Toward a Sustainable Development: Past, Present, and the Future

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Abstract

This study analyzes policy research and global agreements related to the decarbonization of economic development. Climate change and economic development should be viewed as distinct yet equally important issues, with strategies designed to separate responsibility from action. This approach will be essential beyond the frameworks established by the Kyoto and Paris agreements. Linking climate change and development policies will lead to more sustainable development practices.

Moreover, fairness to future generations is grounded in a fundamental principle of equality among different generations regarding the stewardship and use of the natural environment. Sustainability is a necessary condition for achieving justice. The moral responsibility towards future generations, which is embedded in the concept of sustainability, is also a requirement of justice. Sustainability represents an ethical commitment to preserving the conditions necessary for human well-being, both in the present and for a sustainable future.

Throughout the past, present, and future, we have argued for the necessity of a new approach to our shared future and have outlined various authors' ideas on how to achieve this. The main objective was to raise important questions that must be considered when making decisions about the way forward.

JEL Classification: C53, E17, Q01, Q56

Keywords: Climate change and economic development; Kyoto and Paris agreements; Moral responsibility towards future generations; Sustainability represents a moral commitment to preserving the conditions necessary for human well-being

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1. Introduction

This study aimed to examine the relationship between climate change and a sustainable future. It criticizes current policy approaches to the Paris Agreement (Deursen and Gupta 2025; OECD 2020; Wendler 2022) because they have resulted in the separation of climate policy and sustainable development.

1.1 Definitions of Growth, Development, and Sustainability Concepts

It has been established that there is not one definition of sustainable development (Robinson 2002; Robinson and Herbert 2001), and different people with different cultural backgrounds and priorities have different definitions (Thompson and Rayner 1998). Turner (1988) and O'Riordan (1988) echo Redclift (1987, 1990) in distinguishing between

sustainable growth and sustainable development (Huckle 1991). There is virtually no doubt that climate change is already occurring, which is caused by the emission and accumulation of greenhouse gases (GHGs) in the atmosphere (Nakicenovic and Swart 2000).

The structure of the paper is organized as follows: Section 2, Definitions of Growth, Development, and Sustainability Concepts, Section 3 provides a Literature Review, Section 4, Past, Present Methodologies, and Section 5, Cointegration Approach, and Hindcast Evaluations. Section 6 Empirical Results and Discussion. Section 7 Sustainable Future Methodology. Section 8 Future Sustainable Criterion, Section 9 Uncertainty, and finally, Section 10 Concludes the paper with a summary of the key findings.

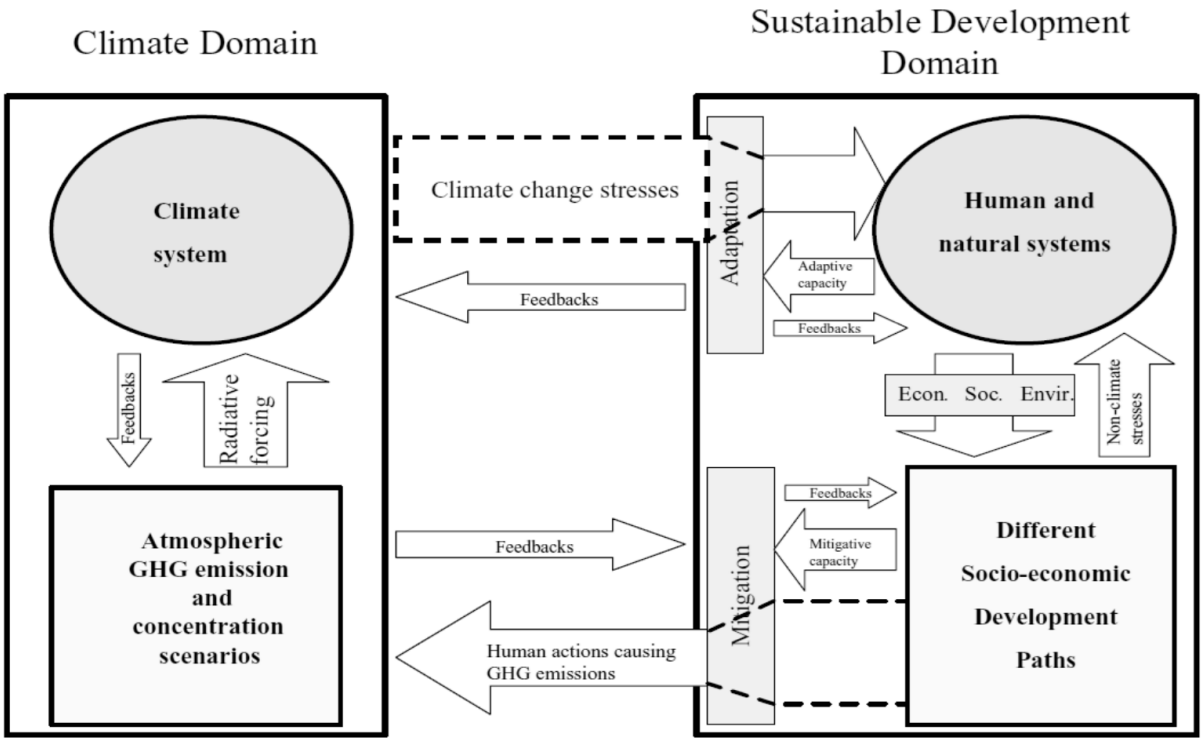


Figure I. Climate change – an integrated framework considering socio-economic development.

Source: IPCC (2001c). https://www.ipcc.ch/report/ar3/syr/
IPCC (2003). https://www.ipcc.ch/site/assets/uploads/2018/03/8.pdf

Figure 1 describes a possible distinction between economic and human sustainability (Porreca 2020). The distinction is a useful reminder that the ultimate objective of sustainability is not human activity, but human beings themselves. The full cycle of cause and effect between climate change and sustainable development is summarized in Figure 1, in which Munasinghe and Swart (1999, 2005) outline an integrated assessment modeling framework (IPCC 2001a, 2001b; Bartelmus 1994a, 1994b; Munasinghe 1999). Initial reactions were emphatic, predicting doom in a revival of Malthusian (Malthus 1996) ideas that were promulgated by the Limits to Growth study of the Club of Rome (Meadows et al. 1972; Gastaldo and Ragot 1996). However, these reactions have succeeded in attracting governmental attention to problems of environmental degradation and the depletion of natural resources, and to the need to reassess the sustainability of accelerated economic growth (Bartelmus 1987).

1.2 Interpreting Sustainable Development

Sustainable development is used and interpreted to vary so much that while O'Riordan (1985) called SD a contraction term, Redclift suggests that it may be just another development truism (Redclift 1987), and sustainable development is summarized. Most people use sustainable development interchangeably with ecologically sustainable or environmentally sound development (Tolba 1984; Lélé 1991).

2. Definitions of Growth, Development, and Sustainability Concepts

Many concepts and ideas appear in the Environment, Growth, and Development (World Bank Development Committee Pamphlet 14) (World Bank 1987). "Green growth" and "degrowth" are key concepts in discussions about the economy and the environment. Proponents of green growth believe that environmental measures can boost economic growth through efficient resource use, while supporters of degrowth contend that protecting the environment requires reducing economic growth (Jakob and Edenhofer 2014).

