pollution on output can be either positive or negative: $\beta_{L,P} = \dfrac{\partial \ln Y}{\partial P} \lesseqgtr 0$. When pollution levels are low, increasing pollution can have a positive impact because GDP is boosted by an increase in energy supply. However, when pollution levels are very high, increasing pollution has a negative impact due to the negative externalities (*e.g.*, infrastructure damage, reduced agricultural yields, water stress) that affect the production system. Therefore, the direct relationship follows a bell curve: $\beta_{L,P}$ is initially positive, but becomes negative as pollution increases. The aggregation of these two effects is not straightforward. While β_P may be positive when pollution levels are low, it is certain to become negative when pollution levels are high.

Modeling climate damage Traditional economic models do not distinguish between the production Y_t and the net output Q_t because we have the identity $Y_t = Q_t$. For Nordhaus and Sztorc (2013), physical and transition climate risks generate losses. We have $Q_t = \Omega_t Y_t$ where $\Omega_t \in [0, 1]$ is the percentage of the loss production. Q_t is then the net output when accounting for negative externalities of climate change. Generally, the survival function is defined as:

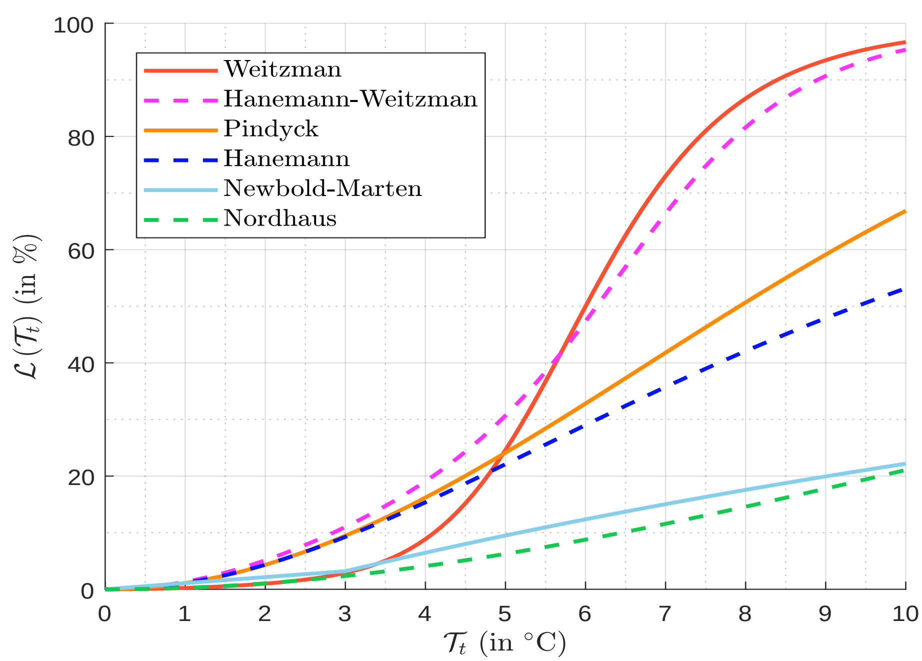
$$\Omega_t = \frac{1 - \Lambda_t}{1 + D_t}$$

where $D_t \geq 0$ is the climate damage function (physical risk) and $\Lambda_t \geq 0$ is the mitigation or abatement cost (transition risk). In what follows, we assume that $\Lambda_t = 0$. The costs D_t result from natural disasters and climatic events, such as wildfires. Nordhaus and Sztorc (2013) assume that D_t depends on the atmospheric temperature $\mathcal{T}_t$:

$$D_t = \psi_1 \mathcal{T}_t + \psi_2 \mathcal{T}_t^2$$

where $\psi_1 \geq 0$ and $\psi_2 \geq 0$ are two parameters. $\mathcal{T}_t$ measures the global mean surface temperature and corresponds to the temperature increase in °C from 1900. Therefore, $\mathcal{L}(\mathcal{T}_t) = 1 - (1 + D_t)^{-1}$ represents the fraction of net output that is lost because of the global warming. Nordhaus and Sztorc (2013) used $\psi_1 = 0$ and $\psi_2 = 2.67 \times 10^{-3}$ for the specification of D_t. In Figure 1, we have represented the loss function $\mathcal{L}(\mathcal{T}_t)$ as a function of the temperature increase $\mathcal{T}_t$. For instance, we obtain $\mathcal{L}(1°\text{C}) = 0.27\%$, $\mathcal{L}(2°\text{C}) = 1.06\%$, $\mathcal{L}(3°\text{C}) = 2.35\%$, $\mathcal{L}(5°\text{C}) = 6.26\%$ and $\mathcal{L}_D(10°\text{C}) = 21.07\%$ (dashed green line). In Figure 1, we also show alternative loss functions published in well-known articles related to climate change.

Figure 1: Loss function due to climate damage costs



Source: Roncalli (2025a, Figure 8.87).

Many economists believe that these damage cost estimates are underestimated. This is especially true of the most recent publications, which report much higher figures. For instance, Bilal and Känzig (2024) estimated that the macroeconomic damages from climate change are six times greater than previously thought. Specifically, they found that a 1°C increase in global temperature leads to a 12% decline in world GDP. Waidelich *et al.* (2024) reported that the global average loss is 10% of gross domestic product when the temperature rises by 3°C. These findings are supported by Kotz *et al.* (2024), who identified even more severe scenarios by accounting not only for temperature changes but also for a broader set of climatic variables, including annual precipitation, the number of wet days, and extreme daily rainfall:

> "*Using an empirical approach that provides a robust lower bound on the persistence of impacts on economic growth, we find that the world economy is committed to an income reduction of 19% within the next 26 years independent of future emission choices (relative to a baseline without climate impacts, likely range of 11-29% accounting for physical climate and empirical uncertainty). These damages already outweigh the mitigation costs required to limit global warming to* 2°C *by sixfold over this near-term time frame and thereafter diverge strongly dependent on emission choices. Committed damages arise predominantly through changes in average temperature, but accounting for further climatic components raises estimates by approximately 50% and leads to stronger regional heterogeneity.*" (Kotz *et al.*, 2024, page 551).

This latest research has been selected by NGFS (2024) as the new damage function for climate stress tests. Table 2 shows different damage estimates for temperature increases of 2°C and 3°C, respectively[9]. NGFS (2024) used a standardized approach based on the GCAM integrated assessment model to compute these values. Notably, the new estimates based on Bilal and Känzig (2024) and Kotz *et al.* (2024) indicate significantly greater impacts on GDP.

Table 2: Damage estimates across damage functions

Study	2°C	3°C	Study	2°C	3°C
Nordhaus and Boyer (2000)	1%	2%	Burke *et al.* (2015)	8%	14%
Tol (2009)	1%	3%	Howard and Sterner (2017)	3%	8%
Pindyck (2012)	4%	9%	Kompas *et al.* (2018)	1%	2%
Weitzman (2012)	1%	3%	Kalkuhl and Wenz (2020)	2%	5%
Dell *et al.* (2012)	4%	22%	Kahn *et al.* (2021)	3%	8%
Tol (2014)	1%	2%	Waidelich *et al.* (2024)	4%	8%
Nordhaus (2014)	1%	2%	Bilal and Känzig (2024)	19%	44%
Dietz and Stern (2015)	2%	13%	Kotz *et al.* (2024)	14%	33%

Source: NGFS (2024, Table 3, page 14).

Remark 1. *According to Roncalli (2025b), natural capital and biodiversity face five main pressures: (1) climate change, (2) habitat loss, (3) invasive species, (4) overexploitation, and (5) pollution. While the previous paragraphs have focused on the economic costs of pollution and climate change, the impact of the remaining three pressures on economic growth is also documented in the academic literature, albeit to a lesser extent. Nevertheless, some estimates of the associated economic losses do exist, particularly in the case of invasive species (Diagne et al., 2021; Haubrock et al., 2021; IPBES, 2023).*

[9]These two scenarios correspond to the projected outcomes under current policy trajectories for the years 2050 and 2100.

3 Empirical analysis

In this section, we begin by reviewing existing studies and summarizing their key empirical findings. We then present our own empirical analysis to explore the relationship between natural capital and economic growth.

3.1 Overview of existing empirical work

3.1.1 Factor contributions to the GDP growth

The OECD has a long history of measuring multifactor productivity, including efforts to incorporate natural capital (Brandt *et al.*, 2013, 2017; Roy and Braathen, 2017; Cárdenas *et al.*, 2018). The study by Cárdenas *et al.* (2023) is the most comprehensive to date. It covers OECD and G20 countries and the period 1996-2018. For each country, the study provides estimates of GDP growth and adjustments for pollution abatement, as well as contributions from produced capital, labor, natural capital, and the Solow residual. Natural capital is measured by accounting for both renewable resources (land, biological resources, ecosystem services, and renewable energy) and non-renewable resources (fossil fuels and minerals). On average across OECD countries, physical capital accounts for 32% of GDP growth, while labor contributes only 15%. The contribution of natural capital is less than 1%, indicating that around 50% of GDP growth is explained by the Solow residual, or total factor productivity.

The low contribution of natural capital is primarily due to its limited variability from one year to the next. More specifically, the contribution of natural capital is determined by the product of its elasticity with respect to output and the change in resource use. Assuming a Walrasian equilibrium, elasticity is replaced by the share of natural capital rents relative to total inputs. Thus, an increase in natural capital leads to a positive contribution to economic growth, while a decrease results in a negative contribution. Consequently, if the use of natural capital does not change, its contribution to GDP growth will be zero. It is important to note that this measure reflects contribution to GDP growth, not the overall level of GDP or economic wealth.

Table 3: Top 15 countries with the highest pollution abatement adjustments

Country	$g_Y^\star$	a_P	$a_P/g_Y^\star$	Country	$g_Y^\star$	a_P	$a_P/g_Y^\star$
Türkiye	3.72	−0.89	−23.95	Italy	0.94	0.35	37.77
Indonesia	3.39	−0.78	−23.05	Greece	1.02	0.35	34.06
China	8.08	−0.58	−7.16	Japan	1.16	0.31	26.98
India	6.27	−0.53	−8.44	Türkiye	3.72	−0.89	−23.95
Korea	3.78	−0.43	−11.40	Indonesia	3.39	−0.78	−23.05
Brazil	1.83	−0.42	−22.77	Brazil	1.83	−0.42	−22.77
Belgium	2.24	0.41	18.52	Argentina	1.78	−0.35	−19.53
UK	2.47	0.39	15.66	Germany	1.72	0.33	19.24
Slovakia	4.12	0.37	8.97	France	1.97	0.37	18.60
France	1.97	0.37	18.60	Belgium	2.24	0.41	18.52
Italy	0.94	0.35	37.77	UK	2.47	0.39	15.66
Argentina	1.78	−0.35	−19.53	Austria	2.09	0.27	13.00
Greece	1.02	0.35	34.06	Bulgaria	1.74	0.22	12.84
Germany	1.72	0.33	19.24	Switzerland	2.27	0.29	12.73
Sweden	2.77	0.33	11.76	Finland	2.46	0.31	12.72

Source: Cárdenas *et al.* (2023, Table A.1, page 42).

Table 4: Top 15 countries with the highest natural capital

Country	$g_Y^\star$	c_N	$c_N/g_Y^\star$	Country	$g_Y^\star$	c_N	$c_N/g_Y^\star$
Saudi Arabia	2.88	0.32	11.12	Saudi Arabia	2.88	0.32	11.12
Russia	3.11	0.25	7.92	Russia	3.11	0.25	7.92
Australia	3.02	0.16	5.37	Norway	2.28	−0.14	−6.15
Norway	2.28	−0.14	−6.15	Australia	3.02	0.16	5.37
Chile	3.96	0.12	3.05	Brazil	1.83	0.08	4.53
China	8.08	0.12	1.44	Chile	3.96	0.12	3.05
Brazil	1.83	0.08	4.53	Denmark	1.75	−0.05	−2.97
Estonia	3.98	0.08	2.01	Colombia	3.03	0.06	2.11
Colombia	3.03	0.06	2.11	Estonia	3.98	0.08	2.01
Peru	4.24	0.06	1.46	New Zealand	2.83	−0.05	−1.76
India	6.27	0.05	0.86	Romania	3.33	−0.05	−1.53
Denmark	1.75	−0.05	−2.97	Mexico	2.44	−0.04	−1.52
Romania	3.33	−0.05	−1.53	Peru	4.24	0.06	1.46
New Zealand	2.83	−0.05	−1.76	China	8.08	0.12	1.44
Indonesia	3.39	0.05	1.36	UK	2.47	−0.03	−1.38

Source: Cárdenas *et al.* (2023, Table A.1, page 42).

Tables 3 and 4 show the top 15 countries with the highest pollution reduction adjustments and the highest contributions from natural capital. As previously discussed, these values can be either positive or negative. For instance, Turkey has the highest negative pollution adjustment, which indicates that increased pollution reduced its economic growth by 0.89% per year. Conversely, Belgium benefited the most from pollution reduction. In relative terms, Italy ranks first, with pollution abatement accounting for 37.77% of its net economic growth. Regarding natural capital, Saudi Arabia, Russia, and Australia experienced positive contributions, each exceeding 5% of economic growth. In contrast, Norway, Denmark, and New Zealand recorded the most negative contributions from natural capital.

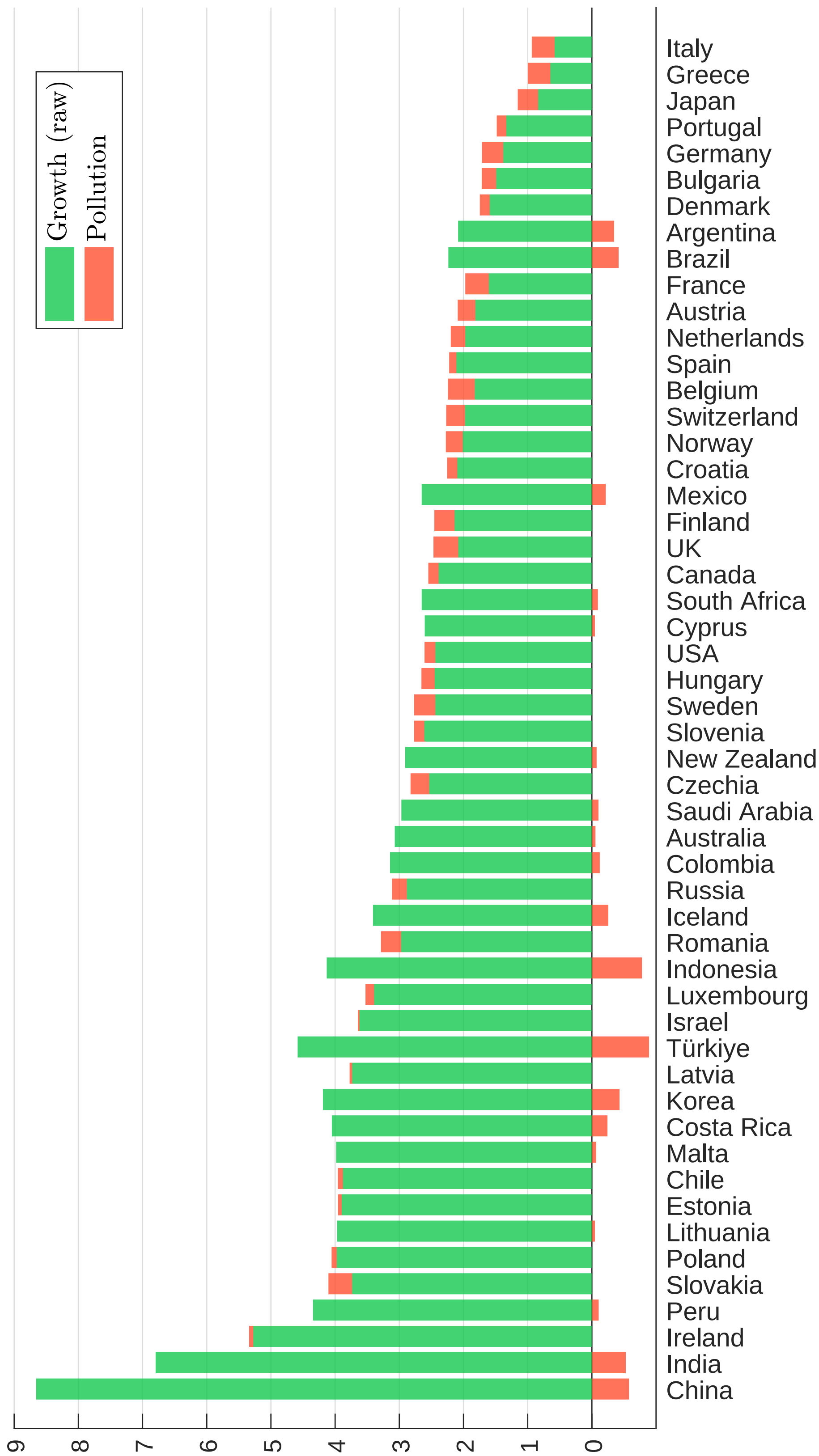
Figures 2, 3 and 4 show the components of Equation (2):

$$g_Y^\star = g_Y + a_P = c_K + c_L + c_N + r_{Solow}$$

The countries are ranked by net economic growth, $g_Y^\star$, over the period 1996 to 2018. Figure 2 illustrates the impact of pollution. We observe that the impact has been negative for most emerging countries (China, India, Costa Rica, Turkey, Mexico, Brazil, and Argentina), while most developed countries have benefited from pollution management. Figure 3 reinforces the earlier observation regarding the generally low contribution of natural capital, with a few notable exceptions. Finally, the figure also highlights the contrast between pollution abatement and natural capital contributions.

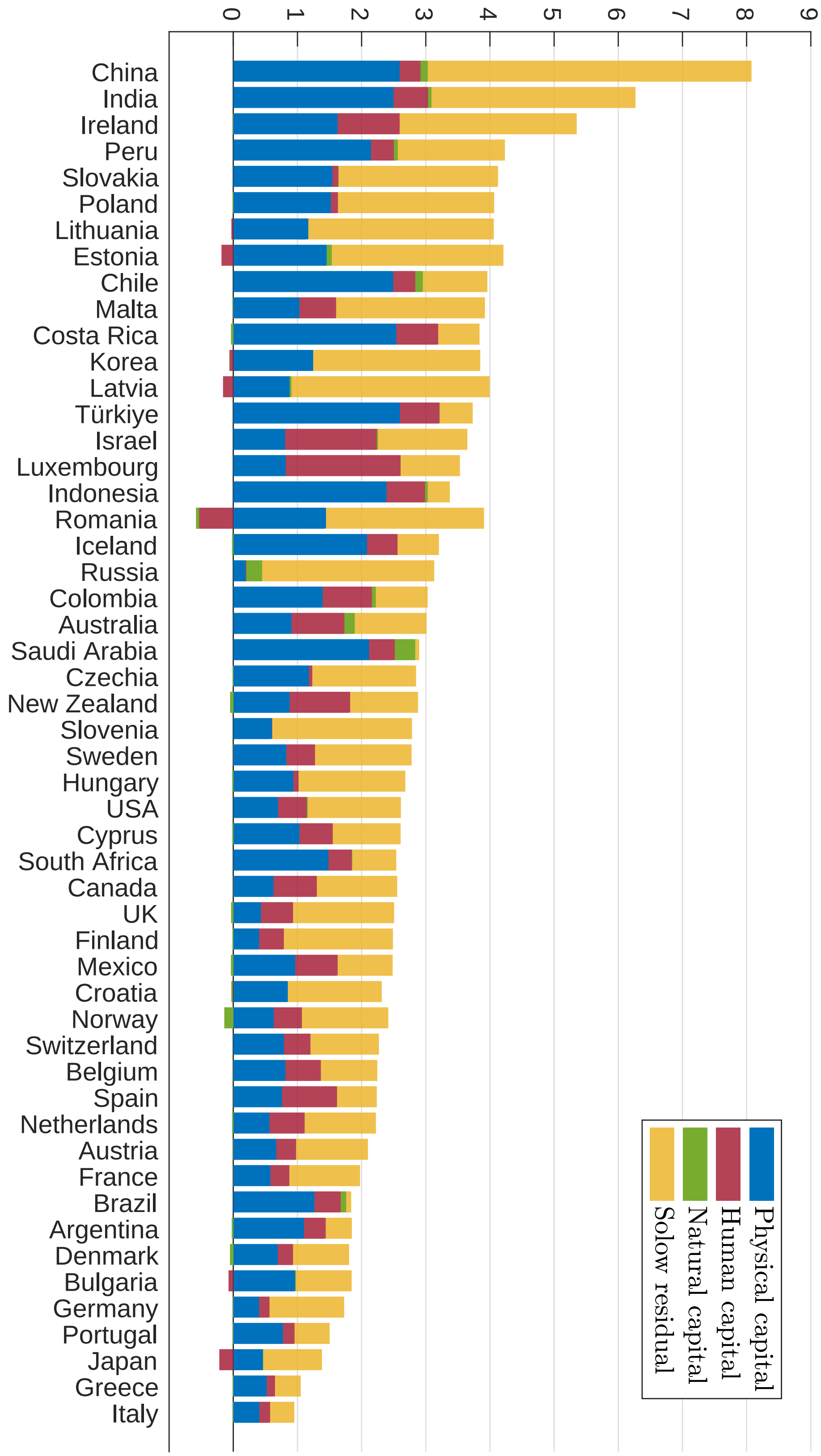
Table 5 provides a detailed breakdown by component of the top 15 countries with the highest contributions from natural capital. For instance, natural capital accounts for 11.1%of pollution-adjusted GDP growth in Saudi Arabia. Almost all of this contribution comes from fossil fuel energy (11.0%), while minerals account for only 0.1%. There is no contribution from renewable resources, such as land, biological resources, or ecosystem services. In contrast, Russia shows a more balanced profile. Of its total contribution of 7.9% from natural capital, 7.0% comes from fossil fuels, 0.5% from minerals, and 0.3% from biological resources. Some countries exhibit offsetting effects, where positive contributions from certain components are partially negated by negative contributions from others. For instance, in Peru, minerals make a strong positive contribution (3.2%), but this is partially offset by negative contributions from land resources (−0.3%), biological resources (−1.1%), ecosystem services (−0.1%), and fossil fuel energy (−0.3%).

Figure 2: Output growth — long-term annual geometric average (1996-2018)



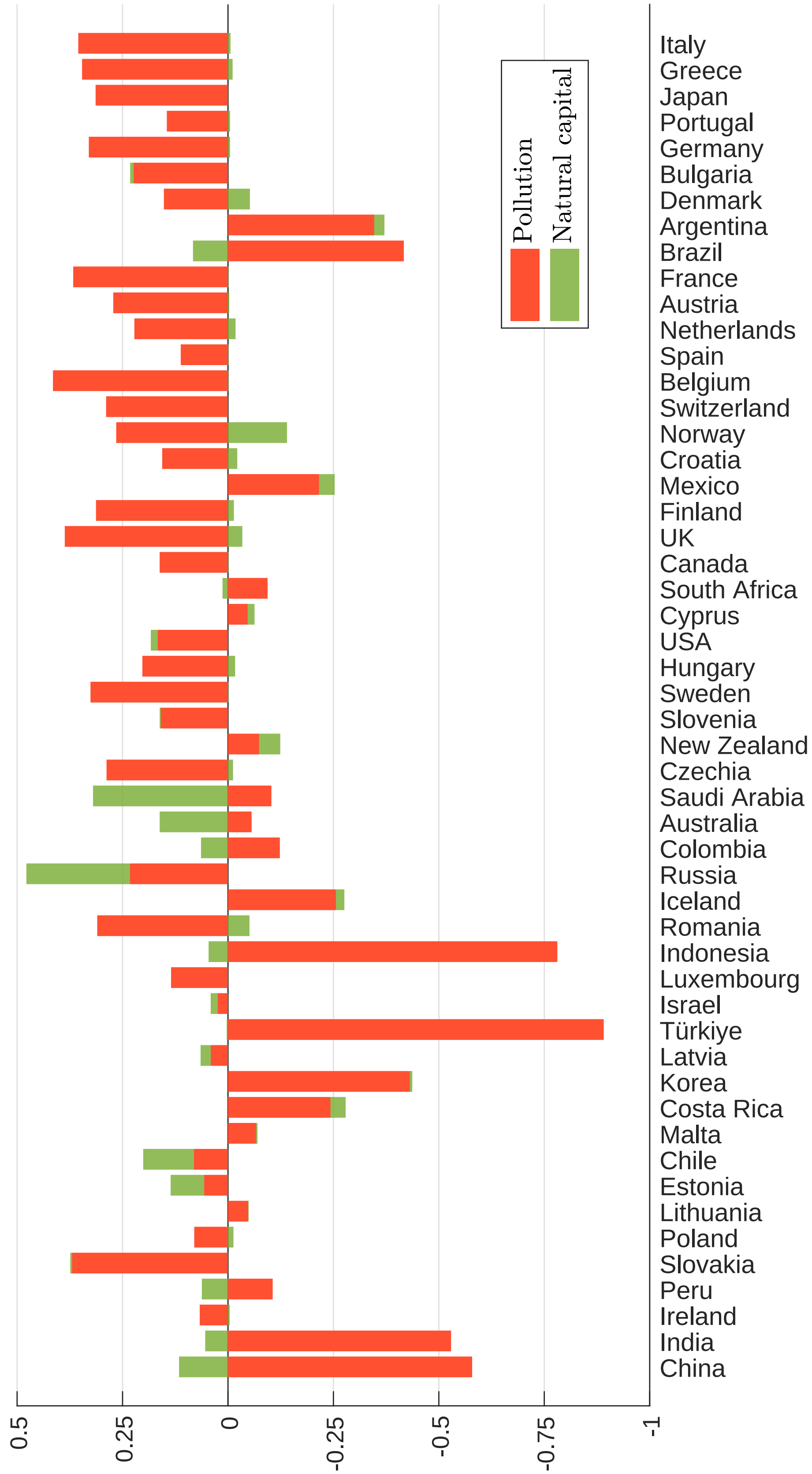
Source: Cárdenas *et al.* (2023, Table A.1, page 42).

Figure 3: Input growth — long-term annual geometric average (1996-2018)



Source: Cárdenas *et al.* (2023, Table A.1, page 42).

Figure 4: Annual contribution of pollution abatement and natural capital to economic growth (1996-2018)



Source: Cárdenas *et al.* (2023, Table A.1, page 42).

Table 5: Breakdown of the natural capital contribution

Country	$c_N/g_Y^\star$	Land resources	Biological resources	Ecosystem services	Fossil fuel energy	Minerals
Saudi Arabia	11.1	0.0	0.0	0.0	11.0	0.1
Russia	7.9	0.0	0.3	0.0	7.0	0.5
Norway	−6.1	0.1	0.0	0.0	−6.3	0.1
Australia	5.4	−0.1	0.0	−0.1	0.7	4.8
Brazil	4.5	0.0	0.3	−0.2	3.0	1.4
Chile	3.0	−0.2	−0.1	0.1	0.0	3.3
Denmark	−2.9	−0.2	−0.2	0.0	−2.6	0.0
Colombia	2.1	−0.5	0.0	−0.1	2.8	0.0
Estonia	2.0	0.3	1.4	0.0	0.3	0.0
New Zealand	−1.8	−2.5	0.6	0.0	0.1	0.0
Romania	−1.5	−0.5	0.1	0.0	−1.0	−0.1
Mexico	−1.5	−0.1	0.0	0.0	−2.1	0.7
Peru	1.5	−0.3	−1.1	−0.1	−0.3	3.2
China	1.4	0.0	0.0	0.0	1.0	0.4
United Kingdom	−1.4	0.0	0.0	0.0	−1.4	0.0
OECD	0.2	−0.1	0.0	0.0	0.1	0.2
G20	1.2	0.0	0.0	0.0	0.9	0.3

Source: Cárdenas *et al.* (2023, Table A.2, page 44).

Remark 2. *The results of Cárdenas et al. (2023) are confirmed by Ghosal et al. (2024), who use a similar decomposition method by incorporating intangible human capital H:*

$$g_Y = c_K + c_L + c_H + c_N + r_{Solow}$$

They apply their model to 14 emerging countries over the period 1995-2020. Results are reported in Table 20 on page 51. The contribution of natural capital is generally very low[10], less than 5% in most cases, except for Chile, where natural capital accounts for 14% of GDP growth.

3.1.2 Estimated value of output elasticity of natural capital

The study by Cárdenas *et al.* (2023) is undoubtedly one of the most comprehensive empirical investigations of the relationship between natural capital and economic growth. However, the study does not report the individual elasticities, since it only provides the global effect. Below, we review several empirical studies that estimate the coefficients α, β and γ of the extended Cobb-Douglas production function.

Giannakis *et al.* (2025) estimated a Cobb-Douglas aggregate production function by incorporating indirect effects using a spatial Durbin model:

$$\begin{aligned} \ln Y_{i,t} \quad = \quad & c + \alpha \ln K_{i,t} + \beta \ln L_{i,t} + \gamma \ln N_{i,t-1} + \varepsilon_{i,t} + \\ & g\left(Y_{i,t}, K_{i,t}, L_{i,t}, N_{i,t-1}\right) + \delta_i + \eta t \end{aligned}$$

The first row of this specification represents the traditional Cobb-Douglas regression model, while the second row accounts for the indirect spatial effects — denoted as $g\left(Y_{i,t}, \ldots\right)$ — as

[10] Brandt *et al.* (2017) obtained similar results for OECD countries. From 1986 to 2008, they found that the contribution of natural capital was very low for all countries except Norway (16.77%), Chile (6.63%), Australia (4.35%), and Canada (3.97%).

well as region-specific fixed effects δ_i and a linear time trend ηt. Using a database on the European NUTS 2 regions, the authors found a coefficient of determination of 78.7% . The estimated coefficients are summarized below[11]:

Effects	K	L	N
Direct	0.227	0.733	0.039
Indirect	−0.069	0.096	0.032
Total	0.158	0.829	0.071

These results suggest that a 10% increase in natural capital leads to a 0.71% increase in gross value added, with 0.39% attributed to direct effects and 0.32% attributed to spillover benefits from neighboring regions.

These findings are supported by several other studies. For example, Singh *et al.* (2024) found that a 1% increase in the use of natural resources led to a 13% decrease in economic growth in the P5+1 countries (US, UK, France, China, Russia, and Germany) in the short- and long-run from 1988 to 2019. Using a panel of 100 countries from 1999 to 2018, Tenaw (2025) found that the output elasticity of natural capital is lower than that of human capital, but higher than that of produced capital. Their estimate of γ lies between 0.35 and 0.40 and is significant at the 1% level. In contrast, Wang and Xu (2024) obtained a coefficient between 0.13 and 0.17 when focusing on the Global South. While all of these studies found a positive and significant output elasticity with respect to natural capital, the magnitudes varied substantially. This variability highlights the sensitivity of γ to various factors. γ is sensitive to factors such as the data sample, observation period, definition of natural capital, data sources, and econometric methods.

The extent to which natural capital can be substituted by physical and human capital is still an open and contested issue:

> "*We review the empirical literature examining whether aggregate production levels can be maintained as natural capital declines, by using more manufactured capital or labor. Most econometric estimates are based on old studies using methods that are not able to deal with pervasive endogeneity issues. [...] In both the energy and agricultural sectors, the evidence suggests that substitutability between energy and land (both key forms of natural capital) and other forms of capital can only be plausibly low to moderate.*" (Cohen *et al.*, 2019).

These results call the relevance of the Cobb-Douglas production function into question and suggest that nested CES functions may be a better option.

3.1.3 The case of negative externalities

Galiano Bastarrica *et al.* (2023) introduced two biodiversity pressures into the Cobb-Douglas production function:

$$\begin{aligned}\ln Y_{i,t} &= c_i + \alpha \ln K_{i,t} + \beta \ln L_{i,t} + \varepsilon_{i,t} + \\ &\quad \gamma_m \ln M_{i,t} + \gamma_m' \ln M_{i,t-1} + \gamma_e \ln E_{i,t-2} + \gamma_e' \ln E_{i,t-3}\end{aligned}$$

where $M_{i,t}$ is the domestic extraction and importation of materials in Europe, and $E_{i,t}$ is the CO_2 emissions. Using the evolution of GDP for the 27 member states of the European

[11] We will not address the appropriateness of the data here, particularly with regard to the definition and boundaries of natural capital. For instance, the authors report the following average ratios: $K/Y = 330\%$, $L/Y = 60\%$, and $N/Y = 0.90\%$. These figures raise concerns about the data used to measure natural capital. We will return to this issue later.

Union from 2000 to 2018, the following estimated coefficients were found:

Effects	$\hat{\alpha}$	$\hat{\beta}$	$\hat{\gamma}_m$	$\hat{\gamma}'_m$	$\hat{\gamma}_e$	$\hat{\gamma}'_e$
Direct	0.969	0.298	-0.858	0.499	-0.131	0.176

Therefore, the net effect of material exploitation is negative, while the net effect of carbon emissions is positive. Overall, the authors showed that the global impact of these two externalities is negative (Galiano Bastarrica *et al.*, 2023, Figure 1, page 124). Rusiadi *et al.* (2024) used a similar approach to estimate the elasticities for ASEAN countries from 2000 to 2021. The authors found that γ takes the values 0.250 and 0.137 for natural resources and renewable energy, respectively, while the impact of CO_2 emissions is zero. In fact, the impact of air pollution has been extensively documented in numerous empirical studies (see the review by Roncalli (2025b)). A similar consensus exists for other negative externalities, such as overexploitation. However, the effects of biodiversity pressures are less well-documented.

Remark 3. *Table 6 presents the various natural variables used by academics in empirical economic growth models. These variables fall into three categories: inputs of non-renewable resources, inputs of renewable resources, and biodiversity pressures. As will be explained later, using more granular data is not always robust for estimation purposes.*

3.1.4 The resource curse: economic wealth versus economic growth

The resource curse refers to the paradoxical situation where countries rich in natural resources (especially non-renewable resources like oil, gas, and minerals) tend to have slower economic growth, weaker development outcomes, and greater political instability compared to countries with fewer natural resources. The negative relationship between natural resource abundance and long-term economic performance was first highlighted by Auty (1993) and Sachs and Warner (1995, 2001), who showed that a higher share of natural capital in national wealth is frequently associated with poorer growth trajectories[12]. Several mechanisms have been proposed to explain the resource curse, including Dutch disease, weak institutions and governance, rent-seeking behavior, imperfect markets, neglect of human capital, and macroeconomic volatility stemming from commodity price fluctuations. Additionally, Gylfason and Zoega (2006) argues that heavy dependence on natural resources can directly undermine saving and investment by impeding financial system development, creating another channel through which resource abundance may paradoxically hinder long-term economic growth. Although there is extensive literature supporting the resource curse hypothesis, a growing body of research has begun to challenge this assumption by identifying positive relationships between natural resource wealth and economic performance. For instance, Sharma and Paramati (2022) found evidence of the positive impact of natural capital on economic growth. As previously mentioned, other studies have also reported a positive output elasticity of natural capital.

[12] The concept of wealth is not straightforward and will be discussed later, so it is generally replaced by a proxy variable:

> "*One of the surprising features of modern economic growth is that economies with abundant natural resources have tended to grow less rapidly than natural-resource-scarce economies. In this paper we show that economies with a high ratio of natural resource exports to GDP in 1971 (the base year) tended to have low growth rates during the subsequent period 1971-89. This negative relationship holds true even after controlling for variables found to be important for economic growth, such as initial per capita income, trade policy, government efficiency, investment rates, and other variables.*"(Sachs and Warner, 1995, page 1).

Table 6: Natural capital inputs in empirical economic growth models

Non-renewable resources	Fossil fuel	Brown coal
		Crude oil
		Hard coal
		Natural gas
	Mineral	Aluminum
		Bauxite
		Copper
		Gold
		Iron ore
		Lead
		Nickel
		Phosphate
		Silver
		Tin
		Zinc
Renewable resources	Land	Cropland
		Pastureland
		Forestland
	Biological	Marine capture fisheries
		Non-cultivated timber
	Ecosystem services	Carbon sequestration
		Coastal flooding protection (mangrove)
		Crop pollination
		Flood control
		Non-wood forest products (forest)
		Soil retention
		Watershed protection (forest)
	Energy	Hydro
		Wind
		Solar
Biodiversity pressures	Climate	Carbon dioxide
		Methane
		Nitrous oxide
		Nitrogen trifluoride
		Sulphur hexafluoride
		Temperature anomaly
	Pollution	Sulphur oxides
		Nitrogen oxides
		Particulate matters
		Carbon monoxide
		Ammonia
		NMVOC
		Black carbon
	Species	Living Planet Index
		Habitat maintenance
		Biodiversity intactness index
Global		Natural capital rent

How can we explain these divergent findings? One key reason is the heterogeneity of econometric methodologies, data quality, and variable selection across studies. Additionally, many analyses conflate economic growth with economic wealth[13], leading to divergent interpretations of the role of natural capital in development outcomes. To understand this distinction, consider the Cobb-Douglas production function: $Y_t = A_t K_t^{\alpha} L_t^{\beta} N_t^{\gamma}$. In this specification, the share of GDP attributable to natural capital depends on the absolute level N_t of natural capital and the elasticity parameter γ. However, the share of GDP growth explained by natural capital depends on the growth rate of natural capital and the same elasticity:

$$\mathrm{d}\ln Y_t = \mathrm{d}\ln A_t + \alpha \mathrm{d}\ln K_t + \beta \mathrm{d}\ln L_t + \gamma \mathrm{d}\ln N_t$$

This illustrates an important distinction: empirical analyses conducted in levels differ fundamentally from those based on growth rates. For instance, if natural capital does not grow over time (*i.e.*, $\Delta \ln N_t = 0$), its contribution to economic growth is effectively zero. Moreover, because natural capital tends to change very slowly from year to year — a common empirical observation — it can often be approximated as constant — $N_t = N$. In that case, the production function simplifies to:

$$Y_t = A'_t K_t^{\alpha} L_t^{\beta}$$

where $A'_t = A_t N^{\gamma}$. When variations in natural capital are minimal, this creates an econometric identification problem. The value of γ cannot be reliably estimated, and the contribution of natural capital becomes absorbed into the Solow residual, or total factor productivity. This highlights a fundamental difference between natural capital and other forms of capital. While physical and human capital generally exhibit sustained growth over time, natural capital often fluctuates or remains stable, complicating its empirical treatment in growth models[14] (Table 7).

Table 7: Growth rate of investment (1995–2000)

Country	K	L	N
United States	3.46%	1.52%	0.03%
China	11.79%	2.04%	−0.04%
Brazil	0.32%	2.88%	−0.52%
India	7.31%	2.99%	−0.16%
Venezuela	0.35%	2.22%	−0.62%

Source: Arrow *et al.* (2012, Table 2, pages 341-342).