Sustainability has been applied to a vast array of situations, ranging from the conditions for the success of a World Bank agricultural development project to the problem of creating conditions for the improvement of the situation of the entire human race in the future (Kneese and Kopp 1988). The origin of the concept of sustainable development goes far back in history to trace its roots. It shows how the idea of sustainability evolved over the centuries as a counter to notions of progress (Du Pisani 2006). The development process poses challenges for sustainability in capitalism and raises questions for Marxism, as well as for intellectual traditions that recognize many harmful aspects of global capitalist relations (Redclift 1987). Ecological economics is an approach that promotes sustainable development, also known as sustainability economics. It encompasses neoclassical environmental economics but is broader in scope and partly critiques neoclassical economics (Costanza 1991; Söderbaum 2007). The requirement that human well-being should never decline is unreasonable. Sustainability is often

a constraint on welfare maximization unless a clear conflict is demonstrated, which has yet to happen (Beckerman 1994).

Hepburn and Groom (2007) found that certainty-equivalent discount rates decrease over time with the expected present value (EPV) criterion but increase with the expected future value (EFV) criterion. Additionally, a project's positive discounted net present value (NPV) contributes to overall economic welfare. The EPV of CO_2 emissions was calculated using the Nordhaus (1991) equation as follows,

$$EPV = \beta / [(\theta + \phi)(\theta + \beta)] \quad (1)$$

where β is the delay parameter for a response time of 50 years, θ is the discount rate (the difference between the real rate of return on capital and the economic growth rate), and ϕ is the rate of CO_2 disappearance for an atmospheric residence time of 200 years (Nordhaus 2019; Destais 1996; Belle-Larant et al. 2021). The DICE model indicates that achieving the 1.5°C target is unfeasible, and the 2°C path requires near-term negative emissions. Notably, the cost-benefit optimum may rise above 3°C by 2100, exceeding international policy targets (Nordhaus 2019). For the central case, the real SCC grows at 3% per year over the period to 2050. The paper also compares the estimates with those from other sources (Nordhaus 2016, 2017).

Meadows et al. (1972) assumed that exponential growth is a dynamic phenomenon that involves elements that change over time. In addition, Bomhoff (1994) assumed that anything that grows tends to grow exponentially rather than linearly. In the case of exponential decay, Caplin and Leahy (2004) analyze and estimate the future discount rates. They show that this

rate should be exponential and that the exponential discount function is characterized by a constant discount rate.

3. Literature

3.1. Definitions of Growth, Development, and Sustainability Concepts

It has been established that there is not one definition of sustainable development (Robinson 2002; Robinson and Herbert 2001), and different people with different cultural backgrounds and priorities have different definitions (Thompson and Rayner 1998). Turner (1988) and O'Riordan (1988) echo Redclift (1987, 1990) in distinguishing between sustainable growth and sustainable development (Huckle 1991).

Daly (1990) states that our attention will naturally become focused on limiting the scale to an optimal, or at least sustainable, level, thereby giving the discussion of sustainable development a firmer theoretical foundation. Like democracy and globalization, the concept of sustainable development has become one of the most ubiquitous, contested, and indispensable concepts of our time (Castro 2004). The dominant economic approach to environmental policy views environmental goods as capital that provides services for human well-being, assigning them monetary value for comparison with other goods. Wiggins (2011) critiques key assumptions about well-being, practical reason, and ethical deliberation. This paper outlines his arguments and examines their implications for ethical responsibilities across generations, especially regarding sustainability (O'Neill 2022). It is also related to the fairness-based sustainability

proposed by Woodward (2000) and the stochastic sustainability introduced by Asheim and Brekke (2002). Furthermore, there is a close relationship between optimal resource use and uncertain future preferences (Krysiak and Krysiak 2006).

3.2 Past Studies Literature

Past studies have employed various quantitative and qualitative methods for analyzing interactions between the Sustainable Development Goals (SDGs). These methods include consensus-based expert elicitation (Nilsson et al. 2016; van Soest et al. 2019), literature-based content analysis (Bandari et al. 2021; McCollum et al. 2018), indicator-based pairwise statistical correlation (Kroll et al. 2019; Pradhan et al. 2017), statistical modeling of interactions (Anderson et al. 2021), remote sensing tracking (Singha et al. 2021), network analysis (Le Blanc 2015), and integrated assessment modeling (Gao and Bryan 2017; Moallemi et al. 2022; Obersteiner et al. 2016; Pedercini et al. 2019; Soergel, Kriegler, Weindl et al. 2021).

Some studies have focused specifically on interactions within particular sectors, such as energy (Fuso Nerini et al. 2018), health (Schmidt et al. 2015), and food (Herrero et al. 2021). In contrast, others have taken a broader approach, analyzing multiple SDGs simultaneously (Allen et al. 2019; Kroll et al. 2019; Pradhan et al. 2017; Soergel, Kriegler, Weindl et al. 2021).

The questions addressed in these studies have primarily revolved around understanding interaction behaviors. This includes mapping the degree of association between various SDGs based on historical or extrapolated data (Kroll et al. 2019; Pradhan et al. 2017), monitoring SDG interactions (Singha et al. 2021), and quantitatively projecting their trajectories under future scenarios (Gao and Bryan 2017; Soergel, Kriegler, Weindl et al. 2021; Moallemi,

Hosseini et al. 2022).

4. Past and Present Methodologies

4.1 Ramsey Function

The foundational work on optimal growth comes from Ramsey (1928). In his groundbreaking paper, he addressed the challenge of maximizing total utility over an infinite time horizon, given specific technology and an initial capital stock.

Pearce and Ulph (1998) proposed that the social discount rate encompasses the market interest rate, the social opportunity cost of investment, and the consumer discount rate. Furthermore, Fujii and Karp (2008) selected the social rate of time preference, which assesses social profitability through public sector cost-benefit analysis. Beckerman and Hepburn (2007) presented the following equation based on Ramsey (1928):

$$r = s = \rho + \mu g \tag{2}$$

where r is the market interest rate, s is the social rate of time preference, ρ is the pure rate of time preference, μ is the marginal utility elasticity of consumption, and g is the real growth rate of consumption per capita. Furthermore, Tinbergen (1960) regards an appropriate individual savings rate as maximizing utility over time. As a result, Fankhauser and Tol (2005) assume that savings rates are determined internally and are influenced by climate change.

This foundational research led to a significant body of literature in the 1960s, which has been reviewed by Koopmans (1967a, 1967b, 1977) and other works.

In general, Samuelson (1937) demonstrates that marginal utility decreases with income in a monotonic manner. Additionally, Loewenstein and Prelec (1992) indicate that the discounted utility model played a dominant role in the economic analyses of intertemporal choice. Pearce and Nash (1981) show that the concept of marginal utility elasticity of consumption refers to the marginal elasticity within a consumption scheme. Furthermore, Scott and Monica (1977) assume a preference for egalitarianism, which tends to increase the upper end of the range in social elasticity. Nordhaus (1993) defines utility as the population size [P(t)] multiplied by the utility of per capita consumption u[c(t)]. The resulting utility function is

$$U[c(t), P(t)] = Pt\{[c(t)]^{1-\alpha} - 1\}/(1-\alpha) \quad (3)$$

where α is a measure of the social valuation of different levels of consumption. When α = 0, the utility function is linear, and there is no social aversion to inequality. When α =1, the function is a logarithmic or Bernoullian utility function (Bernoulli 1954; von Neumann and Morgenstern 1953).