[13] The concept of wealth that includes natural capital has been developed over the past 30 years (Barbier, 2017, 2019). In fact, the original idea of natural capital, introduced by David Pearce, already encompassed the notion of wealth measurement (Pearce, 1988). Nevertheless, it was Robert Costanza who popularized natural capital as a key component of wealth in his seminal 1997 paper on the valuation of ecosystem services and natural capital (Costanza *et al.*, 1997).

[14] We can illustrate these phenomena with an example. Consider two economies that differ only in terms of natural capital: $A_t^{(1)} = A_t^{(2)} = 0.5$, $K_t^{(1)} = K_t^{(2)} = 100$, $L_t^{(1)} = L_t^{(2)} = 200$, $N_t^{(1)} = 100$, $N_t^{(2)} = 5\,000$, $\alpha^{(1)} = \alpha^{(2)} = 20\%$, $\beta^{(1)} = 70\%$, $\beta^{(2)} = 78\%$, $\gamma^{(1)} = 10\%$ and $\gamma^{(2)} = 2\%$. We obtain $Y_t^{(1)} = 81.23$ and $Y_t^{(2)} = 92.84$. The second economy is 14% richer than the first because it has more natural capital. Assuming a 10% increase in natural capital yields GDP growth of 0.96% and 0.19% for the first and second economies, respectively. Since the second economy has a larger initial natural capital endowment than the first economy, we assume that natural capital increases by 20% in the first economy and decreases by 10% in the second economy. In this case, we obtain economic growth rates of +1.84% and −0.21%, respectively. These differences are not significant because the elasticity γ is low. However, if we consider a 10% increase in human capital, the impact is much larger, with economic growth reaching +6.90% and +7.72% respectively.

Table 8: Description of the production factors

Variable / Code	Description
K (NW.PCA.TO)	Produced capital includes the value of machinery, buildings, equipment, and urban land. The values are reported in real chained 2019 US dollars, calculated using the Törnqvist index method.
L (NW.HCA.TO)	Human capital is calculated as the present value of future earnings for the working population, categorized by age, gender, and education. The values are reported in real chained 2019 US dollars, calculated using the Törnqvist volume index method.
N (NW.NCA.SSOI.TO)	Non-renewable natural capital includes assets such as oil, natural gas, coal, and metals and minerals (bauxite, copper, gold, iron ore, lead, nickel, phosphate, silver, tin, cobalt, molybdenum, platinum, and lithium). The values are reported in real chained 2019 US dollars, calculated using the Törnqvist volume index method. Individual sub-components of non-renewable natural capital are not calculated using the Törnqvist index, as their trends follow changes in physical volumes expressed in real 2019 chained US dollars.
R (NW.NCA.TOTL.TO)	Renewable natural capital includes assets such as agricultural land (cropland and pastureland), forests (timber, and three ecosystem services: water, recreation, and non-wood forest products), mangroves, marine fish stocks, and hydropower. The values are reported in real chained 2019 US dollars, calculated using the Törnqvist volume index method.

Source: World Bank (2024), https://databank.worldbank.org/source/wealth-accounts.

3.2 New empirical evidence

3.2.1 Analysis of the production factors

We use the production factors coming from the Wealth Accounts database[15] provided by the World Bank. The variables are described in Table 8. The data are in constant 2019 USD. Figure 5 shows the evolution of production factors using an index set to 100 in 1995. We distinguish three categories. At the global level, physical capital K_t has shown the strongest growth, while renewable natural capital R_t has grown only marginally. Human capital L_t and non-renewable resources N_t have experienced similar growth trends, although the trajectory for N_t has been more erratic. In Table 9, we obtain the following figures: the average annual growth rate is 2.8% for the physical capital, 1.6% for human capital, 1.2% for non-renewable resources and 0.2% for renewable resources.

Table 9: Statistics of the production factors (global, 1995–2020)

Statistic	K_t	L_t	N_t	R_t	Total
Value in 1995 (in \$ tn)	131.60	358.04	17.02	44.34	550.99
Value in 2020 (in \$ tn)	263.55	526.37	22.96	46.89	859.77
Annual growth rate (in %)	2.82	1.55	1.20	0.22	1.80
Share in 1995 (in %)	23.88	64.98	3.09	8.05	100.00
Share in 2020 (in %)	30.65	61.22	2.67	5.45	100.00
Share in 2100 (estimated)	55.86	41.48	1.37	1.29	100.00

[15]The data are available at https://databank.worldbank.org/source/wealth-accounts.

Figure 5: Evolution of production factors (global, 1995–2020)

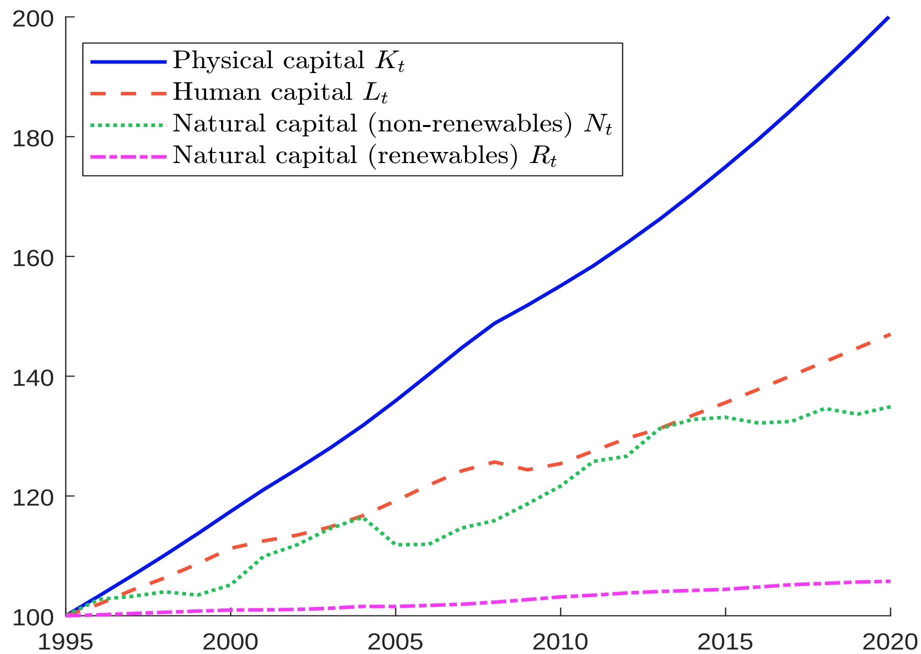
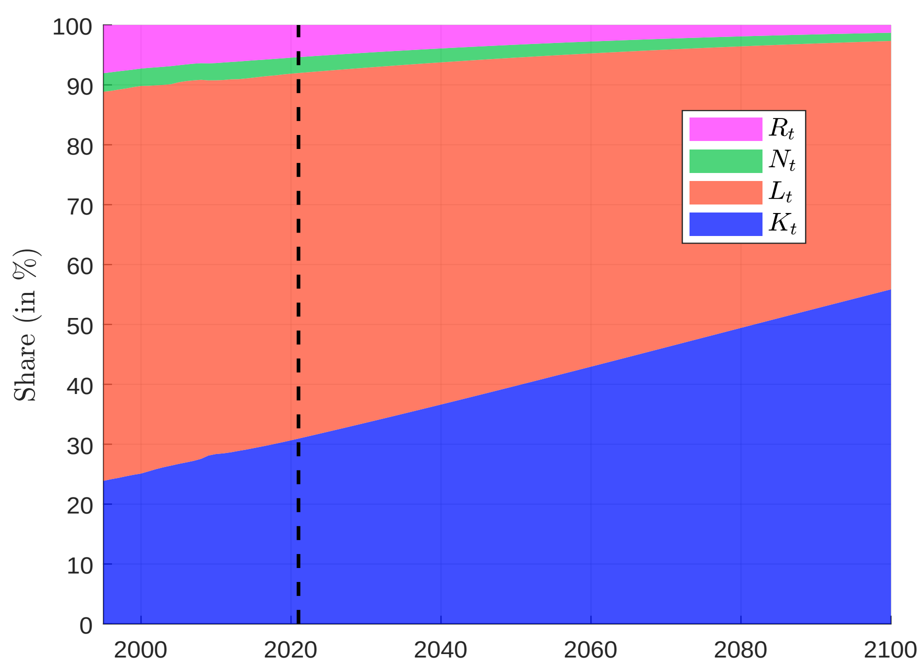


Figure 6: Total capital by component and projected trends (global, 1995–2100)

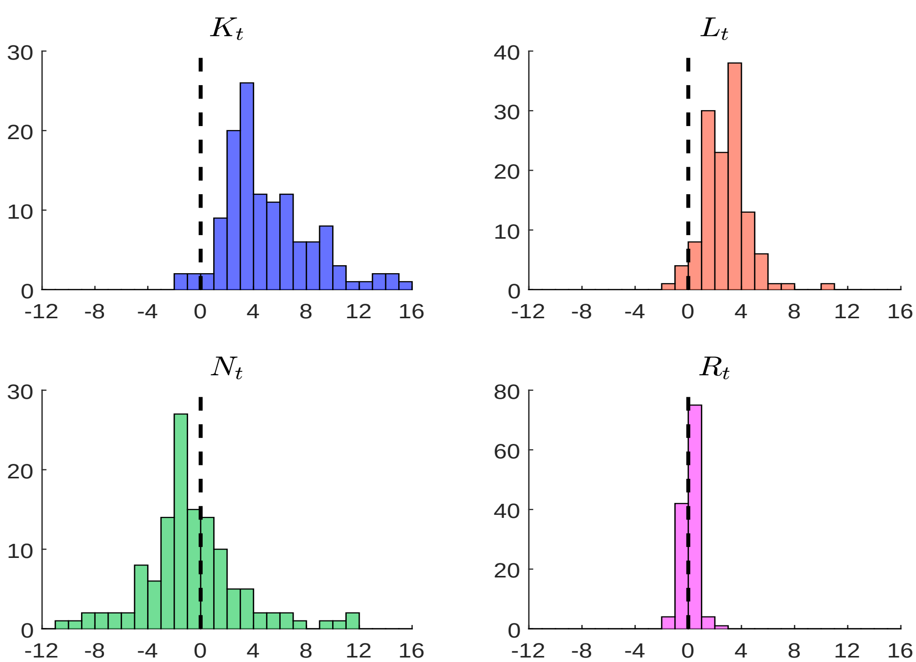


These differences in growth rates raise important questions about the sustainability of economic growth. Let us consider two factors $F_{1,t}$ and $F_{2,t}$, with respective growth rates g_1 and g_2. We define their evolution as $F_{j,t} = F_{j,0}\left(1+g_j\right)^t$. It follows that:

$$\frac{F_{2,t}}{F_{1,t}} = \frac{F_{2,0}}{F_{1,0}}\left(\frac{1+g_2}{1+g_1}\right)^t$$

If $g_1 \gg g_2$, the ratio $\dfrac{F_{2,t}}{F_{1,t}}$ rapidly tends toward zero, regardless of the initial allocation $\left(F_{1,0}, F_{2,0}\right)$. Based on historical growth rates from 1995 to 2020, we have projected the values of each production factor and computed the breakdown of total capital for the period 2021 to 2100. The results are presented in Figure 6. We observe a substantial increase in produced (physical) capital, to the detriment of human capital. *Ceteris paribus*, the projections indicate that physical capital will match human capital by 2075, with each accounting for approximately 48% of total capital. At the same time, we observe a sharp decline in natural capital, with the projected shares of non-renewable and renewable resources both falling to around 1.3% by 2100 (Table 9). This leads to a critical question: Is it possible to sustain economic growth with such low levels of natural capital among production factors?

Figure 7: Histogram of annual growth in % (all countries, 1995–2020)



We replicate the previous analysis by examining individual countries rather than the world region[16]. In Appendix on pages 51 and 52, we present the evolution of the production factors K_t, L_t, N_t, and R_t for the twelve richest nations in 2020. Significant disparities emerge across these countries. For China and India, the index values are set to 10 and 50,

[16]The original World Bank database includes information from 151 countries. However, some countries have missing data, particularly regarding natural capital. This is either because some countries are relatively new, such as Montenegro and Serbia, or because the data are unavailable, as is the case for Luxembourg, Haiti, and Sudan. Consequently, we excluded countries with at least one missing value for any of the four production factors. This results in a filtered dataset of 126 countries with complete data from 1995 to 2020.

respectively, due to the exceptionally large growth in physical capital, which makes direct comparison with other countries difficult. Overall, we observe an increase in both physical and human capital over the period, while the trends in natural capital vary considerably. Figure 7 displays a histogram of annual growth rates across a broader set of 126 countries. It shows that natural capital behaves quite differently from physical and human capital. The latter exhibit positive skewness, with few negative values. However, this is not the case for natural capital. Over long periods, growth in natural capital can be either positive or negative. Therefore, the four forms of capital do not have the same status within the production function.

3.2.2 Estimation of Cobb-Douglas production function

By combining the data on production factors with the GDP metric from the World Bank database[17], we estimate the following Cobb-Douglas production function at the global level:

$$\ln Y_t = c + \alpha \ln K_t + \beta \ln L_t + \gamma \ln N_t + \delta \ln R_t + \varepsilon_t$$

where the variables represent aggregated values across countries. The estimated coefficients are reported in Tables 10 and 11, with and without the inclusion of natural capital components. However, this first model is unsatisfactory because only physical capital appears statistically significant. Aggregating data across countries likely smooths out country-specific business cycles, resulting in less reliable parameter estimates. Moreover, when we compute the correlation matrix of annual growth rates (see Figure 19 on page 53), we observe negative correlations between (K_t, L_t) and (N_t, R_t). However, when we perform the analysis to the set of the 126 filtered countries, the results are markedly different. We observe positive correlations between the same variables (see Figure 20 on page 53). These discrepancies highlight how aggregation can obscure important information about the dependencies among production factors.

Table 10: Estimated Cobb-Douglas function without natural capital (global, 1995–2020)

Parameter	estimate	stderr	t-statistic	p-value
c	-11.6014	6.1323	-1.8918^{*}	0.0712
α	0.8748	0.2015	4.3406^{***}	0.0002
β	0.4309	0.3775	1.1415	0.2654

Table 11: Estimated Cobb-Douglas function with natural capital (global, 1995–2020)

Parameter	estimate	stderr	t-statistic	p-value
c	-28.6165	25.9780	-1.1016	0.2831
α	0.6699	0.2925	2.2905^{**}	0.0324
β	0.6536	0.4568	1.4308	0.1672
γ	0.1088	0.1601	0.6798	0.5040
δ	0.4104	0.8784	0.4673	0.6451

To address this limitation, we consider the following panel regression model with fixed effects and a common time trend:

$$\ln Y_{i,t} = (c + \psi_i + \eta t) + \alpha \ln K_{i,t} + \beta \ln L_{i,t} + \gamma \ln N_{i,t} + \delta \ln R_{i,t} + \varepsilon_{i,t}$$

[17] The data are available at https://databank.worldbank.org/source/world-development-indicators.

Table 12: Estimated Cobb-Douglas function without natural capital (all countries, 1995–2020, no trend)

Parameter	estimate	stderr	t-statistic	p-value
c	3.6655	0.3382	10.6885***	0.0000
α	0.4861	0.0107	45.3592***	0.0000
β	0.3385	0.0204	16.6147***	0.0000

Table 13: Estimated Cobb-Douglas function with natural capital (all countries, 1995–2020, no trend)

Parameter	estimate	stderr	t-statistic	p-value
c	−1.0459	1.2022	−0.8606	0.3895
α	0.4771	0.0109	43.6855***	0.0000
β	0.3446	0.0204	16.8984***	0.0000
γ	0.0015	0.0064	0.2366	0.8130
δ	0.1873	0.0469	3.9921***	0.0001

where $Y_{i,t}$ denotes the GDP of country i at time t. This specification accounts for country-specific heterogeneity and temporal dynamics, providing a more nuanced understanding of the role of capital factors. The results are notably improved (see Tables 12 and 13). The estimated output elasticities of physical capital, labor, and renewable natural resources are all statistically significant at the 1% level. Moreover, the sum of the output elasticities is approximately equal to one, suggesting constant returns to scale:

$$\hat{\alpha} + \hat{\beta} + \hat{\gamma} + \hat{\delta} = 0.4771 + 0.3446 + 0.0015 + 0.1873 = 1.0105$$

These results support the consistency of the Cobb-Douglas specification in capturing production dynamics at the country level when accounting for heterogeneity.

Table 14: Estimated Cobb-Douglas function with natural capital (all countries, 1995–2020, with trend)

Parameter	estimate	stderr	t-statistic	p-value
c	6.9421	1.0693	6.4018***	0.0000
η	0.0193	0.0006	32.4403***	0.0000
α	0.3365	0.0104	32.3475***	0.0000
β	0.0787	0.0195	4.0455***	0.0001
γ	0.0422	0.0057	7.3999***	0.0000
δ	0.2437	0.0407	5.9934***	0.0000

When a trend is included, the estimated parameter $\hat{\eta}$ is positive, capturing part of the underlying dynamics of physical and human capital (Table 14). This helps explain the lower estimated values of $\hat{\alpha}$ and $\hat{\beta}$ (0.3365 vs. 0.4771 for physical capital, and 0.0787 vs. 0.3446 for the human capital, respectively). However, the sum of the output elasticities is reduced to approximately 70%, indicating a deviation from constant returns to scale under this specification. Another issue concerns the autocorrelation of residuals, denoted by $\rho_h = \rho\left(\varepsilon_{i,t}, \varepsilon_{i,t-h}\right)$. Indeed, we observe a first-order autocorrelation of 78%, which is considerably high (Table 17), potentially signaling model misspecification or the presence of omitted dynamic effects.

Table 15: Estimated Cobb-Douglas function with natural capital (all countries, 1995–2020, with trend, first difference)

Parameter	estimate	stderr	t-statistic	p-value
c	0.0187	0.0088	2.1581**	0.0310
η	−0.0013	0.0001	−11.8717***	0.0000
α	0.4353	0.0297	14.6421***	0.0000
β	0.3592	0.0385	9.3255***	0.0000
γ	0.0008	0.0044	0.1832	0.8547
δ	0.0285	0.0249	1.1438	0.2528

Table 16: Estimated Cobb-Douglas function with natural capital (all countries, 1995–2020, with trend, first difference, constant returns to scale)

Parameter	estimate	stderr	t-statistic	p-value
c	0.0149	0.0087	1.7035*	0.0830
η	−0.0013	0.0001	−11.9236***	0.0000
α	0.4793	0.0270	17.7455***	0.0000
β	0.4461	0.0295	15.1090***	0.0000
γ	0.0019	0.0044	0.4309	0.6665
δ	0.0727	0.0215	3.3801***	0.0007

Table 17: Estimated autocorrelation function ρ_h

h	0	1	2	3	4	5
Table (14)	100%	78.3%	61.3%	46.0%	31.7%	18.9%
Table (15)	100%	19.3%	5.1%	2.9%	1.1%	−5.6%
Table (16)	100%	19.2%	5.4%	3.2%	1.3%	−5.5%

To obtain stationary residuals, we apply first differences to the variables:

$$\ln \frac{Y_{i,t}}{Y_{i,t-1}} = (c + \psi_i + \eta t) + \alpha \ln \frac{K_{i,t}}{K_{i,t-1}} + \beta \ln \frac{L_{i,t}}{L_{i,t-1}} + \gamma \ln \frac{N_{i,t}}{N_{i,t-1}} + \delta \ln \frac{R_{i,t}}{R_{i,t-1}} + \varepsilon_{i,t}$$

Results are given in Table 15. This new specification has significantly reduced the autocorrelation of the residuals, with ρ_1 now equal to 19%, and the remaining autocorrelation coefficients at or below 5%. The differences between Tables 14 and 15 are as follows. First, the trend remains statistically significant but has now turned negative. In the level specification, the positive trend was likely due to non-stationarity, capturing the upward trajectory of GDP, physical capital, and human capital over time. When using growth rates instead, the trend becomes negative, likely reflecting a recent slowdown in economic growth compared to the past. Second, the coefficient on human capital has increased substantially, from 0.0787 to 0.3592. Third, both non-renewable and renewable resource variables are not statistically significant, although their coefficients are still positive. Additionally, the sum of the output elasticities is equal to 0.82. Therefore, we proceed with a final estimation approach in which we impose the constraint of constant returns to scale. The corresponding results are reported in Table 16. This new specification yields improved results. While it does not significantly alter the estimated parameters c, η, α, β, and γ, it improves the estimation of δ. Moreover, the autocorrelations of residuals remain low (DW = 1.6235). The estimated Cobb-Douglas function is then equal to:

$$Y_{i,t} = A_i e^{-0.001t} K_{i,t}^{0.479} L_{i,t}^{0.446} N_{i,t}^{0.002} R_{i,t}^{0.073}$$

Table 18: Estimated Cobb-Douglas function with natural capital (all countries, 1995–2020, with trend, first difference, constant returns to scale)

Sample	(a)	(b)	(c)	(d)	(e)	(f)
c	0.0149*	0.0125	0.0163*	0.0160***	0.0134	0.0300***
η	−0.0013***	−0.0008***	−0.0013***	−0.0013***	−0.0013***	−0.0016***
α	0.4793***	0.3386***	0.4967***	0.3399***	0.5194***	0.3754***
β	0.4461***	0.5357***	0.3546***	0.6621***	0.3877***	0.2877***
γ	0.0019	−0.0017	0.0024	0.0007	0.0016	0.0034
δ	0.0727***	0.1275***	0.1462***	−0.0028	0.0912**	0.3336***
R^2	51.7%	52.0%	51.2%	57.2%	49.2%	66.6%
ρ_1	19.2%	13.2%	20.5%	12.3%	19.6%	22.6%
DW	1.62	1.83	1.63	1.64	1.65	1.47
n	126	50	90	36	76	14
$\bar{w}_K$	18.9%	24.1%	14.5%	29.7%	13.9%	17.9%
$\bar{w}_L$	55.3%	60.8%	50.9%	66.0%	49.3%	59.4%
$\bar{w}_N$	7.5%	6.7%	10.2%	0.7%	9.1%	15.8%
$\bar{w}_R$	18.4%	8.4%	24.4%	3.3%	27.7%	6.9%
$\bar{y}$ (in \$)	13 153	24 258	6 157	30 645	3 029	23 133

(a) Full sample with all countries ($n = 126$)

(b) Top 50 richest countries ($n = 50$)

(c) Countries whose share of natural capital is greater than 10% ($n = 90$)

(d) Countries whose share of natural capital is less than 10% ($n = 36$)

(e) Countries with natural capital share > 10% and GDP per capita < \$10 000 in 2020 ($n = 76$)

(f) Countries with natural capital share > 10% and GDP per capita ≥ \$10 000 in 2020 ($n = 14$)

We have estimated the previous model using several country samples to understand how the parameters vary depending on the scope of the analysis. Results are presented in Table 18. For each sample, we have calculated the average weight in 2020 of each factor in the production function[18], and the average GDP per capita. Sample (a) corresponds to the full dataset of 126 countries. Sample (b) includes the top 50 richest countries in terms of GDP in 2020. The results are similar to those of the full sample, but the coefficients for human capital and renewable resources are slightly higher. Samples (c) and (d) categorize countries based on their natural capital share, using a 10% threshold. It appears that the coefficient δ (associated with renewable resources) is only significant for countries with a natural capital share above 10%. In Sample (c), the output elasticity of renewable resources is 14.62%, which is relatively high. In contrast, δ is not significant when the natural capital share is below 10% — see Sample (d). Furthermore, we divided the 90 countries with a natural capital share above 10% into two groups based on income: those with a GDP per capita below \$10,000 (Sample e), and those above this threshold (Sample f). The high elasticity observed in Sample (c) is not driven by the lower-income group. In Sample (e), the output elasticity of renewable resources reaches 9.12%, while it is equal to 33.36% in Sample (f). In all cases, the coefficient of non-renewable resources (γ) is close to zero and not significant. One possible explanation is that the exploitation of non-renewable resources may not contribute directly to productivity in a sustainable way, because their economic benefits are offset by volatility and other factors. Adopting a yearly frequency is certainly inadequate for this type of production factor.

[18] We have:

$$w_{i,K} = \frac{K_{i,t}}{K_{i,t} + L_{i,t} + N_{i,t} + R_{i,t}}$$

and $\bar{w}_K = n^{-1} \sum_{i=1}^{n} w_{i,K}$ where n is the number of countries in the sample.

Table 19: Estimated Cobb-Douglas function with natural capital (all countries, 1995–2020, with trend, first difference, constant returns to scale)

Sample	(a) Global	(g) G20	(h) BRICS+	(i) N-11	(j) OECD	(k) Non-OECD	(l) OPEC	(m) HIPC	(n) N (top 25)	(o) R (top 25)
c	0.0149*	0.0043	0.0145*	−0.0080	0.0140***	0.0155	0.0213	0.0151	0.0320**	0.0147
η	−0.0013***	−0.0008***	−0.0007**	−0.0001	−0.0011***	−0.0014***	−0.0021**	−0.0013***	−0.0019***	−0.0009***
α	0.4793***	0.5361***	0.4707***	0.5913***	0.3800***	0.5037***	0.1233	0.4487***	0.3167***	0.3930***
β	0.4461***	0.5303***	0.1592*	0.2757***	0.6348***	0.3958***	0.6712***	0.4823***	0.4720***	0.4402***
γ	0.0019	−0.0076	0.0138	−0.0043	0.0002	0.0027	−0.0016	−0.0074	−0.0008	0.0036
δ	0.0727***	−0.0588	0.3563***	0.1373*	−0.0150	0.0978***	0.2070	0.0764	0.2121***	0.1632**
R^2	51.7%	66.4%	70.7%	72.2%	63.9%	50.4%	25.4%	50.8%	42.3%	54.8%
ρ_1	19.2%	11.5%	24.5%	17.9%	5.0%	22.9%	26.9%	14.7%	26.6%	21.2%
DW	1.62	1.69	1.54	1.65	1.86	1.61	1.75	1.69	1.60	1.60
n	126	19	10	11	33	93	9	29	31	31
$\bar{w}_K$	18.9%	27.1%	14.4%	16.0%	30.0%	14.9%	16.9%	10.0%	15.4%	8.6%
$\bar{w}_L$	55.3%	63.0%	56.2%	56.1%	64.9%	51.8%	40.7%	45.9%	39.0%	41.7%
$\bar{w}_N$	7.5%	3.0%	13.0%	7.8%	1.3%	9.6%	27.5%	7.1%	25.0%	5.2%
$\bar{w}_R$	18.4%	6.9%	16.4%	20.1%	3.7%	23.6%	14.9%	37.0%	20.5%	44.4%
$\bar{y}$ (in $)	13 153	24 741	9 002	7 036	33 874	5 801	12 090	1 367	9 557	1 484

(a) Global: All countries included in the dataset ($n = 126$)

(g) G20: The 20 largest world economies ($n = 19$)

(h) BRICS+: Group of emerging countries ($n = 9$)

(i) N-11: The Next Eleven — Developing countries with high growth potential ($n = 10$)

(j) OCDE: Member countries of the Organisation for Economic Co-operation and Development ($n = 33$)

(k) Non-OCDE: Countries not part of the OECD ($n = 93$)

(l) OPEC: Organization of the petroleum exporting countries ($n = 9$)

(m) HIPC: Heavily indebted poor countries ($n = 29$)

(n) N (top 25): Top 25% of countries where non-renewable resources account for the largest share of total capital ($n = 31$)

(o) R (top 25): Top 25% of countries where renewable resources account for the largest share of total capital ($n = 31$)

The previous construction of country samples was based on statistical clustering. In this analysis, we examine several groups of countries organized by affiliation: G20, BRICS+, Next Eleven (N-11), OECD, non-OECD, OPEC, and HIPC. Additionally, we introduce two other categories: the top 25% of countries with the highest proportions of renewable and non-renewable resources. The results are presented in Table 19. Across all groups, the coefficient γ for non-renewable natural capital is not statistically significant. This supports the earlier hypothesis that the exploitation of non-renewable resources may not directly contribute to sustainable productivity. In the case of G20 countries, we observe increases in α and β relative to the global results. Here, renewable natural capital becomes insignificant, a pattern also observed among OECD countries. Conversely, the BRICS+ and N-11 groups show an increase in the coefficient δ, accompanied by an increase in α and a decrease in β. These findings suggest a greater importance of physical and renewable natural capital, with relatively less emphasis on human capital. Based on these findings, we hypothesize that the coefficient δ is significant for countries where the share of renewable natural capital exceeds 10%. However, this hypothesis does not apply to OPEC and HIPC countries. Additionally, the R^2 values indicate that the BRICS+ and N-11 groups provide the best model fits. Nevertheless, drawing definitive conclusions remains challenging. Although we might expect more developed countries to rely more on physical and human capital for growth, and developing countries to depend more on natural capital, the data also suggest that a country's wealth plays a critical role (see the last row, which shows GDP per capita). This again highlights the complex relationship between economic growth and wealth.

3.2.3 Contribution of natural capital to economic growth

To assess the contribution of natural capital to economic growth between 1995 and 2020, we calculate the growth rates $g_{i,N}$ and $g_{i,R}$ of non-renewable and renewable natural capital, respectively, for each country i over the period 1995–2020. Based on these, we derive the contributions $c_{i,N} = \hat{\gamma} g_{i,N}$ and $c_{i,R} = \hat{\delta} g_{i,R}$ to economic growth. Since a given country may belong to multiple samples or groups[19] $\mathcal{G}_j$ (*e.g.*, BRICS+, OECD, G20), we compute the mean contributions as follows:

$$\mu\left(c_{i,N}\right) = \frac{\sum_{j=1}^{15} \mathbb{1}\left\{i \in \mathcal{G}_j\right\} \hat{\gamma}_j g_{i,N}}{\sum_{j=1}^{15} \mathbb{1}\left\{i \in \mathcal{G}_j\right\}} \text{ and } \mu\left(c_{i,R}\right) = \frac{\sum_{j=1}^{15} \mathbb{1}\left\{i \in \mathcal{G}_j\right\} \hat{\delta}_j g_{i,R}}{\sum_{j=1}^{15} \mathbb{1}\left\{i \in \mathcal{G}_j\right\}}$$

Results[20] are shown in Figures 8 and 9. To understand the magnitude of these contributions, we calculate below the total economic growth over 25 years — the study period between 1995 and 2020 — under different assumptions of annual economic growth rate:

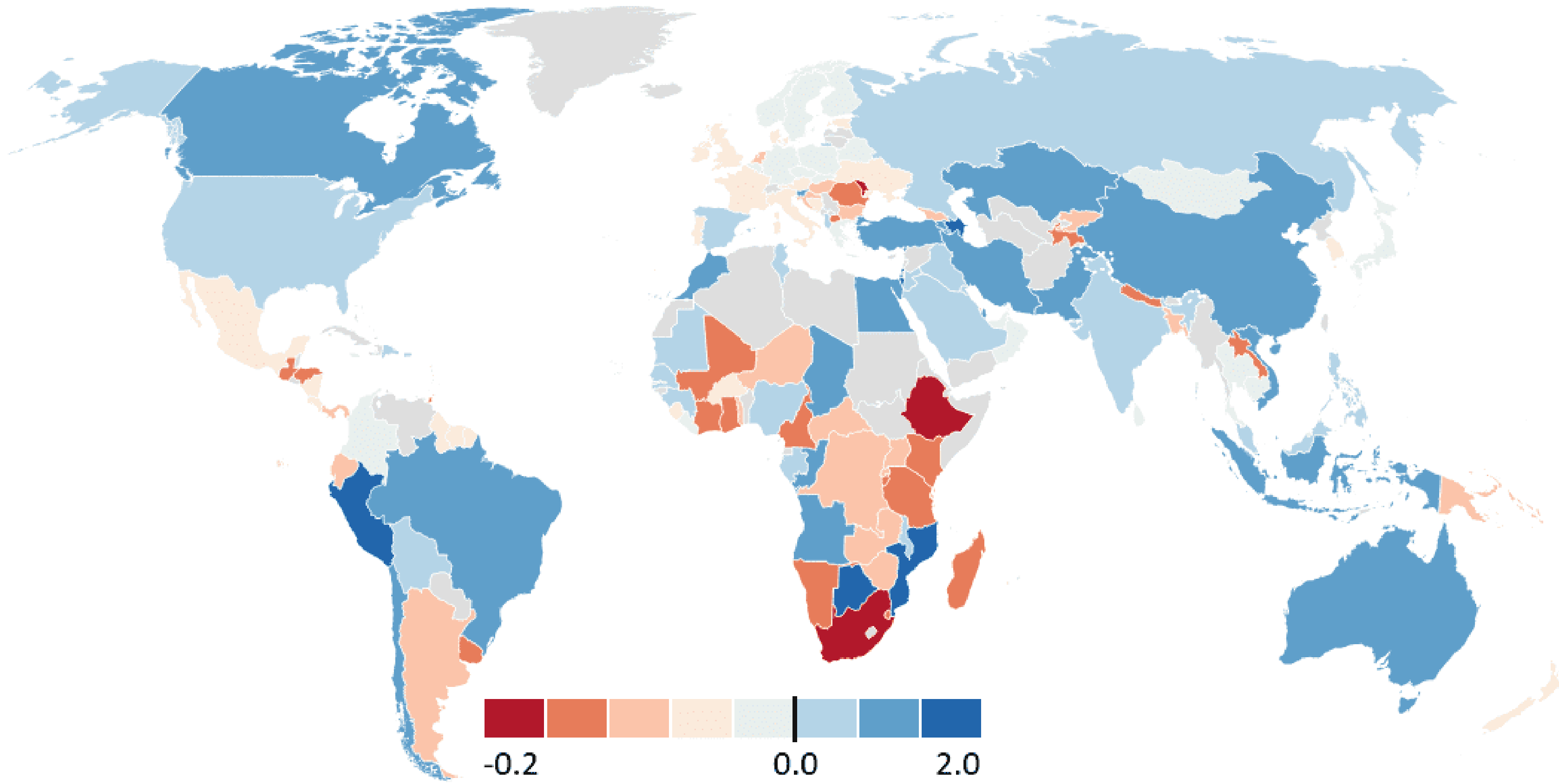
g_Y (1Y)	0.5%	1.0%	1.5%	2.0%	3.0%	4.0%	5.0%	6.0%
g_Y (25Y)	13.3%	28.2%	45.1%	64.1%	109.4%	166.6%	238.6%	329.2%

For example, an annual economic growth rate of 2% implies a total economic growth of 64.1% between 1995 and 2020. The results suggest that, for most countries, the contribution $\mu\left(c_{i,N}\right)$ is close to 0%, with low dispersion. Countries in the HIPC group mostly exhibit negative contributions, which are strongly linked to their highly negative value of γ. In contrast, the contributions $\mu\left(c_{i,R}\right)$ display greater variability, ranging from -3.65% in Iran to 9.16% in Vietnam. The results are robust, as the standard deviation is generally below

[19]For example, the United States belongs to groups (a), (b), (d), (g), and (j), while China belongs to groups (a), (b), (c), (f), (g), (h), and (k).

[20]The mean values $\mu\left(c_{i,N}\right)$ and $\mu\left(c_{i,R}\right)$ are reported in Table 21 on page 56. We also report the standard deviations $\sigma\left(c_{i,N}\right)$ and $\sigma\left(c_{i,R}\right)$ for each country i, along with their total economic growth g_Y over the period 1995–2020.

Figure 8: Average contribution $\mu\left(c_{i,N}\right)$ of non-renewable natural capital to economic growth (1995–2020, in %)



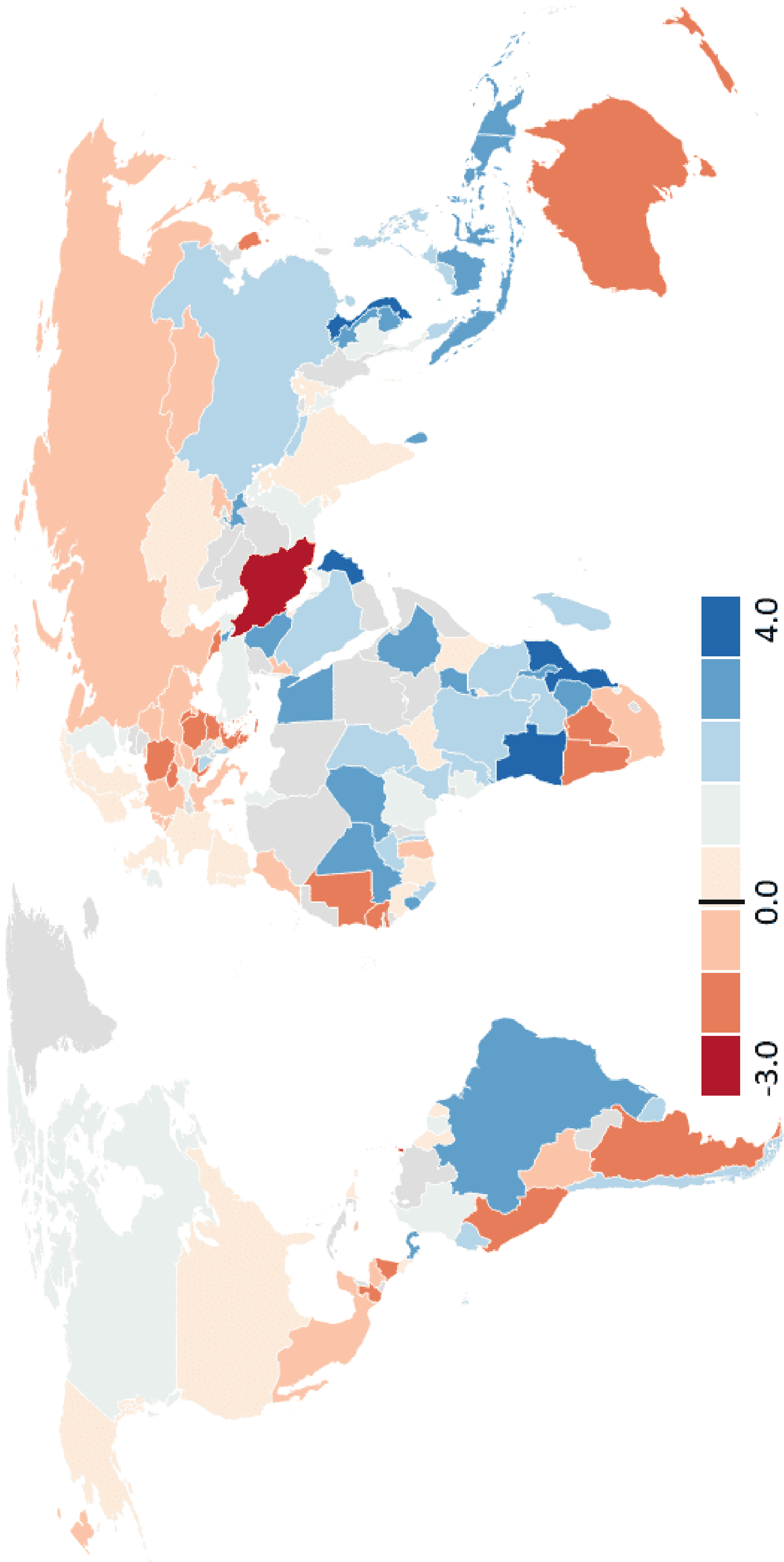


Figure 9: Average contribution $\mu\left(c_{i,R}\right)$ of renewable natural capital to economic growth (1995–2020, in %)

1 for all countries. Countries in the BRICS+ group exhibit greater dispersion. This may be explained by the higher weight of natural capital in their production functions, which makes their economic growth more sensitive to variations in R. However, the magnitude of these contributions remains generally low. For instance, the figures of -3.65% in Iran to 9.16% in Vietnam should be compared to their overall economic growth of 107% and 385%, respectively, during the same period (1995–2020).