Most of this literature adopts the objective of maximizing an integral over time of the discounted utility flow, represented as $e^{-\rho t}\, u(c_t)$, where c_t is the consumption at time t, $u(c)$ is an increasing and strictly concave function, and $\rho > 0$ is the rate of pure time discount. Thus, the common aim is to maximize this optimality criterion:

$$\int_0^{\infty} e^{-\rho t} u(c_t) \mathrm{dt} \quad (4)$$

subject to certain assumptions regarding the aggregate production function, population growth, and technological progress (Anard and Sen 2000), the analysis conducted by Nelson and Phelps (1966) explores how steady-state production levels are influenced by a country's ability to adopt technologies. We assume constant efficiency growth at the world frontier, denoted as W, with L and M representing labor growth rates for a given country, *c*, at time *t*.

$$\hat{A}_t^{L,W} = g^L \text{ and, } \hat{A}_t^{M,W} = g^M \quad (5)$$

Each country's human capital (HC), and thereby its capacity to adopt technologies ($\emptyset_c^L$ and $\emptyset_c^M$), is assumed to remain constant over time. In a steady state, the efficiency in each country is expected to grow at the same rate as the world frontier (Ciccone and Papaioannou 2009).

Sustainable development is a somewhat vague term that was popularized in the Brundtland Commission report (World Commission on Environment and Development, WCED 1987) but was earlier mentioned in the World Conservation Strategy (International Union for Conservation of Nature, IUCN 1980). It is generally understood to mean that the well-being of the current generation should not be pursued at the expense of future generations (Barbier et al. 1990). The concept of economic sustainability is rooted in Solow's theories on capital convertibility (Solow 1974, 1986, 1993) and the Hicks-Lindahl concept of maximum income advocates for preserving essential capital resources for future generations while ensuring fair distribution among them. Economic sustainability focuses on maximizing income and consumption while maintaining the stock of assets that produce beneficial outputs (Hicks 1936; Maler 1990).

A standard justification for aggregation is based on the Hicks-Leontief composite commodity theorem (Hicks 1936; Leontief 1936), which states that perfectly correlated variables can be aggregated freely (Lewbel 1993).

Dickey and Fuller (1979) and Phillips and Perron (1988) propose nonparametric methods for controlling serial correlation when testing for a unit root. This study uses the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests to determine the order of integration of the variables. The Johansen cointegration approach estimates the trace and maximum eigenvalue statistics. In cases of conflicting results, the choice depends on the interpretability of the cointegration relationships (Johansen 1988; Johansen and Juselius 1990; Saikkonen 1991).

The accuracy of a world hindcast is confirmed using several metrics, including the mean absolute percentage error (MAPE), mean absolute error (MAE), root mean squared error (RMSE), and the Theil inequality coefficient (Makridakis et al. 1998; Fair 1986; Sohn 2019).

This study analyzes the relationship between three components of human capital: world gross product (WGP), global public expenditure on education (WPEE), and worldwide life expectancy at birth (WLEB). Control variables include world gross fixed capital formation (WGFCF), world population (WPOP), the global human development index (WHDI), and resident patent applicants (WPAT).

4.2 Time Series Perspective

The decomposition from a time series perspective is formulated as follows:

$$WGP_t = f\,(WPOP_t,\ WLEB_t,\ WPEE_t,\ WGRCE_t,\ WHDI_t,\ WPAT_t) \qquad (6)$$

where world gross product (WGP), world public expenditure on education (WPEE), and world life expectancy at birth (WLEB) are components of human capital. Control variables include world gross fixed capital formation (WGFCF), world population (WPOP), world human development index (WHDI), and world patents (WPAT) at time *t*.

According to the Granger representation theorem, if there exists a cointegration relationship among the variables in the equation, there will be Granger causality in at least one direction, provided that the variables are integrated of order one (Granger 1986). Engle and Granger (1987) caution that the Granger causality test may yield misleading results in the presence of cointegration with first-differenced VAR estimation. They also indicate that a dynamic ECM can be derived from the ARDL specification through a linear transformation, as demonstrated by Alogoskoufis and Smith (1991), Banerjee et al. (1986), Bårdsen (1989), Hassler and Wolters (2006), Maddala and Kim (1998), and Wickens and Breusch (1988).

5. Cointegration Approach

Pesaran and Shin (1998) emphasize that the ARDL approach consistently produces reliable long-run coefficient estimates that are asymptotically normal, regardless of whether the regressors are I(1) or I(0). To enhance accuracy, we will transform all variables using natural logarithms, allowing us to effectively establish and estimate the long-run relationships among these variables:

$$LWGP_t = \eta_1 + \eta_2 \text{LWPOP}_t + \eta_3 \text{LWLEB}_t + \eta_4 \text{LWPEE}_t + \eta_5 \text{LWGRCF}_t + \eta_6 \text{LWHDI}_t + \eta_7 \text{LWPAT}_t + \varepsilon_t \quad (7)$$

In analyzing the long-run relationships among variables, we employ the ARDL bounds testing approach to cointegration. The model can be represented as follows:

$$\begin{aligned}\Delta \text{LWGP}_t = \alpha_0 + {} & \Sigma_{i=1}^{p} \mu_i \Delta \text{LWGP}_{t-i} + \Sigma_{i=1}^{p} \phi_i \Delta \text{LWPOP}_{t-i} + \Sigma_{i=1}^{p} \varphi_i \Delta \text{LWLEB}_{t-i} + \Sigma_{i=1}^{p} \omega_i \Delta \text{LWPEE}_{t-i} \\ & + \Sigma_{i=1}^{p} \delta_i \Delta \text{LWGRCF}_{t-i} + \Sigma_{i=1}^{p} \beta_i \Delta \text{LWHDI}_{t-i} + \Sigma_{i=1}^{p} \xi_i \Delta \text{LWPAT}_{t-i} + \theta_G LWGP_{\text{t-1}} + \\ & \theta_P \text{LWPOP}F_{\text{t-1}} + \theta_E \text{LWLEB}_{\text{t-1}} + \theta_K \text{LWPEE}_{\text{t-1}} + \theta_R \text{LWGRCF}_{\text{t-1}} + \theta_S \text{LWHDI}_{\text{t-1}} + \\ & \theta_T \text{LWPAT}_{\text{t-1}} + \varepsilon_{\text{t-1}} \quad (8)\end{aligned}$$

Here, Δ serves as the first difference operator; α_0 is the parameter, and μ, ϕ, φ, ω, δ, β, ξ, and ρ represent the short-run parameters. The long-run coefficients are denoted by θ_G, θ_P, θ_E, θ_K, θ_R, θ_S and θ_T, while ε_t remains the error term at time t. The null hypothesis of no cointegration is stated as H_0: $\theta_G = \theta_P = \theta_E = \theta_K = \theta_R = \theta_S = \theta_T = 0$. Rejecting the null hypothesis H_1: $\theta_G \neq \theta_P$

$\neq \theta_E \neq \theta_K \neq \theta_R \neq \theta_S \neq \theta_T \neq 0$ indicates the presence of cointegration. The F-statistic is used for this cointegration analysis: if it exceeds the upper critical bound (UCB), it signifies that all variables are I(1), whereas the lower critical bound (LCB) indicates that all variables are I(0). If the F-statistic is below the LCB, no cointegration exists. However, if it lies between the LCB and UCB, the inference remains inconclusive.