3.3 Stress testing scenarios

In this section, we use the estimated coefficients from the previous section to conduct a nature-related scenario analysis, specifically a stress testing exercise based on the worst-case approach (Roncalli, 2020, Chapter 14). The stress scenario for country i and time horizon T is estimated as follows[21]:

$$\mathbb{S}_N(T) = \hat{\gamma}_{\max}\left(\left(1 + g_N^{\mathrm{wcs}}\right)^T - 1\right)$$

where $\mathbb{S}_N(T)$ is the stress test value, $\hat{\gamma}_{\max} = \max_j \left(\mathbb{1}\left\{i \in \mathcal{G}_j\right\}\hat{\gamma}_j\right)$ is the maximum elasticity of natural capital to economic growth, and g_N^{wcs} is the worst-case scenario on natural capital[22]. To estimate g_N^{wcs}, we consider two approaches: the first is a historical approach, while the second is a parametric method based on skew distributions. These estimates are further complemented by a third approach based on extreme value theory.

3.3.1 Historical stress testing

To conduct historical stress testing, we estimate g_N^{wcs} as the average of the five worst historical scenarios, that is the average of the five lowest values of $N_{i,t}/N_{i,t-1}-1$. Thus, g_N^{wcs} represents the average annual growth of natural capital during the five worst years. Since $g_N^{\mathrm{wcs}} \leq 0$ and $\hat{\gamma}_{\max} \geq 0$, the resulting stress value $\mathbb{S}_N$ is negative. We have reported the stress values in Table 22 on page 57 and Figure 10. Overall, the stress test values are relatively low. Most countries exhibit a loss less than 0.35%, with the exception of seven countries: South Africa (-1.37%), Brazil (-1.34%), China (-1.27%), Ethiopia (-1.24%), India (-1.26%), Indonesia (-1.23%),and Egypt (-1.15%). These seven countries are all members of the BRICS+ group. The other countries of this group are less affected because of low values of g_N^{wcs}. Concerning countries outside the BRICS+ group, the value taken by $\gamma_{\max}$ is too small to generate high stress test values.

The case of renewable natural capital differs greatly from that of non-renewable natural capital (see Table 22 on page 57 and Figure 11). The median stress test value for N is -0.2%, but for R, it drops significantly to -5.5%. Iran is the most impacted country, with a stress value of -28.65%. The countries with the next highest stress values are the United Arab Emirates (-23.26%), New Zealand (-23.14%), Trinidad and Tobago (-22.32%), Ethiopia (-21.54%), Chile (-19.98%), Poland (-19.94%), and Australia (-17.89%). A total of 24 countries experience stress greater than -10%, and 71 countries experience stress greater than -5%. In South America, Chile and five other countries are heavily impacted: Brazil (-16.6%), Peru (-11.1%), Ecuador (-10.1%), Uruguay (-9.8%), and Guatemala (-8.5%). Other significantly affected countries are located in the Middle East (*e.g.*, Iraq, Turkey, Oman, and Qatar), Africa (*e.g.*, Egypt, Ghana, Zimbabwe, and Zambia), and Europe. In fact, ten European countries have a stress value greater than -8%: Romania (-15.43%),

[21] We omit the index i for the sake of clarity and simplicity.

[22] In the case of renewable natural capital, we have $\mathbb{S}_R(T) = \hat{\delta}_{\max}\left(\left(1 + g_R^{\mathrm{wcs}}\right)^T - 1\right)$.

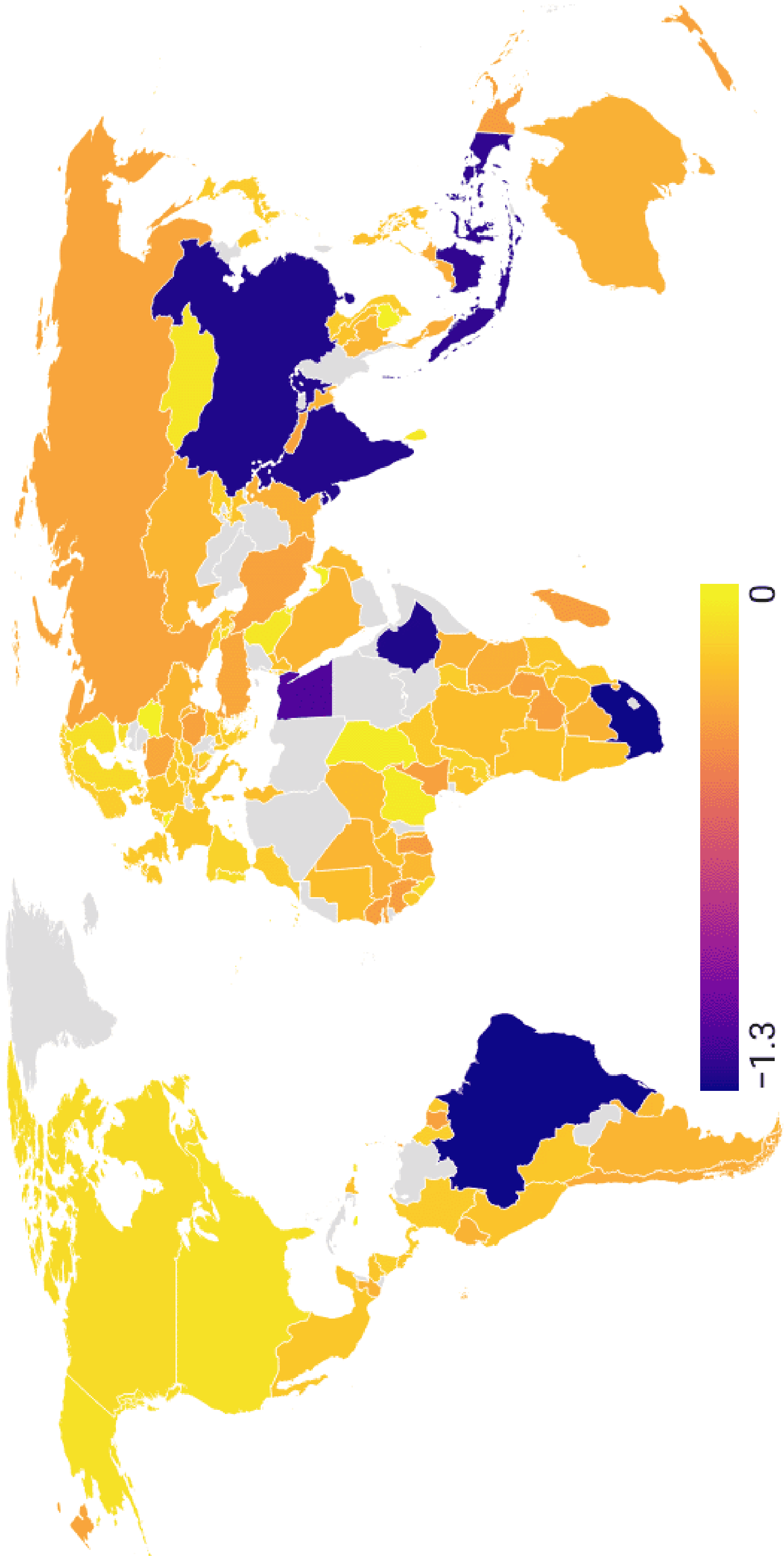


Figure 10: Historical stress test scenario $\mathbb{S}_N(25)$ (in %)

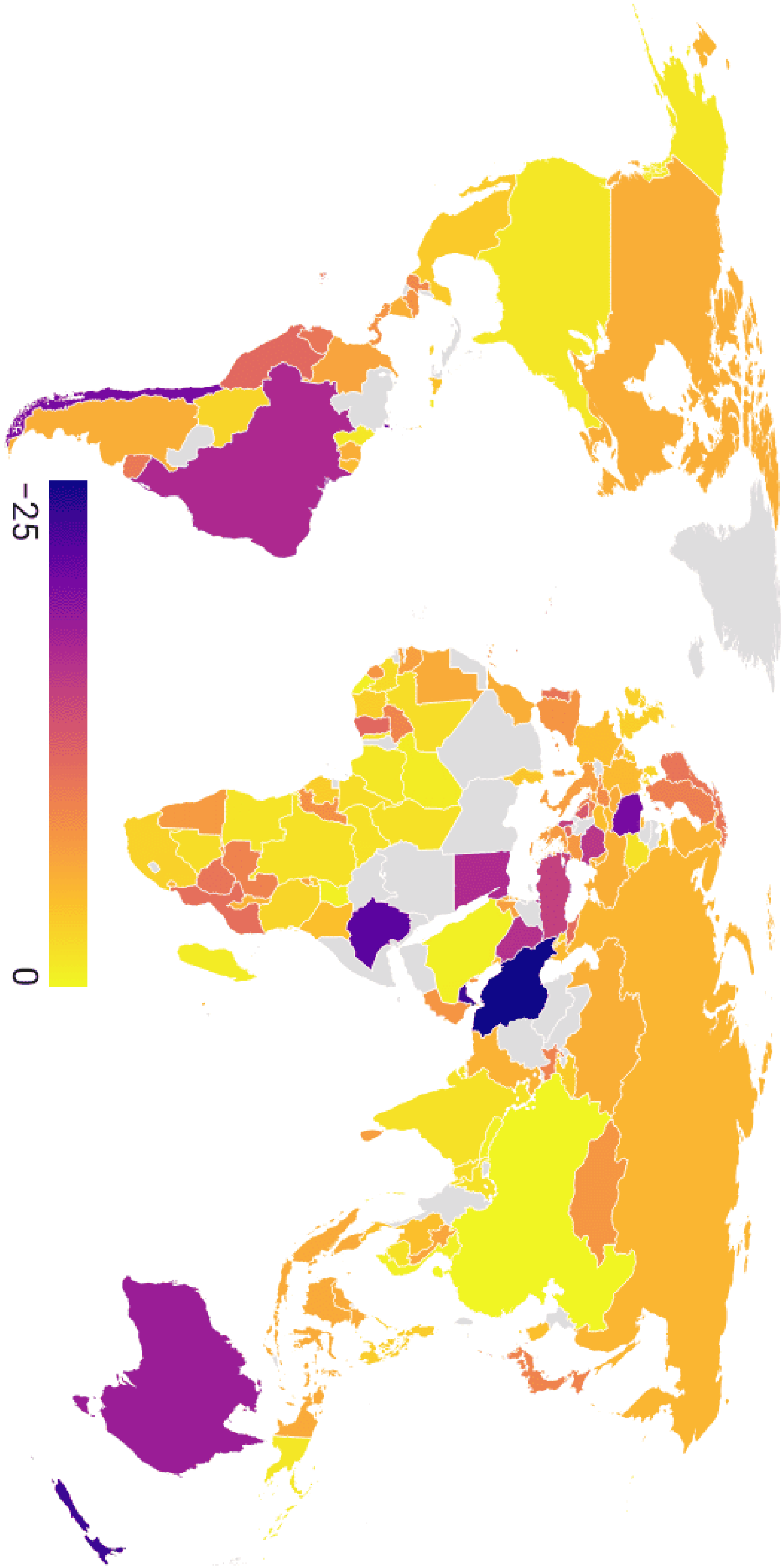


Figure 11: Historical stress test scenario $\mathbb{S}_R(25)$ (in %)

Albania (-14.52%), Bosnia and Herzegovina (-12.43%), North Macedonia (-11.03%), Portugal (-10.18%), Norway (-10.15%), Sweden (-9.3%), Croatia (-9.12%), and Austria (-8.16%). Stress values are generally lower in Asia, except in Tajikistan (-9.05%), Japan (-8.79%), and Mongolia (-7.31%).

3.3.2 Parametric stress testing

The previous approach has the advantage of simplicity but lacks flexibility, and it does not allow for associating a return time or a probability with the scenario. For this reason, we adopt a parametric approach by assuming that the annual growth rate g_N of natural capital follows a skew distribution, for example, the skew t distribution:

$$g_N \sim \mathcal{ST}\left(\xi, \omega^2, \eta, \nu\right)$$

We define the worst case scenario for the annual growth of natural capital as the quantile corresponding to a given low probability level α:

$$g_N^{\text{wcs}}(\alpha) = \mathbf{F}^{-1}(\alpha)$$

where $\mathbf{F}(x)$ is the cumulative distribution function of the skew t distribution. Assuming that the annual growth rates of natural capital are perfectly correlated over time[23], the corresponding stress scenario for economic growth over a time horizon T is given by[24]:

$$\mathbb{S}_N(T, \alpha) = \gamma_{\max}\left(\left(1 + g_N^{\text{wcs}}(\alpha)\right)^T - 1\right)$$

Using the annual growth of natural capital from 1995 to 2020, we calibrate the skew distribution using the method of maximum likelihood. We consider three probability distributions: two skew t distributions with one and four degrees of freedom, and the skew normal distribution, which is the limiting case of the skew t distribution as the degrees of freedom tend to infinity. An example of the calibration is provided in Figure 12. Next, we calculate the parametric stress scenarios and compare them with the historical stress scenarios. On average, across the different countries, the optimal distribution appears to be the skew t distribution with four degrees of freedom. Based on this specification, we obtain the results shown in Table 22 on page 57, and in Figures 14 and 23 on pages 39 and 58, respectively. The results are remarkably consistent with those obtained using the historical approach. We observe a correlation of 98.47% between the two methods for non-renewable natural capital and 94.58% for renewable natural capital. For non-renewable natural capital, the stress scenarios are not particularly significant, as the maximum stress scenario is a 1.3% loss of GDP[25]. This is not the case for renewable natural capital. In fact, 12 countries face stress scenarios exceeding 10% of GDP loss: Ethiopia, Chile, New Zealand, Brazil, Iran, Poland, Australia, Egypt, Romania, Iraq, Türkiye, and the United Arab Emirates. Additionally, 72 countries have a stress scenario greater than 5% of GDP loss, only 16 countries have a stress scenario lower than 2% of GDP loss, and the median value is -5.85%.

[23] One reason is that natural capital is influenced by long-term structural drivers, such as climate change, land degradation, biodiversity loss, and unsustainable extraction of resources. These drivers evolve gradually but persistently over time. Therefore, we can assume that the shocks are structural or persistent.

[24] The return time associated with this scenario is:

$$\mathcal{T} = \frac{T}{\alpha}$$

[25] Only seven countries have a stress greater than 0.50% of GDP loss: Brazil, South Africa, Ethiopia, Indonesia, India, China, and Egypt. The median value is -0.20%, which is low for a 25-year stress period.

Figure 12: Calibrated density function of g_R (China, renewable resources, 1995-2020)

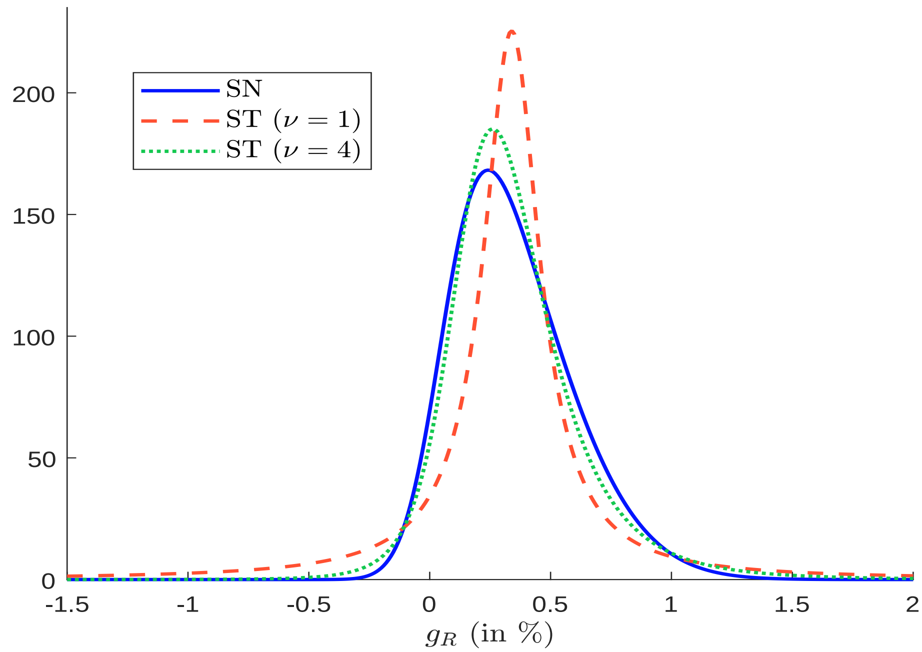


Figure 13: Density function of the smallest order statistic $g_{R,1:25}$ (China, renewable resources, 1995-2020)

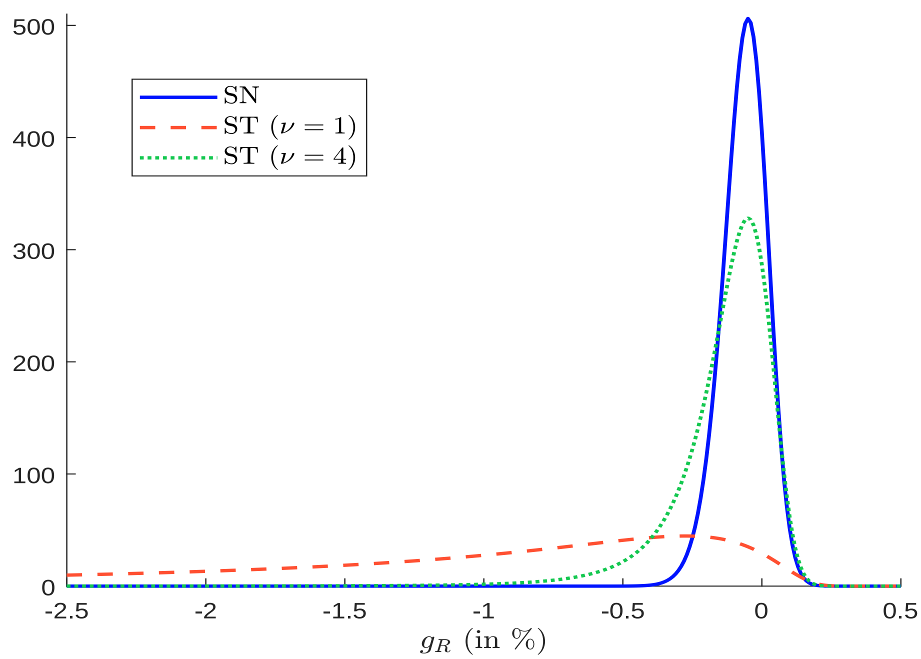
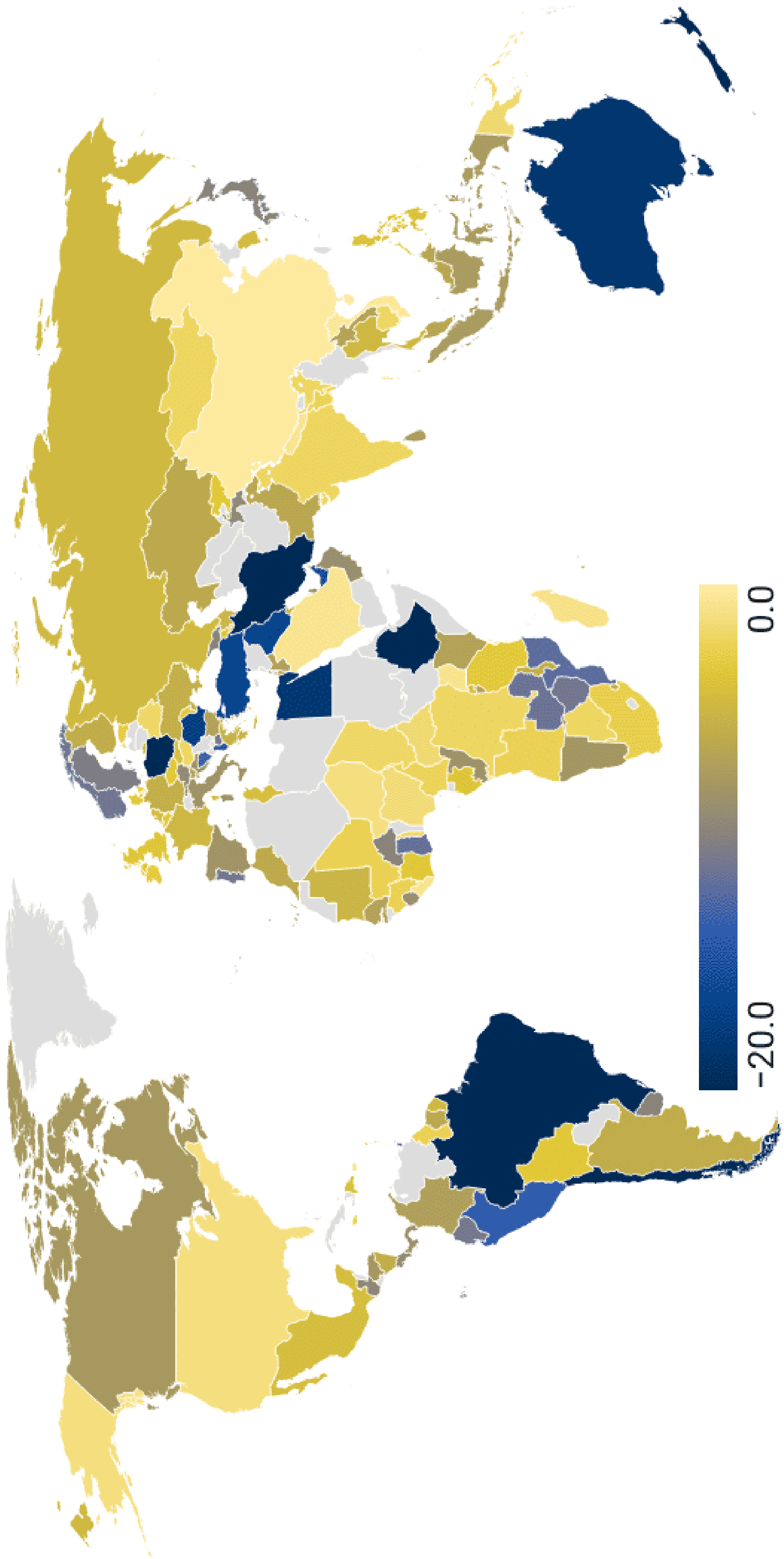


Figure 14: Parametric stress test scenario $\mathbb{S}_R\,(25, 5\%)$ (in %)



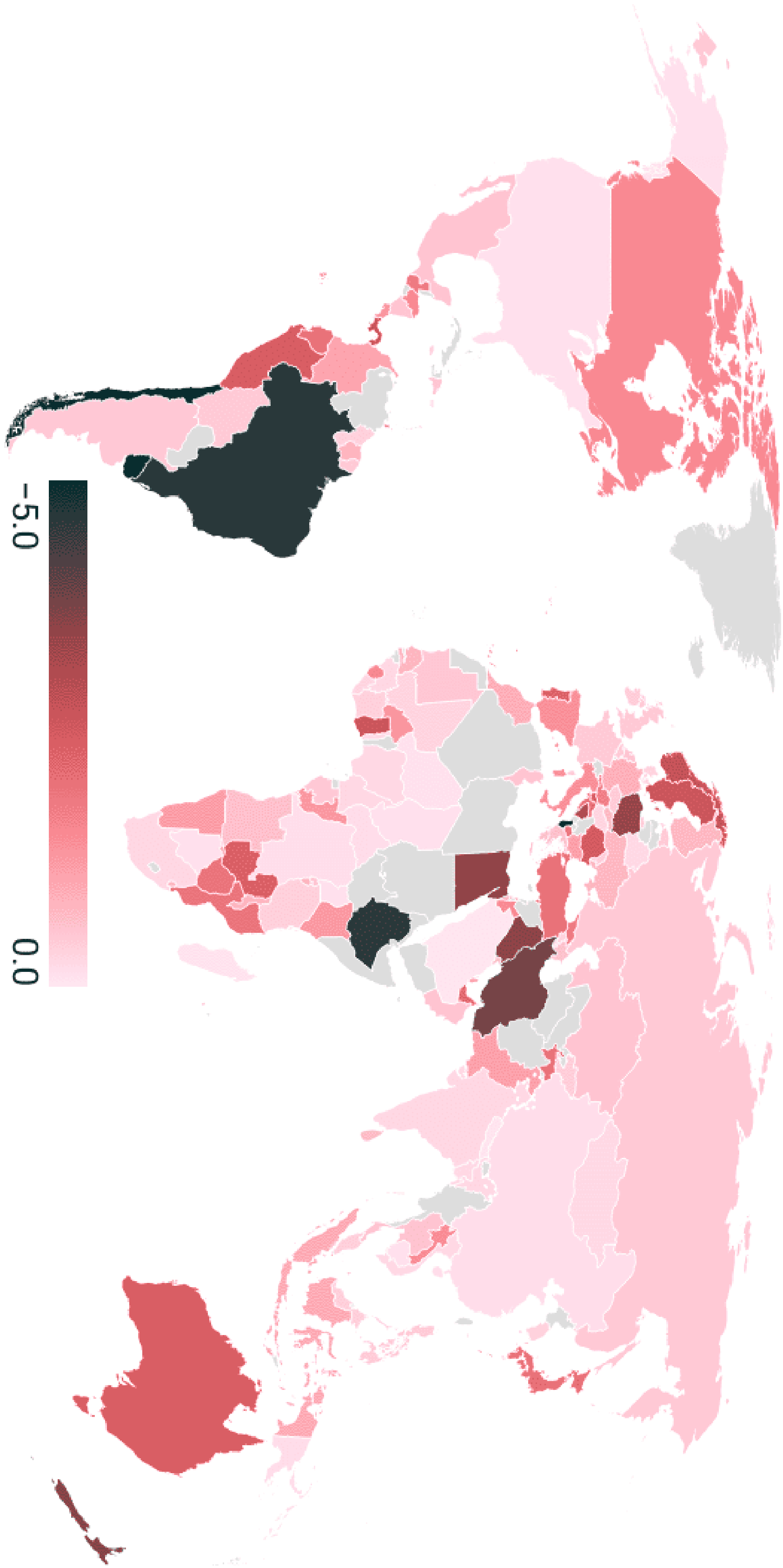


Figure 15: EVT stress test scenario $\mathbb{S}_R(25, 5\%)$ (in %)

3.3.3 EVT stress testing

Generally, parametric stress testing is performed using extreme value theory (EVT), as described by Roncalli (2020, Chapter 12). Two main approaches are typically implemented: one based on modeling block maxima using the generalized extreme value (GEV) distribution, and the other based on tail modeling using the generalized Pareto distribution (GPD). However, in our case, the number of observations in the sample is too small to reliably apply these methods. Therefore, we use the method of order statistics to approximate a stress testing approach within the EVT framework. Let T be the stress testing horizon (*e.g.*, 25 years), and let $\mathbf{F}(x)$ denote the cumulative distribution function (CDF) of annual growth. Since $g_N \sim \mathbf{F}$, the distribution function of the smallest order statistic over the period T is given by:

$$\mathbf{F}_{1:T}(x) = 1 - \left(1 - \mathbf{F}(x)\right)^T$$

We can then deduce the expression of the quantile function:

$$g_N^{\text{evt}}(T, \alpha) = \mathbf{F}_{1:T}^{-1}(\alpha) = \mathbf{F}^{-1}\left(1 - (1 - \alpha)^{1/T}\right)$$

Here, $g_N^{\text{evt}}(T, \alpha)$ is the worst-case scenario for the annual growth of natural capital over a T-year period. Accordingly, the stress scenario is defined as:

$$\mathbb{S}_N(T, \alpha) = \gamma_{\max} \cdot g_N^{\text{evt}}(T)$$

We apply this methodology under the assumption that the annual growth of natural capital follows a skew t distribution, $T = 25$ years and $\alpha = 5\%$. This setup remains consistent with the parametric framework described above. For example, the density function of the smallest order statistic $g_{R,1:25}$, shown in Figure 13, is derived from the density function of g_R presented in Figure 12. As expected, the resulting density is shifted to the left, reflecting the worst-case annual growth over a 25-year period.

Results are given in Table 22 on page 57. How should these figures be interpreted? For example, the parametric stress testing scenario for Brazil indicates a potential loss of 20.49% of GDP over a 25-year period, while the EVT-based stress test estimates a worst-case annual loss of 4.66% for renewable natural capital. This implies that, under the stress scenario, Brazil could lose up to 20.49% of GDP over 25 years, with the most severe single-year contribution being 4.66%. By construction, the EVT stress scenario is lower than and nested within the parametric scenario because it captures the severity of the worst-case event in a single year. For some countries, the cumulative stress over 25 years is driven by a few extreme events. For others, however, it results from the accumulation of several moderate losses across multiple years. Australia is a typical example, with a 25-year parametric stress scenario of 18.36% and an EVT stress scenario of 2.42%. This explains the differences between the maps in Figures 14 and 15.

Remark 4. *The previous analysis can be extended to consider not only the first order statistic but also subsequent ones. Specifically, the parametric stress scenario can be decomposed into contributions from the worst-case outcome, the second worst-case outcome, and the remaining order statistics:*

$$\mathbb{S}_T = \mathbb{S}_{1:T} + \mathbb{S}_{2:T} + \ldots + \mathbb{S}_{\text{residual}} \tag{3}$$

This decomposition enables a more granular understanding of the key drivers behind the cumulative stress. The results are reported in Table 23 on page 60. In some cases, the stress scenario is primarily driven by a single worst year, for example, in the case of China. In contrast, the stress scenarios of other countries are shaped by multiple bad years. For instance, in Saudi Arabia, the five worst years together explain only 22% of the total stress scenario.

4 Conclusion

This paper reexamines the complex and frequently misinterpreted relationship between natural capital and economic growth. Our empirical analysis is based on an extended Cobb-Douglas production function incorporating produced (or physical) capital, labor (or human capital), non-renewable resources, and renewable resources. Using World Bank data, we conduct a panel econometric analysis covering 126 countries from 1995 to 2020. This estimation enables us to quantify the contribution of natural capital to economic growth in various economies. Finally, we use a forward-looking stress-testing framework to evaluate the risks associated with natural capital degradation over a 25-year period ending in 2050.

One of our most notable findings is that the contribution of non-renewable resources to economic growth has not been statistically significant over the past 25 years. Although these assets represent a substantial portion of national wealth, averaging 7.5% of total capital globally[26], their year-to-year variations do not meaningfully affect GDP growth within our econometric framework. The output elasticity associated with non-renewable resources is indistinguishable from zero at conventional significance levels. This result remains robust across multiple country groupings and model specifications. In contrast, renewable natural capital demonstrates a positive and statistically significant output elasticity. This relationship is particularly pronounced in countries where natural capital constitutes a large proportion of overall wealth, including both developing countries and some advanced economies. These results underscore a critical distinction. Not all components of natural capital contribute equally to economic growth. Instead of depleting exhaustible stocks, it appears that the regenerative capacity of renewable systems is more closely aligned with long-term economic performance.

The analysis reveals significant differences among countries regarding the relationship between natural capital and economic growth. While natural capital has contributed positively to the economies of countries such as Vietnam and Indonesia, it has contributed negatively to the economies of countries such as Iran and Australia. These results illustrate that resource endowments alone are insufficient for determining economic performance. These asymmetries highlight the importance of effectively managing and integrating natural capital into productive systems. Our stress-testing framework reinforces this conclusion, showing that the most significant long-term growth risks arise from the degradation of renewable natural capital. Over a 25-year horizon, countries such as Ethiopia, Chile, New Zealand, and Brazil are particularly vulnerable to adverse shocks affecting their renewable resources. Furthermore, decomposing the stress-testing results reveals two distinct risk profiles. In some cases, vulnerability stems from one or two acute shocks. In other cases, vulnerability reflects a more persistent and cumulative erosion of natural capital over time.

These findings have significant implications for economic theory and policy. First, they suggest prioritizing the preservation and enhancement of renewable natural capital, such as forests, fisheries, and agricultural land, over the extraction of non-renewable resources in long-term growth strategies. While non-renewable resources have a relatively modest measured contribution to economic growth, they remain fundamentally important. These resources are essential components of national wealth and income, providing critical ecosystem services that underpin economic activity. Second, these results underscore the need to refine existing economic growth models. Future models should distinguish between different types of natural capital and move beyond treating natural resources as homogeneous

[26] This figure corresponds to the unweighted arithmetic mean across countries. For comparison, the average composition of total capital across the 126 countries in our sample is 18.9% for physical capital, 55.3% for human capital, and 18.4% for renewable natural capital.

production inputs. This more nuanced approach is essential for capturing the diverse and complex ways in which natural capital influences economic performance.

Although our study provides robust empirical evidence, it has limitations. First, using annual data may not fully capture the slow, cumulative effects of environmental degradation or natural capital regeneration. Second, the Cobb-Douglas production function assumes unitary elasticity of substitution between inputs. This restrictive assumption could be relaxed in future research by adopting more flexible functional forms, such as the constant elasticity of substitution (CES) specification. In a general equilibrium framework, output elasticities should correspond to factor shares of total capital. However, this condition is not met in our empirical estimates. Our estimates clearly violate this condition, suggesting potential model misspecification. Future research could extend this work in several ways. For example, it could incorporate explicit damage functions to model environmental feedback, explore alternative data frequencies, or conduct granular, country-level studies. Finally, an important conceptual challenge remains. Our methodology is based on the conventional assumption that economic wealth (a stock) and economic growth (a flow) are two sides of the same coin: economic performance. However, the determinants of wealth and growth may differ substantially, and conflating the two could obscure key dynamics. Distinguishing between wealth and growth is essential for a deeper understanding of the long-term interplay between natural capital and economic development. This distinction is especially important when evaluating the evolution of natural capital over time. Our findings suggest that renewable resources play a more significant role in driving economic growth, while non-renewable resources may play a more prominent role in shaping economic wealth. Future research should explore this hypothesis further, helping clarify how different forms of natural capital contribute to the broader goals of sustainable economic development.

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A Appendix

A.1 Skew distributions

A.1.1 Skew normal distribution

$X \sim \mathcal{SN}\left(\xi, \omega^2, \eta\right)$ follows a skew normal distribution if the density function is:

$$f\left(x\right) = \frac{2}{\omega}\phi\left(\frac{x-\xi}{\omega}\right)\Phi\left(\eta\left(\frac{x-\xi}{\omega}\right)\right)$$

The cumulative distribution function has the following expression:

$$\mathbf{F}\left\{x\right\} = 2\left(\Phi\left(\frac{x-\xi}{\omega}\right) - \Phi_2\left(0, \frac{x-\xi}{\omega}; \delta\right)\right) = 2\Phi_2\left(0, \frac{x-\xi}{\omega}; -\delta\right)$$

where $\delta = \eta/\sqrt{1+\eta^2}$. We note $m_0 = \delta\sqrt{2/\pi}$. The moments of the SN distribution are:

$$\begin{aligned}
\mu\left(X\right) &= \xi + \omega m_0 \\
\sigma^2\left(X\right) &= \omega^2\left(1 - m_0^2\right) \\
\gamma_1\left(X\right) &= \left(\frac{4-\pi}{2}\right)\frac{m_0^3}{\left(1-m_0^2\right)^{3/2}} \\
\gamma_2\left(X\right) &= 2\left(\pi-3\right)\frac{m_0^4}{\left(1-m_0^2\right)^2}
\end{aligned}$$

A.1.2 Skew t distribution

$X \sim \mathcal{ST}\left(\xi, \omega^2, \eta, \mu\right)$ follows a skew t distribution if the density function is:

$$f\left(x\right) = \frac{2}{\omega}t_1\left(\frac{x-\xi}{\omega}; \nu\right)\mathbf{T}_1\left(\eta\left(\frac{x-\xi}{\omega}\right)\sqrt{\frac{\nu+1}{q+\nu}}; \nu+1\right)$$

where $q = \left(x-\xi\right)^2/\omega^2$. The cumulative distribution function has the following expression:

$$\mathbf{F}\left\{x\right\} = 2\mathbf{T}_2\left(0, \frac{x-\xi}{\omega}; -\delta; \nu\right)$$

Let m_0 and v_0 be two scalars defined as follows:

$$\begin{aligned}
m_0 &= \delta\sqrt{\frac{\nu}{\pi}}\exp\left(\ln\Gamma\left(\frac{\nu-1}{2}\right) - \ln\Gamma\left(\frac{\nu}{2}\right)\right) \\
v_0 &= \frac{\nu}{\nu-2} - \mu_0^2
\end{aligned}$$

The moments of the ST distribution are:

$$\begin{aligned}
\mu\left(X\right) &= \xi + \omega m_0 \\
\sigma^2\left(X\right) &= \omega^2 v_0 \\
\gamma_1\left(X\right) &= m_0 v_0^{-3/2}\left(\frac{\nu\left(3-\delta^2\right)}{\nu-3} - \frac{3\nu}{\nu-2} + 2m_0^2\right) \\
\gamma_2\left(X\right) &= m_0 v_0^{-2}\left(\frac{3\nu^2}{\left(\nu-2\right)\left(\nu-4\right)} - \frac{4m_0^2\nu\left(3-\delta^2\right)}{\nu-3} + \frac{6m_0^2\nu}{\nu-2} - 3m_0^4\right) - 3
\end{aligned}$$

A.2 Order statistics

Let $X_1, \ldots, X_n$ be *iid* random variables, whose probability distribution is denoted by $\mathbf{F}(x)$. We arrange these random variables in increasing order:

$$X_{1:n} \leq X_{2:n} \leq \cdots \leq X_{n-1:n} \leq X_{n:n}$$

$X_{i:n}$ is called the i^{th} order statistic in the sample of size n. The smallest order statistic corresponds to the minimum of the sample:

$$X_{1:n} = \min(X_1, \ldots, X_n)$$

We can show that:

$$\mathbf{F}_{1:n}(x) = 1 - \left(1 - \mathbf{F}(x)\right)^n$$

We deduce that the probability density function of $X_{1:n}$ is:

$$f_{1:n}(x) = n\left(1 - \mathbf{F}(x)\right)^{n-1} f(x)$$

From the expression for the CDF, the quantile function is:

$$\mathbf{F}_{1:n}^{-1}(\alpha) = \mathbf{F}^{-1}\left(1 - (1 - \alpha)^{1/n}\right)$$

The previous results can be extended to the other order statistics. We have:

$$\begin{aligned} \mathbf{F}_{i:n}(x) &= \Pr\{X_{i:n} \leq x\} \\ &= \sum_{k=i}^{n} \binom{n}{k} \mathbf{F}(x)^k \left(1 - \mathbf{F}(x)\right)^{n-k} \end{aligned}$$

and:

$$f_{i:n}(x) = \frac{n!}{(i-1)!\,(n-i)!} \mathbf{F}(x)^{i-1} \left(1 - \mathbf{F}(x)\right)^{n-i} f(x)$$

The quantile is computed using a grid search:

$$\mathbf{F}_{i:n}^{-1}(\alpha) = \inf\left\{x : \mathbf{F}_{i:n}(x) \geq \alpha\right\}$$

A.3 Additional results

Table 20: Factor contributions in % to GDP growth (1995-2020)

Country	g_Y	c_K	c_L	c_H	c_N	r_{Solow}	c_N/g_Y
Argentina	1.76	1.16	0.47	0.45	0.09	−0.42	5.14
Cameroon	4.07	1.74	0.80	0.22	0.20	1.12	4.81
Chile	3.51	2.12	0.57	0.44	0.50	−0.12	14.28
China	8.69	3.99	0.18	0.48	0.25	3.79	2.87
India	6.00	2.61	0.28	0.37	0.15	2.59	2.55
Indonesia	4.13	2.36	0.72	0.17	0.23	0.66	5.46
Mexico	1.98	1.11	0.69	0.20	0.06	−0.08	3.13
Morocco	3.84	2.09	0.34	0.28	0.14	1.00	3.70
Nigeria	4.86	0.97	0.97	0.19	0.07	2.66	1.41
Pakistan	3.91	1.17	1.23	0.18	0.03	1.31	0.64
Philippines	4.55	1.87	0.54	0.19	0.03	1.92	0.64
South Africa	2.30	0.87	0.41	0.28	0.17	0.58	7.19
Tajikistan	6.09	1.10	0.17	0.37	0.02	4.42	0.31
Thailand	2.94	0.76	0.42	0.16	0.00	1.60	0.08

Source: Ghosal *et al.* (2024, Table 1, page 22).