To explore causality among the series, we employ the Granger causality test within the vector error correction model (VECM). According to Granger and Weiss (1983), if a pair of I(1) series is cointegrated, causation must exist in at least one direction. The error correction model (ECM) facilitates the analysis of long-run relationships, as supported by various studies (Lütkepohl and Saikkonen 1999; Kilian and Lütkepohl 2017; Banerjee and Marcellino 2009; Boswijk 1994, 1995; Garratt et al. 2006; Hassler 2000; Pradel and Rault 2003; Burke and Hunter 2005). The Granger causality test using VECM can be formulated as follows:

$$(1\text{-}A)(LWGP_t, LWPOP_t, LWLEB_t, LWPEE_t, LWGRCF_t, LWHDI_t, LWPAT_t) \quad (9)$$

$$\psi_i + \Sigma_{i=1}^{p} (1\text{-}A)\, \beta_i\, (LWGP_{t-1}, LWPOP_{t-1}, LWLEB_{t-1}, LWPEE_{t-1}, LWGRCF_{t-1}, LWHDI_{t-1},$$

$$LWPAT_{t-1}) + ECM_{t-1}\phi_i + \omega_i \quad (10)$$

where, (1-*A*) is the difference operator, ψ_i (i = 1,….,7) denotes the time-variant constant, β_i (i = 1,….,7) represents the optimal lag length determined by minimizing the Akaike information criterion (AIC), ECM_{t-1} is the lagged residual from the long-run relationship, ϕ_i (i

= 1,….,7) is the adjustment coefficient, and ω_i (i = 1,….,7) is the disturbance term, which is assumed to be uncorrelated with a mean of zero.

For bounds testing, AIC is used to determine the optimal lag length for the variables. Research by Lütkepohl (1991, 2005), Judge et al. (1980), Pesaran and Shin (1998), Gonzalo and Pitarakis (1999), and Hsiao (1979a, 1979b) suggests that AIC lag length criteria yield efficient results. Additionally, stability tests, as outlined by Brown et al. (1975) and Johnston and DiNardo (1997), are conducted for both short- and long-run coefficients using the cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) tests. These tests are based on recursive residuals to assess the constancy of the regression relationship over time (Ploberger 1989).

5.1 Data

Figure 3 data were collected from the UNDP Human Development Reports (2024), http://hdr.undp.org, the World Development Indicators of the World Bank (2025), http://data.worldbank.org/indicator, the UN Educational, Scientific and Cultural Organization (UNESCO), https://databrowser.uis.unesco.org/resources, and the World Intellectual Property Organization (WIPO 2025), https://www.wipo.int, for the period from 1990 to 2021. The Human Development Index (HDI) is defined as the process of enlarging people's choices (UNDP 2024).

The world gross product (WGP), public expenditure on education (WPEE), and life expectancy at birth (WLEB) are key components of human capital. Additionally, we analyze control variables such as gross fixed capital formation (WGFCF), world population (WPOP), human development index (WHDI), and patents (WPAT), all expressed in natural logarithms.

Table 1 presents the world descriptive statistics and the correlation matrix. The Jarque-Bera test (1980) indicates that the data are normally distributed. The correlation analysis shows a positive correlation among all variables at time *t*.

Table 1. World Descriptive statistics and correlation matrix

Variable	$LWGP_t$	$LWPOP_t$	$LWLEB_t$	$LWPEE_t$	$LWGFCF_t$	$LWHDI_t$	$LWPAT_t$
Mean	3.884243	1.883834	4.235779	0.701068	2.465839	-0.386821	0.117621
Median	3.908309	1.890077	4.238297	0.689434	2.473262	-0.379080	0.055286
Maximum	4.588736	2.069391	4.288677	1.418650	3.246102	-0.294371	0.869744
Minimum	3.131573	1.667707	4.176078	-0.112620	1.747459	-0.497580	-0.509160
Std. Dev.	0.469512	0.121595	0.036106	0.477681	0.492298	0.068475	0.459488
Skewness	-0.079701	-0.143520	-0.155946	-0.038266	0.028860	-0.173468	0.412020
Kurtosis	1.484814	1.832168	1.660425	1.462027	1.459562	1.628084	1.829890
Jarque-Bera	3.094929	1.928298	2.522316	3.161623	3.168375	2.670025	2.730930
Probability	0.212787	0.381308	0.283326	0.205808	0.205114	0.263155	0.255262
$LWGP_t$	1.000000						
$LWPOP_t$	0.983569	1.000000					
$LWLEB_t$	0.981255	0.988090	1.000000				
$LWPEE_t$	0.992486	0.970428	0.968347	1.000000			
$LWGFCF_t$	0.998130	0.980321	0.976147	0.991674	1.000000		
$LWHDI_t$	0.988484	0.996144	0.995391	0.974468	0.984562	1.000000	
$LWPAT_t$	0.946139	0.964861	0.952400	0.936643	0.955678	0.960591	1.000000

Sources: World Bank (2025), http://www.worldbank.org. UNDP (2024), http://hdr.undp.org. WIPO (2025), https://www.wipo.int UNESCO, https://databrowser.uis.unesco.org/resources