Figure 16: Evolution of production factors per country (1995–2020)

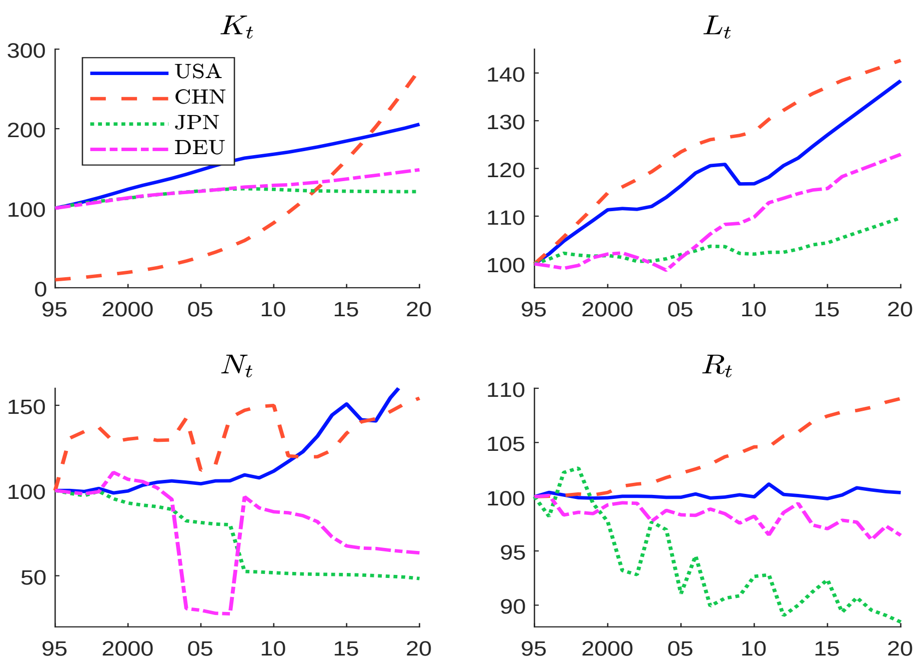

Figure 17: Evolution of production factors per country (1995–2020)

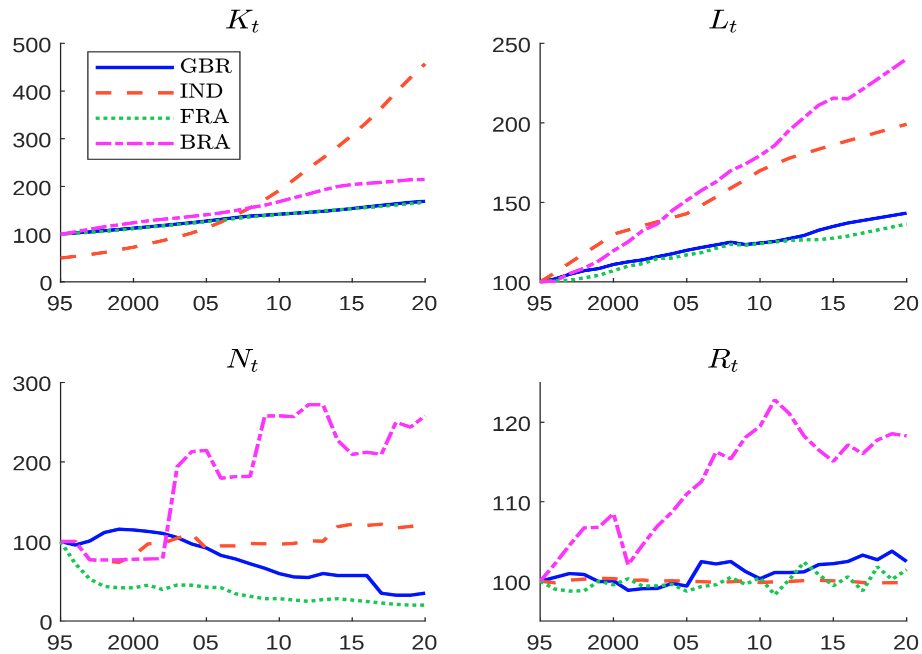

Figure 18: Evolution of production factors per country (1995–2020)

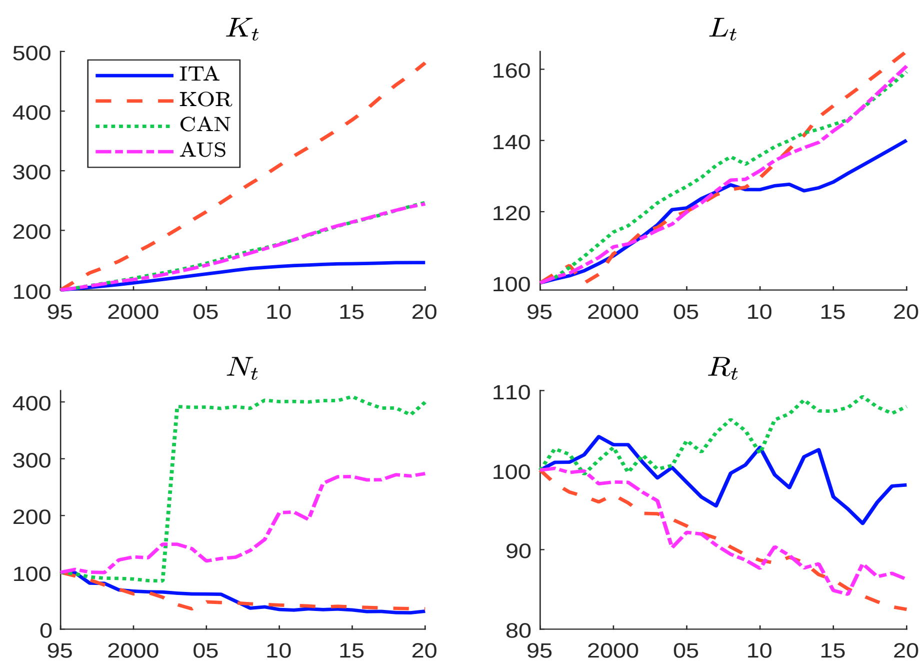

Figure 19: Correlation in % of annual growth rates (global, 1995–2020)

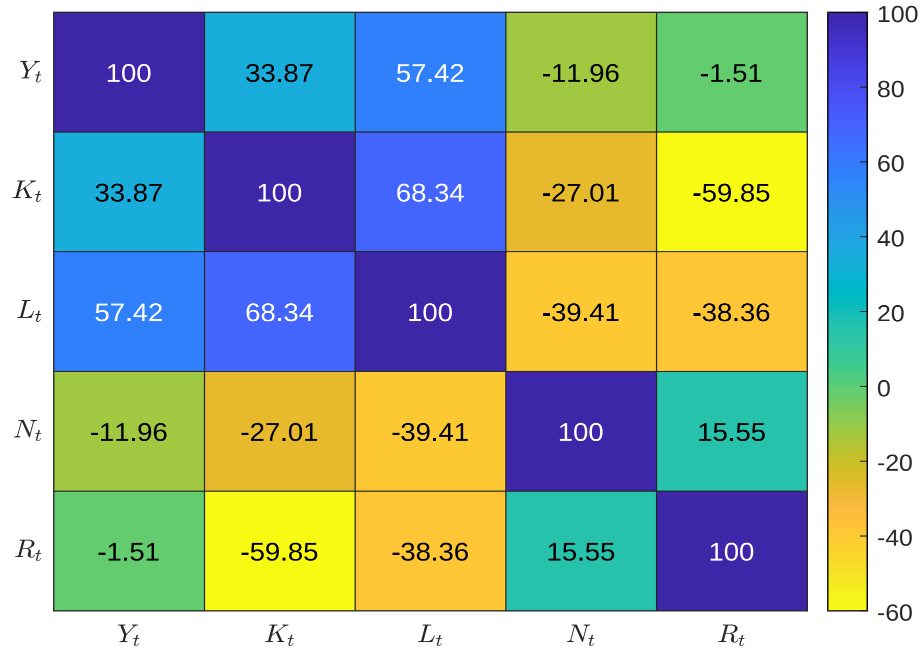

Figure 20: Correlation in % of annual growth rates (all countries, 1995–2020)

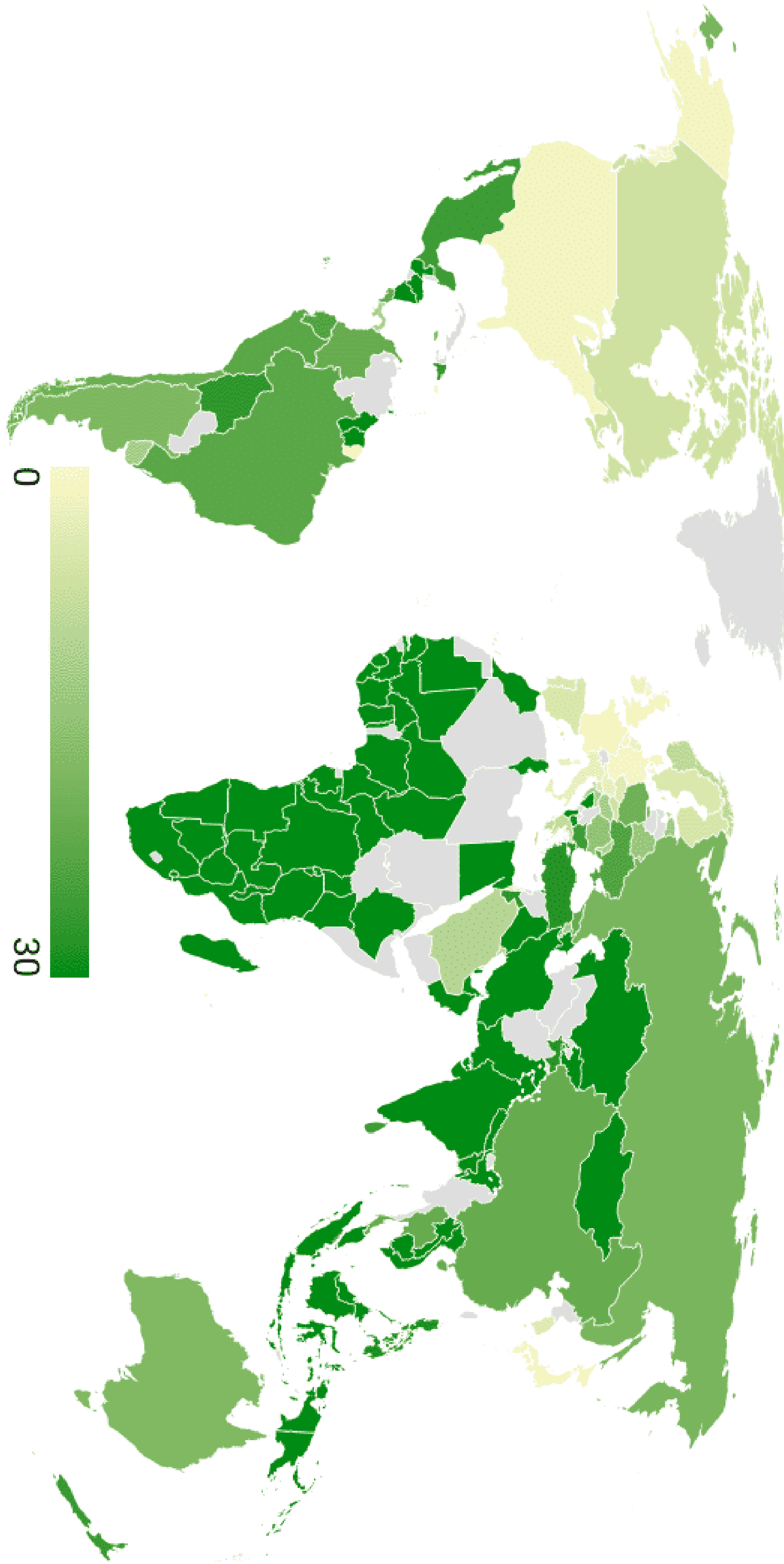

Figure 21: Share of natural capital in total capital by country (1995)

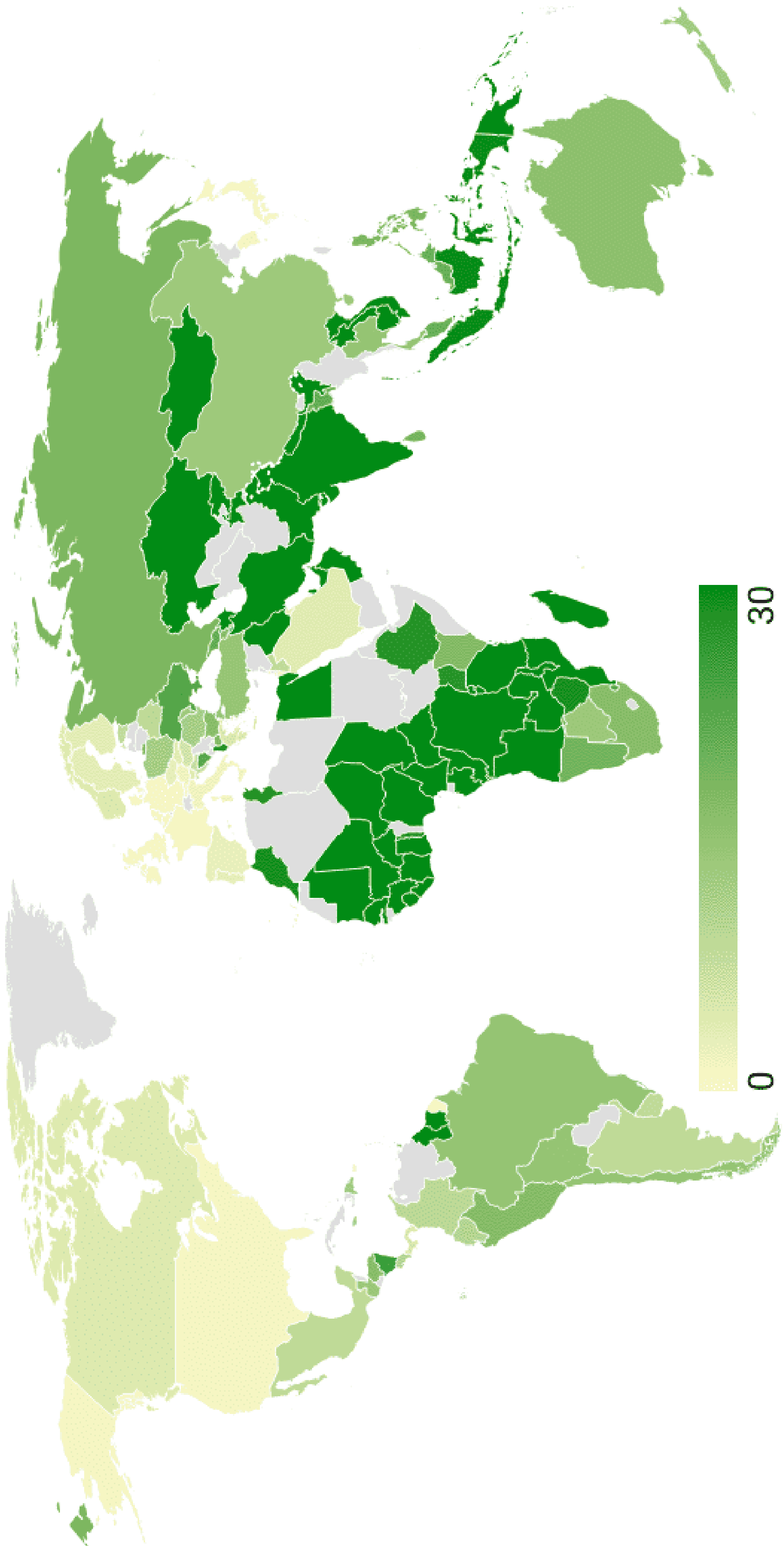

Figure 22: Share of natural capital in total capital by country (2020)

Table 21: Contribution of natural capital to economic growth (1995–2020, in %)