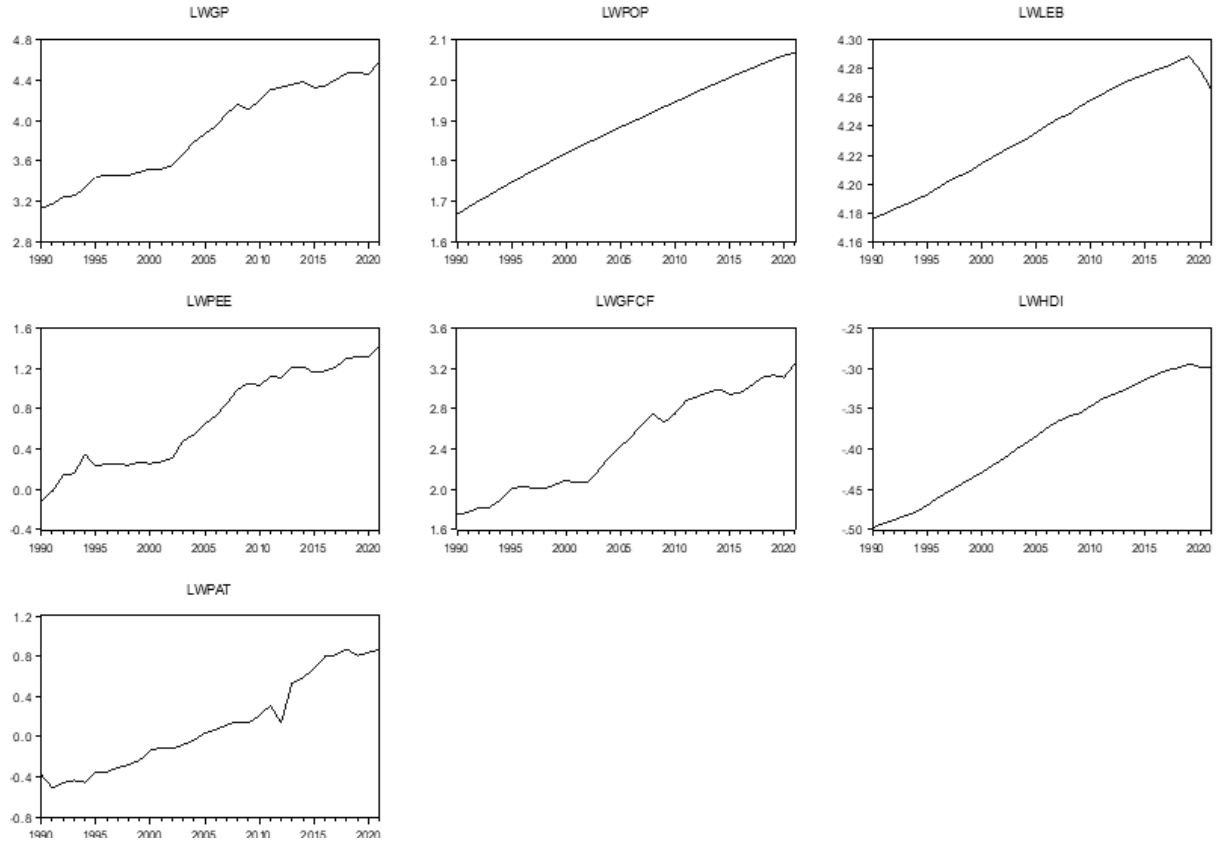


Figure 2. World variables graphs.

Sources: World Bank (2025), http://www.worldbank.org. UNDP (2024), http://hdr.undp.org. WIPO (2025), https://www.wipo.int UNESCO, https://databrowser.uis.unesco.org/resources

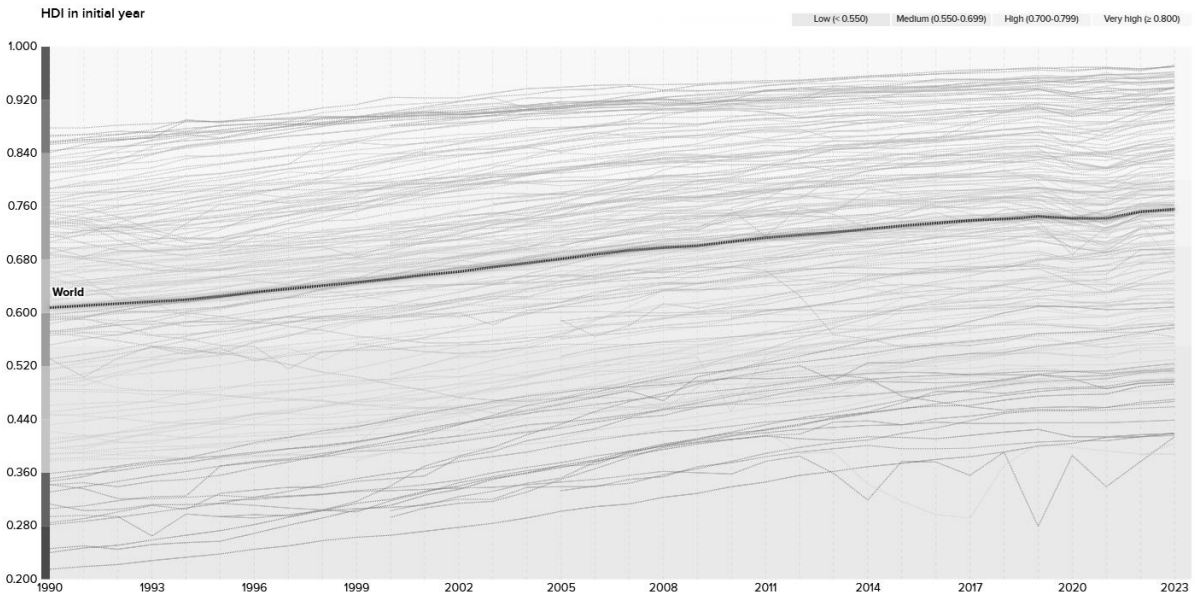


Figure 3. Human Development Index 1990-2023 (captured 2026-01-23 3:13 pm).
Source: UNDP-Human Development Report (2024). http://hdr.undp.org.
https://hdr.undp.org/data-center/human-development-index#/indicies/HDI

5.2 Unit root tests

Unit roots are non-stationary processes in AR and ARMA time series, often used in economics and finance. Unit root tests check the null hypothesis of a unit root against the alternative of stationarity (Herranz 2017). Considering the slope heterogeneity and cross-sectional dependency, the conventional unit root tests and cointegration methods, such as Pedroni (2001) and Kao and Chiang (2001) will provide spurious results (Dogan and Seker 2016).

The results for the Augmented Dickey-Fuller (ADF) test and the Phillips-Perron (PP) test from 1990 to 2021 for the variables $LWGP_t$, $LWPOP_t$, $LWLEB_t$, $LWPEE_t$, $LWGFCF_t$, $LWHDI_t$, and $LWPAT_t$ are summarized in Table 2. The findings indicate that all tests consistently show that the level data for all variables are nonstationary (Kapetanios et al. 2011). However, the first differences of these variables exhibit stationarity at a 1% critical level.

Table 2. Unit Root Test

	ADF		PP	
Variables	Level	1ST difference	Level	1st difference
$LWGP_t$	-0.580218	-4.247866***	-0.583490	-4.247866***
$LWPOP_t$	-1.302117	1.248226	-11.35600***	-0.845708
$LWLEB_t$	-1.958384	2.027730	-1.841178	1.418932
$LWPEE_t$	-0.546907	-5.872535***	-0.831384	-5.515119***
$LWGFCF_t$	-0.016038	-4.506659***	-0.031412	-4.117629***
$LWHDI_t$	-1.956329	0.301390	-1.705327	-1.918625
$LWPAT_t$	0.351780	-8.367587***	0.498200	-8.424394***

Sources: World Bank (2025). http://www.worldbank.org. UNDP (2024). http://hdr.undp.org. WIPO (2025), https://www.wipo.int. UNESCO, https://databrowser.uis.unesco.org/resources
Note: The asterisks *** denote significance at 1 % level.

5.3 Johansen cointegration test

In their research, the trace statistic and the maximum eigenvalue statistic were estimated using the Johansen cointegration approach (Johansen 1988; Johansen and Juselius 1990), as presented in Table 3. The findings show that both the trace statistic and the maximum eigenvalue statistic indicate a single cointegration relationship at the 0.05 significance level, enabling us to reject the null hypothesis. It's important to note that these statistics can sometimes conflict, and the choice between them depends on the clarity of the relationships (Johansen and Juselius 1990).

Table 3. Johansen cointegration test

Unrestricted Cointegration Rank Test (Trace)

Hypothesize No. of CE(s)	Eigenvalue	Trace statistics	0.05 Critical value	Prob.**
None *	0.930796	225.5613	125.6154	0.0000
At most 1*	0.821173	145.4403	95.75366	0.0000
At most 2*	0.728890	93.80019	69.81889	0.0002
At most 3*	0.570705	54.64323	47.85613	0.0101
At most 4*	0.403562	29.27493	29.79707	0.0573
At most 5*	0.320060	13.77152	15.49471	0.0894
At most 6*	0.070678	2.199003	3.841466	0.1381

Trace test indicates 7 cointegrating eqn(s) at the 0.05 level
* Denotes rejection of the hypothesis at the 0.05 level. ** Mackinnion-Haug-Michelis (1999) p-value

Unrestricted Cointegration Rank Test (Maximum Eigenvalue)

Hypothesized No. of CE(s)	Eigenvalue	Max-eigen statistics	0.05 Critical value	Prob.**
None *	0.930796	80.12106	46.23142	0.0000
At most 1*	0.821173	51.64009	40.07757	0.0017
At most 2*	0.728890	39.15695	33.87687	0.0107
At most 3*	0.570705	25.36830	27.58434	0.0936
At most 4*	0.403562	15.50341	21.13162	0.2552

At most 5*	0.320060	11.57252	14.26460	0.1278	
At most 6*	0.070678	2.199003	3.841466		0.1381

Sources: World Bank (2025), http://www.worldbank.org. UNDP (2024), http://hdr.undp.org. WIPO (2025), https://www.wipo.int. UNESCO, https://databrowser.uis.unesco.org/resources.
Max-eigenvalue test indicates 7 cointegration eqn(s) at the 0.05 level
* denotes rejection of the hypothesis at the 0.05 level. **Mackinnon-Haug-Michelis (1999) p-values.

5.4 World Hindcast Evaluation

A hindcast accuracy, the hindcast data from 1990 to 2021, is evaluated by using the mean absolute percentage error (MAPE), mean absolute error (MAE), root mean squared error (RMSE), and the Theil inequality coefficient (Makridakis et al. 1998; Fair 1986). All the statistics supply a distance between the hindcast and actual values as shown in Table 4 and Figure 4.

Table 4. World Hindcast Evaluation 1990-2021

Variable	Obs	RMSE	MAE	MAPE	Theil
LWGP	32	0.012310	0.009963	0.256877	0.001573

Sources: World Bank (2025), http://www.worldbank.org. UNDP (2024), http://hdr.undp.org. WIPO (2025), https://www.wipo.int. UNESCO, https://databrowser.uis.unesco.org/resources

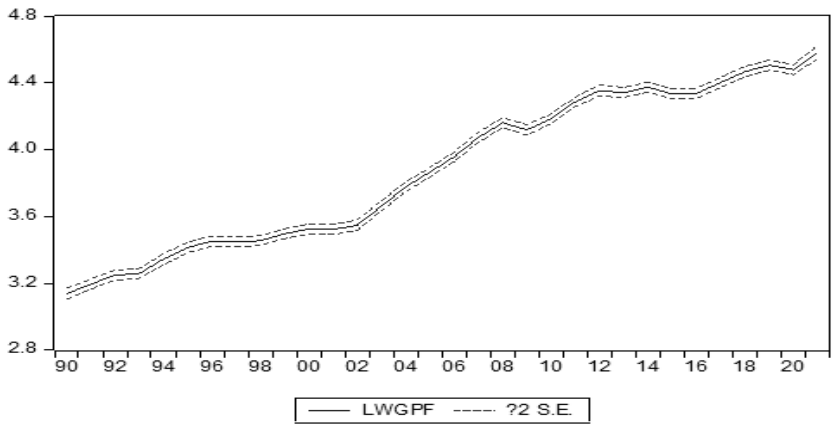


Figure 4. World Hindcast Evaluation 1990-2021.
Sources: World Bank (2025), http://www.worldbank.org. UNDP (2024), http://hdr.undp.org. WIPO (2025), https://www.wipo.int. UNESCO, https://databrowser.uis.unesco.org/resources

6. Empirical Results and Discussion

6.1 World Empirical Results of the Long-Run Causation

The results from the estimation of Equations (6), (7), and (8) are shown in Table 5. The ARDL bounds test F = 4.122853, indicating a significant relationship between the variables from 1990 to 2021.

A 1% increase in $LWGP_t$ leads to a 0.248246% increase in $LWPOP_t$, boosts $LWHDI_t$ by 1.445512%. Similarly, $LWGP_t$ rising by 1% increases $LWGFCF_t$ by 0.731542%, rising $LWLEB_t$ by 0.158686%.

Moreover, with other factors constant, a 1% rise in $LWGP_t$ raises $LWPEE_t$ by 0.090216% but decreases $LWPAT_t$ by 0.152295%. These findings underscore the significant impacts of $LWGP_t$ on various socio-economic variables.

Table 5. World Empirical Results of Long-Run Causation

Dependent variable: $LWGP_t$			
Variable	Coefficient	T-statistic	Prob. value
$LWPOP_t$	0.248246	0.877595	0.3885
$LWLEB_t$	0.158686	0.185752	0.8541
$LWPEE_t$	0.090216	2.029041	0.0532
$LWGFCF_t$	0.731542	12.43971	0.0000
$LWHDI_t$	1.445512	1.660791	0.1092
$LWPAT_t$	-0.152295	-6.749748	0.0011
C	1.454385	0.342789	0.0000

Diagnostic tests	
R^2	0.999290
Adjusted-R^2	0.999120
F-statistic (Prob. value)	5868.035(0000)***
SERIAL	0.232263(0.7946)
RAMSEY	12.71537(0.0016)
ARCH	3.770613(0.0619)
WHITE	4.613425(0.0028)
CHOW	3.718853(0.0116)

Sources: World Bank (2025), http://www.worldbank.org. UNDP (2024), http://hdr.undp.org. WIPO (2025), https://www.wipo.int. UNESCO, https://databrowser.uis.unesco.org/resources

Note: The asterisks *** denote significance at 1 % level. The numbers in parentheses are probability values. SERIAL is for Lagrange Multiplier (LM) serial correlation test, RAMSEY for Ramsey Reset test, ARCH for Autoregressive Conditional Heteroskedasticity, WHITE for white heteroscedasticity, and the CHOW test.

6.2 World Empirical Results of Short-Run Causation

The results from estimating Equations (9) and (10) are shown in Table 6. The ARDL bounds test F = 3.567204, indicating a significant relationship between the variables from 1990 to 2021.

A 1% increase in $LWGP_t$ leads to a 2.610408% rise in $LWPOP_t$ and a 1.223501% increase in $LWHDI_t$. Additionally, this growth is associated with a 0.826813% rise in $LWGFCF_t$ and a 1.390112% decrease in $LWLEB_t$. Finally, a 1% increase in $LWGP_t$ correlates with a 0.046259% rise in $LWPEE_t$ and a 0.012756% drop in $LWPAT_t$. These findings emphasize the vital impact of economic growth on advancing human development.

Table 6. World Empirical Results of Short-Run Causation

Dependent variable = $d(LWGP_t)$

Variable	Coefficient	T-statistic	Prob. value
$d(LWPOP_t)$	2.610408	2.077509	0.0486
$d(LWLEB_t)$	-1.390112	-1.415424	0.1698
$d(LWPEE_t)$	0.046259	1.344141	0.1915

$d(LWGFCF_t)$	0.826813	17.73799	0.0000
$d(LWHDI_t)$	1.223501	0.978686	0.3375
$d(LWPAT_t)$	-0.012756	-0.553797	0.5848
C	-0.032402	-1.935094	0.0648

Diagnostic test

R^2	0.961218
Adjusted-R^2	0.951523
F-statistic (Prob. value)	99.14126(0.000000)***
SERIAL	0.451989(0.6421)
ARCH	1.167389(0.2892)
WHITE	0.233530(0.9613)
RAMSEY	0.362349(0.5531)
CHOW	0.782549(0.6109)

Sources: World Bank (2025). http://www.worldbank.org. UNDP (2024). http://hdr.undp.org. WIPO (2025), https://www.wipo.int. UNESCO, https://databrowser.uis.unesco.org/resources.
Note: The asterisks *** denote 1% significance level. The numbers in parentheses are probability values.