Group	Country	$\mu\left(c_{i,N}\right)$	$\mu\left(c_{i,R}\right)$	$\sigma\left(c_{i,N}\right)$	$\sigma\left(c_{i,N}\right)$	g_Y
BRICS+	Brazil	0.51	2.33	0.76	2.03	64.98
	China	0.19	1.47	0.26	1.21	698.09
	Egypt	0.12	3.27	0.18	1.80	202.61
	Ethiopia	−0.25	2.15	0.31	1.50	584.13
	India	0.07	−0.02	0.09	0.02	325.10
	Indonesia	0.37	3.90	0.65	2.84	169.80
	Iran	0.19	−3.65	0.33	1.99	107.08
	Russian Federation	0.04	−0.29	0.07	0.23	97.20
	South Africa	−0.26	−0.39	0.39	0.34	74.60
	United Arab Emirates	0.00	0.25	0.00	0.13	150.48
N-11	Bangladesh	−0.06	0.60	0.05	0.15	304.62
	Korea	−0.03	−0.98	0.05	1.15	168.96
	Mexico	−0.03	−0.45	0.05	0.52	61.68
	Pakistan	0.11	0.46	0.08	0.13	158.96
	Philippines	0.03	1.35	0.02	0.35	200.03
	Nigeria	0.09	0.65	0.10	0.25	223.56
	Turkiye	0.16	0.58	0.20	0.56	200.31
	Viet Nam	0.91	9.16	0.70	2.52	384.73
OPEC	Congo	0.14	1.07	0.14	0.50	72.53
	Gabon	0.06	0.21	0.05	0.09	58.68
	Iraq	0.05	1.70	0.05	0.69	334.56
	Kuwait	0.03	0.21	0.02	0.19	101.58
	Liberia	−0.02	1.31	0.02	0.56	564.66
	Saudi Arabia	0.02	1.42	0.02	1.34	122.07
G20	Argentina	−0.06	−0.75	0.07	0.73	47.79
	Australia	0.20	−1.75	0.25	1.64	110.67
	Canada	0.17	0.32	0.24	0.46	68.68
	France	−0.04	0.06	0.06	0.08	38.00
	Germany	−0.02	−0.14	0.03	0.21	34.83
	Italy	−0.04	−0.07	0.06	0.11	4.78
	Japan	−0.03	−0.46	0.04	0.67	15.57
	United Kingdom	−0.04	0.10	0.05	0.14	47.86
	United States	0.04	0.02	0.05	0.02	77.58
HIPC	Bolivia	0.07	−0.28	0.04	0.09	138.13
	Burkina Faso	−0.05	1.46	0.04	0.62	316.00
	Burundi	−0.10	0.19	0.06	0.07	53.19
	Cameroon	−0.12	1.08	0.07	0.38	171.12
	Central African Republic	−0.06	0.06	0.03	0.02	27.91
	Ghana	−0.12	−0.39	0.07	0.14	286.64
	Madagascar	−0.14	0.88	0.08	0.31	91.72
	Mali	−0.11	1.61	0.06	0.56	222.62
	Mauritania	0.08	−1.55	0.07	0.72	117.85
	Mozambique	2.61	6.22	2.01	2.65	438.19
	Nicaragua	−0.05	−1.36	0.03	0.41	124.43
	Niger	−0.06	2.80	0.04	0.98	208.09
	Rwanda	−0.08	2.17	0.05	0.76	523.12
	Senegal	0.10	−0.65	0.06	0.23	168.93
	Tanzania	−0.10	1.20	0.06	0.42	309.71
	Togo	−0.05	0.84	0.03	0.26	147.70
	Uganda	−0.05	1.88	0.03	0.57	347.11
	Zambia	−0.07	1.51	0.05	0.65	247.06

Table 22: Natural capital stress testing in % ($T = 25$ years, $\alpha = 5\%$)

Group	Country	Historical		Parametric		EVT	
		$\mathbb{S}_N$	$\mathbb{S}_R$	$\mathbb{S}_N$	$\mathbb{S}_R$	$\mathbb{S}_N$	$\mathbb{S}_R$
BRICS+	Brazil	−1.34	−16.60	−1.34	−20.49	−0.49	−4.66
	China	−1.27	−0.16	−1.20	−0.25	−0.35	−0.17
	Egypt	−1.15	−16.36	−1.14	−18.17	−0.27	−3.51
	Ethiopia	−1.27	−21.54	−1.28	−23.98	−0.34	−4.61
	India	−1.26	−1.68	−1.22	−2.12	−0.35	−0.26
	Indonesia	−1.23	−5.89	−1.25	−7.54	−0.29	−0.96
	Iran	−0.33	−28.65	−0.43	−20.17	−0.04	−3.79
	Russian Federation	−0.33	−4.87	−0.38	−4.69	−0.03	−0.48
	South Africa	−1.37	−2.76	−1.31	−2.66	−0.45	−0.26
	United Arab Emirates	−0.02	−23.26	−0.01	−15.28	−0.00	−2.17
N-11	Bangladesh	−0.27	−2.04	−0.27	−2.36	−0.09	−0.23
	Korea	−0.19	−4.23	−0.19	−4.43	−0.07	−0.34
	Mexico	−0.19	−3.39	−0.19	−4.26	−0.08	−0.54
	Nigeria	−0.06	−1.28	−0.08	−1.50	−0.01	−0.24
	Pakistan	−0.28	−5.15	−0.30	−6.43	−0.05	−1.13
	Philippines	−0.22	−3.25	−0.21	−3.82	−0.03	−0.44
	Turkiye	−0.32	−14.65	−0.27	−16.33	−0.04	−2.00
	Viet Nam	−0.17	−0.56	−0.20	−0.48	−0.03	−0.25
OPEC	Congo .	−0.15	−7.80	−0.16	−8.32	−0.03	−1.27
	Gabon	−0.21	−3.15	−0.01	−3.57	−0.00	−0.50
	Iraq	−0.07	−15.93	−0.08	−16.54	−0.01	−3.57
	Kuwait	−0.04	−4.79	−0.03	−5.33	−0.00	−0.66
	Liberia	−0.12	−0.60	−0.10	−0.78	−0.01	−0.29
	Saudi Arabia	−0.26	−0.60	−0.22	−0.70	−0.06	−0.04
G20	Argentina	−0.27	−5.51	−0.27	−5.90	−0.10	−0.50
	Australia	−0.28	−17.89	−0.29	−18.36	−0.06	−2.42
	Canada	−0.11	−5.54	−0.12	−7.78	−0.01	−1.54
	France	−0.19	−4.38	−0.19	−4.82	−0.11	−0.47
	Germany	−0.19	−4.60	−0.18	−5.63	−0.04	−0.88
	Italy	−0.19	−6.83	−0.19	−8.30	−0.10	−1.43
	Japan	−0.18	−8.79	−0.12	−9.81	−0.02	−2.04
	United Kingdom	−0.19	−3.07	−0.19	−3.54	−0.07	−0.47
	United States	−0.09	−1.21	−0.10	−1.26	−0.02	−0.12
HIPC	Bolivia	−0.20	−2.57	−0.20	−3.29	−0.03	−0.46
	Burkina Faso	−0.22	−8.65	−0.21	−9.85	−0.03	−1.33
	Burundi	−0.30	−6.20	−0.30	−6.87	−0.07	−0.82
	Cameroon	−0.34	−1.96	−0.16	−2.29	−0.02	−0.26
	Central African Republic	−0.18	−1.55	−0.20	−1.68	−0.03	−0.17
	Ghana	−0.35	−11.30	−0.35	−11.68	−0.15	−2.64
	Madagascar	−0.35	−0.84	−0.28	−0.96	−0.06	−0.06
	Mali	−0.26	−1.92	−0.27	−2.47	−0.04	−0.30
	Mozambique	−0.19	−10.67	−0.13	−11.98	−0.02	−1.93
	Nicaragua	−0.16	−5.36	−0.17	−5.83	−0.03	−0.55
	Niger	−0.23	−0.92	−0.25	−1.27	−0.04	−0.10
	Rwanda	−0.28	−3.46	−0.27	−4.39	−0.05	−0.55
	Senegal	−0.35	−6.64	−0.27	−6.86	−0.04	−0.76
	Tanzania	−0.29	−2.55	−0.26	−3.10	−0.04	−0.37
	Togo	−0.24	−1.75	−0.21	−2.12	−0.04	−0.25
	Uganda	−0.17	−0.58	−0.19	−0.85	−0.03	−0.11
	Zambia	−0.34	−9.02	−0.20	−11.42	−0.03	−2.36

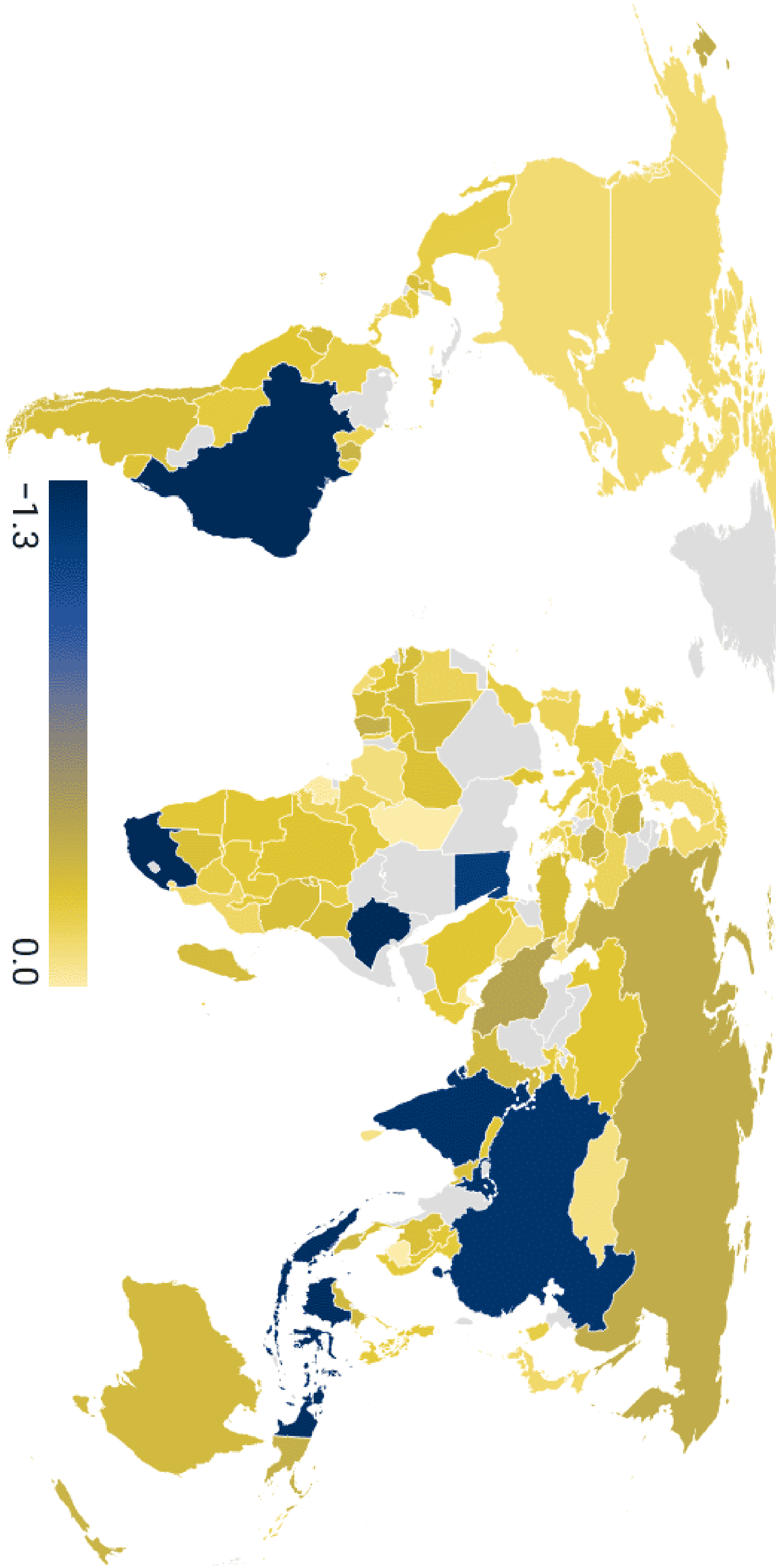

Figure 23: Parametric stress test scenario $\mathbb{S}_N$ (25, 5%) (in %)

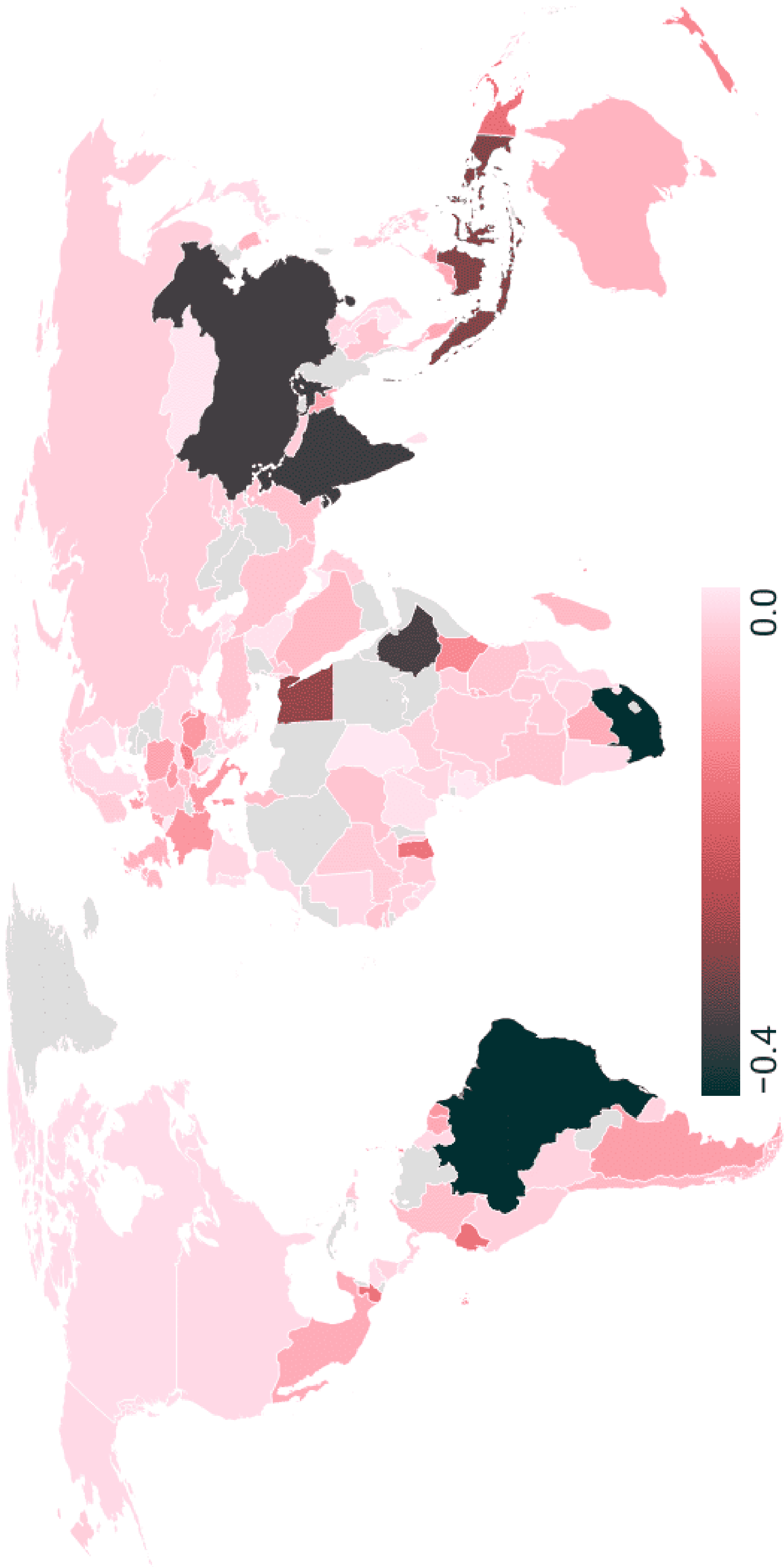

Figure 24: EVT stress test scenario $\mathbb{S}_N(25, 5\%)$ (in %)

Table 23: Natural capital stress testing in % and top 5 worst years ($T = 25$ years, $\alpha = 5\%$, Renewables)

Group	Country	Total	Worst years 1st	2nd	3rd	4th	5th	Contri- -bution
BRICS+	Brazil	−20.49	−4.66	−2.28	−1.49	−1.07	−0.79	50%
	China	−0.25	−0.17	−0.06	−0.02	−0.00		99%
	Egypt	−18.17	−3.51	−1.79	−1.23	−0.91	−0.70	45%
	Ethiopia	−23.98	−4.61	−2.53	−1.84	−1.43	−1.20	48%
	India	−2.12	−0.26	−0.14	−0.10	−0.08	−0.07	33%
	Indonesia	−7.54	−0.96	−0.55	−0.40	−0.31	−0.24	30%
	Iran	−20.17	−3.79	−1.99	−1.40	−1.10	−0.87	45%
	Russian Federation	−4.69	−0.48	−0.29	−0.23	−0.19	−0.16	29%
	South Africa	−2.66	−0.26	−0.16	−0.12	−0.11	−0.09	27%
	United Arab Emirates	−15.28	−2.17	−1.23	−0.91	−0.74	−0.61	37%
N-11	Bangladesh	−2.36	−0.23	−0.15	−0.12	−0.10	−0.08	28%
	Korea	−4.43	−0.34	−0.25	−0.22	−0.21	−0.19	28%
	Mexico	−4.26	−0.54	−0.31	−0.23	−0.19	−0.16	33%
	Nigeria	−1.50	−0.24	−0.12	−0.08	−0.06	−0.04	35%
	Pakistan	−6.43	−1.13	−0.58	−0.40	−0.29	−0.23	41%
	Philippines	−3.82	−0.44	−0.27	−0.20	−0.16	−0.14	32%
	Turkiye	−16.33	−2.00	−1.26	−1.00	−0.84	−0.72	36%
	Viet Nam	−0.48	−0.25	−0.10	−0.04	−0.01		84%
OPEC	Congo .	−8.32	−1.27	−0.69	−0.50	−0.38	−0.32	38%
	Gabon	−3.57	−0.50	−0.26	−0.19	−0.15	−0.12	34%
	Iraq	−16.54	−3.57	−1.99	−1.46	−1.18	−0.96	54%
	Kuwait	−5.33	−0.66	−0.38	−0.28	−0.23	−0.19	33%
	Liberia	−0.78	−0.29	−0.11	−0.06	−0.02	−0.00	62%
	Saudi Arabia	−0.70	−0.04	−0.03	−0.03	−0.03	−0.03	22%
G20	Argentina	−5.90	−0.50	−0.38	−0.33	−0.30	−0.28	30%
	Australia	−18.36	−2.42	−1.50	−1.16	−0.99	−0.87	38%
	Canada	−7.78	−1.54	−0.81	−0.57	−0.43	−0.35	47%
	France	−4.82	−0.47	−0.32	−0.26	−0.23	−0.20	30%
	Germany	−5.63	−0.88	−0.48	−0.34	−0.27	−0.23	39%
	Italy	−8.30	−1.43	−0.81	−0.60	−0.49	−0.41	45%
	Japan	−9.81	−2.04	−1.14	−0.84	−0.67	−0.57	53%
	United Kingdom	−3.54	−0.47	−0.26	−0.19	−0.15	−0.13	34%
	United States	−1.26	−0.12	−0.08	−0.06	−0.05	−0.04	28%
HIPC	Bolivia	−3.29	−0.82	−0.51	−0.39	−0.34	−0.29	34%
	Burkina Faso	−9.85	−1.33	−0.79	−0.60	−0.49	−0.41	37%
	Burundi	−6.87	−0.82	−0.51	−0.39	−0.34	−0.29	34%
	Cameroon	−2.29	−0.26	−0.15	−0.12	−0.09	−0.08	30%
	Central African Republic	−1.68	−0.17	−0.10	−0.08	−0.07	−0.06	29%
	Ghana	−11.68	−2.64	−1.37	−0.95	−0.74	−0.58	54%
	Madagascar	−0.96	−0.06	−0.05	−0.04	−0.04	−0.03	23%
	Mali	−2.47	−0.30	−0.17	−0.13	−0.10	−0.08	31%
	Mozambique	−11.98	−1.93	−1.11	−0.81	−0.64	−0.52	42%
	Nicaragua	−5.83	−0.55	−0.38	−0.32	−0.29	−0.26	30%
	Niger	−1.27	−0.10	−0.07	−0.06	−0.05	−0.04	25%
	Rwanda	−4.39	−0.55	−0.32	−0.24	−0.19	−0.15	33%
	Senegal	−6.86	−0.76	−0.49	−0.39	−0.34	−0.30	33%
	Tanzania	−3.10	−0.37	−0.21	−0.16	−0.13	−0.11	31%
	Togo	−2.12	−0.25	−0.14	−0.11	−0.08	−0.07	30%
	Uganda	−0.85	−0.11	−0.06	−0.04	−0.03	−0.02	32%
	Zambia	−11.42	−2.36	−1.18	−0.80	−0.59	−0.45	47%