The diagnostic test results, including the Lagrange Multiplier (LM) for serial correlation, the autoregressive conditional heteroskedasticity (ARCH) test, White's heteroskedasticity, Ramsey's regression equation specification error test (RESET), and other specifications, showed that short and long-run models passed diagnostic tests. The stability of regression is tested using Chow (1960), Brown et al. (1975), Hansen (1992), Hansen and Johansen (1992), and Quintos (1997). Cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) tests show the stability test graphs for the constancy of the regression relation over time in Figures 5 and 6 (Ploberger and Krämer 1990). The graphs are within almost the critical bounds at the 5% significance level. This indicates that all the variables in the ECM are comparatively stable and constant.

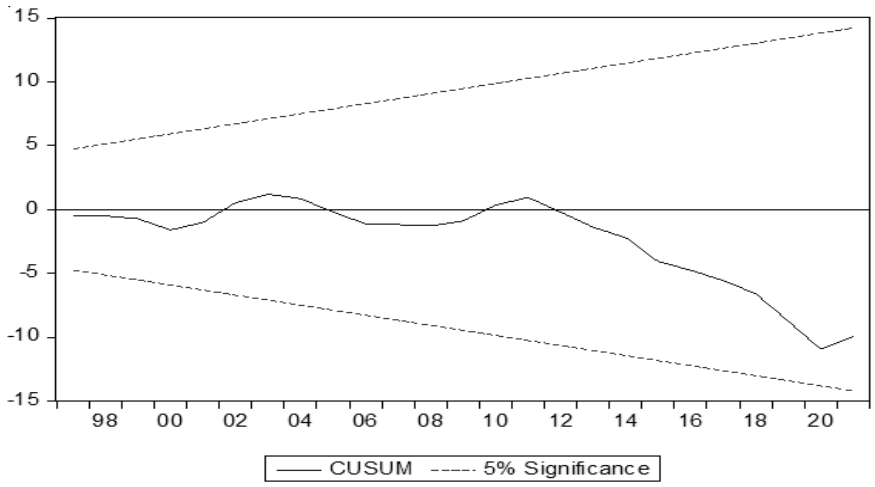


Figure 5. Plot of the cumulative sum of recursive residuals

Source: World Bank (2025), http://www.worldbank.org. UNDP (2024), http://hdr.undp.org. WIPO (2025), https://www.wipo.int. UNESCO, https://databrowser.uis.unesco.org/resources

Note: The straight lines represent critical bounds at 5% significance level.

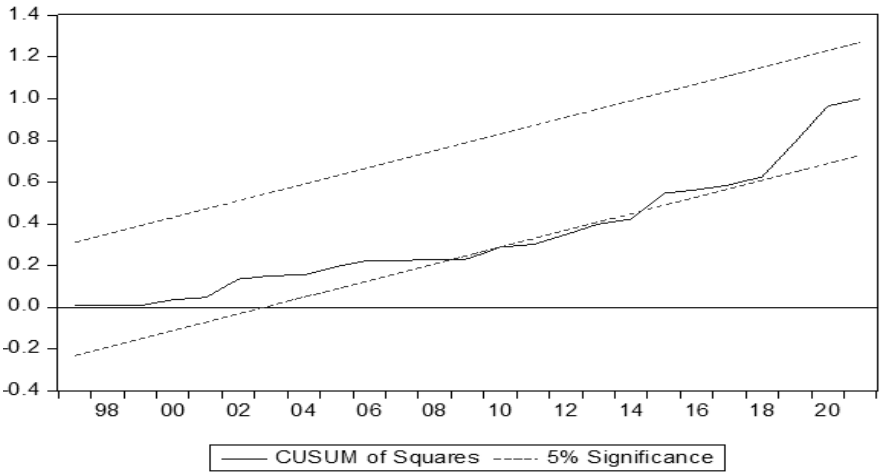


Figure 6. Plot of the cumulative sum of squares of recursive residuals

Source: World Bank (2025), http://www.worldbank.org. UNDP (2024), http://hdr.undp.org. WIPO (2025), https://www.wipo.int. UNESCO, https://databrowser.uis.unesco.org/resources

Note: The straight lines represent critical bounds at 5% significance level.

7. Sustainable Future Methodology

7.1 Sustainable Future Methodology

In the context of sustainable future methodology, we can explore various definitions of growth, development, and sustainability. Q: aggregate output, C: consumption, U: social welfare, S: aggregate resource stock, S_r: renewable resource stock, P: aggregate pollution stock, w: consumption per capita, and G: resource growth. Additional notation: $\theta > 0$ is the social discount rate, t is time, $T > 0$ is the lifespan of a generation, and subscripts bn = basic needs, sub = subsistence, and es = ecologically sustainable.

All survivability and sustainability concepts applied (Goodland et al. 1991; Pezzey 1989, 1992; van den Bergh 2007).

Economic growth = increase in Q or C

Development (process) I = increase in U = U(C, S, P)

Development (process) II = increase in c

Development (state) III = min w > c_{bn}

$$\text{Optimal path} = \text{path maximizing } \int_0^{\infty} U(t)^{e^{-\theta t}} \, dt \qquad (11)$$

Survivable growth = min w > w_{sub}

Sustainable growth I = non-declining Q (or C)

Sustainable growth II = positive and non-declining $\dot{Q}/Q$ or $\dot{C}/C$

Survivable development = min w > w_{sub} and G < G_{es}

Sustainable development I = non-declining U

Sustainable development II = non-declining U, and with min c increasing

Sustainable development III = non-declining U, and min c > c_{bn} and max c < c_{es},

Sustainable resource use I = non-declining s_r

Sustainable resource use II = non-declining S_r

Sustainable resource use III = non-declining S

Sustainable resource use IV = non-declining s_r and non-increasing p

Lifetime sustainability = instead of non-declining Z (whatever Z is),

$$\text{non-declining } \int_t^{t+T} Z(t)^{e^{-\theta t}}\, dt \qquad (12)$$

present value of Z for generation at time *t* with a time horizon stretching *T* years into the future. (Sohn 2026).

7.2 Ramsey-Cass-Koopmans growth methodologies

Malthus (1996) assumes that population, when unchecked, increases in a geometric ratio, but subsistence increases in only an arithmetic ratio. Galor and Weil (1999, 2000) found that historical evidence suggests that the key event separating the Malthusian and Post-Malthusian regimes is the acceleration in the pace of technological progress. Regarding the Ramsey-Cass-Koopmans model, Romer (2012) assumes that the model avoids all market imperfections and links among generations, whereas Gillman (2011) supposes that it is used to maximize consumer utility. Furthermore, Gillman (2011) treats the savings rate and savings behavior as endogenous and introduces exogenous technological progress to enable sustainable growth. In

addition, Barro (1999b) modifies the neoclassical growth model to include a variable rate of time preference. Hibbs (2001) assumes that the equilibrium consumption in the Ramsey-Cass-Koopmans model depends on the utility and time preference parameters. Thus, the equilibrium consumption would be maximized at the Golden Rule level,

$$f(k) = n + \phi + \lambda \tag{13}$$

where $f(k)$ is the economic growth rate, n is the population growth rate, ϕ is the technological progress rate, and λ is the rate of depreciation.

In the neoclassical growth model, the Ramsey-Cass-Koopmans model, Kremer (1993) assumes that technological progress is an increasing function of population, and income gradually increases over time with the rate of technological change. Thus, Equation (13) is used to estimate the GDP per capita technological progress rate, where λ is the depreciation rate and is assumed to be zero.

Groom et al. (2005) assume that the level of the social discount rate is critical in determining whether an individual public investment or policy will pass a CBA test. Consequently, Weitzman (2010) concludes that the economics of distant-future events, such as climate change, is critically dependent on the choice of discount rate.

7.2.1 Growth rate of consumption per capita

The GDP growth rate per capita is estimated using long-term projections and is incorporated into the Ramsey-Cass-Koopmans model to determine consumption growth. This study uses United Nations population statistics (2004) from 2000 to 2300, projecting an annual population growth rate of 0.13% for this period.

7.2.2 Exponential function

Exponential functions can be classified as (a) the constant form $G(0) = G_0$; (b) the linear form $G(t) = G_0e^{kt}$, $G(t) = G_0e^{-kt}$; (c) the nonlinear form $G(t) = G_0e^{kt^2}$; and so on. Here, G is the economic growth rate, t is time, and k is a parameter (Allen 1938; Caplin and Leahy 2004; Stewart 2012). Meadows et al. (1972) assume that exponential growth is a dynamic phenomenon, which means that it involves elements that change over time. In addition, Bomhoff (1994) assumes that anything that grows tends to grow exponentially rather than linearly. In the case of exponential decay, Caplin and Leahy (2004) analyze and estimate the future discount rate. They show that a constant discount rate characterizes the exponential discount function. In addition, Stewart (2012) shows that when economic growth decays exponentially, it decreases at a rate proportional to its size at time t. Thus, the model for exponential decay is

$$dG/dt = -kG,\ G(0) = G_0 \tag{14}$$

where $k = -1/G \times dG/dt$ is a constant decay rate and $k > 0$. Since the economic growth rate is decreasing, $dG/dt < 0$, and $k = -1/G \times dG/dt$. Thus, the value is

$$G(t) = G_0e^{-kt} \tag{15}$$

where $G(0)$ is the initial economic growth at time $t = 0$, k is a constant decay rate, $k > 0$, t is the time taken for the economic decay, and $G(t)$ is the economic growth at time t.

Furthermore, Nordhaus (2004) assumes that the erosion of Schumpeterian profits follows an exponential decay process with a decay rate of λ per year. This implies that if an innovation was introduced θ years ago, the appropriation rate would be $\alpha e^{-\lambda\theta}$ after θ years, where α is the ratio of the fundamental appropriability to cost savings from the innovation (Schumpeter 1934, 1939).

7.2.3 Exponential decay function

In context of exponential decay, the GDP growth rate is expected to decrease exponentially (Allen 1938; Kemp and Thānh 1966; Hansen 2008; Caplin and Leahy 2004; Stewart 2012), and the exponential decay function $G(t)$ is formed as follows:

$$G(t) = exp\ (\alpha t + \beta) \tag{16}$$

$$t = (y_x - y_b)/n \tag{17}$$

α = -102689, β = 1.540335

where $\alpha \neq 0$, $\beta \neq 0$, α, β are constant, t is time, y_x is an application year, y_b is a base year, and n is a period (Sohn 2019).

Using Equations (16) and (17), the social cost of carbon (SCC) is estimated about US$21 per ton of CO_2 in 2010 (United States Government Interagency Working Group on Social Cost of Carbon - Under Executive Order 12866 2010; Ackerman and Stanton 2010; Greenstone et al. 2011) and the SCC increases over time (Tol 2023; Dong et al. 2024; Sohn 2019).

8. Future Sustainable Criterion

Forecasting the future is challenging. While traditional reductionist science analyzes current phenomena, it is less effective for predictions. A preferred approach is an ex ante perspective that emphasizes emerging ideas and techniques (van der Leeuw 2020; Tan et al. 2020).

Sustainability challenges necessitate a thorough exploration of future perspectives that include cultural and philosophical viewpoints. Sustainability science should integrate natural and social sciences, using scenario analysis as a key tool for knowledge generation (Swart et al. 2004; DPCSD 1997). As diagnostic tools, the interaction archetypes can bring a deeper understanding of causal drivers or policy resistance in SDG progress and their potential dynamic behavior in the future (Mokhtar and Aram 2017; Zare et al. 2017; Moallemi, Hosseini et al. 2022).

Key challenges include managing land and water resources, maintaining ocean integrity, addressing the energy-economy-environment dilemma, and striving for nuclear disarmament (Holdren 2008). Sustainability also involves integrating science with justice, economics, and policy (Niesenbaum 2020), emphasizing intergenerational equity (WCED 1987; Faber et al. 2005; Huq et al. 2006).

The neoclassical economic growth theory discusses the Hicks-Solow sustainability criterion (Pierantoni 2004; van den Bergh 2007). The sustainability criteria are presented in a set of matrices, separating the criteria into product life-cycle phases and socio-ecological sustainability principles (Hallstedt 2017). Ethical guidelines significantly impact environmental outcomes, with modifications potentially mitigating adverse effects (Pearce 1983). Wiggins (2006b) has offered a set of arguments against central assumptions about the nature of well-being, practical reason, and ethical deliberation that underpin this dominant

economic approach (O'Neill 2022).

The Resilience Project evaluates whether solutions yield more viable problems and opportunities (Holling 2000), while Weitzman (1997) argues that sustainability relates to future consumption. Addressing missing data in predictive tasks is crucial, with recent approaches like the Uncertainty-Aware Self-Attention (UASA) model enhancing reliability (Jiabao et al. 2025). All types of data can play a role in the design of smart products and digital services, and allow the technical, operational, and managerial changes necessary to lead such a data-driven transformation to be depicted (Monti et al. 2025).

Sustainable development embodies adaptive management and social learning, emphasizing knowledge (Cash et al. 2003). Critical issues involve optimal depletion of environmental goods (Dasgupta and Heal 1974) and incorporating uncertainty about future generations' preferences (Beltratti et al. 1993, 1998).

Wiek and Iwaniec (2013) outline three conclusions to improve sustainability visioning: First, more empirical evidence is needed for quality criteria. Second, methodologies should meet all criteria. Lastly, specialized educational programs should train researchers and professionals in sustainability visioning. Fauré et al. (2017) found that no single tool effectively evaluates scenarios. Quantitative tools are suitable for short-term assessments, while qualitative methods work better for long-term evaluations. More tools are also needed to address a wider range of environmental and social impacts.

9. Uncertainty

Weitzman (1998, 2001, 2010, 2011) suggested that the appropriate discount rate for the distant future is uncertain, making it essential to establish reasonable rates to determine the time profile of discount factors (Pearce et al. 1990; Filar and Haurie 2010; Traeger 2009, 2014). Guo et al. (2006) indicated that the decrease in the certainty-equivalent discount rate depends on the assumed probability distribution of discount rates. Gollier (2002, 2013) linked discount rate uncertainty to growth rate consumption and the risk aversion parameter. Uncertainty can foster innovation but may also impede the adoption of new technologies (Rosenberg 1983, 1994), making it a crucial element in the innovation process (Schumpeter 1934, 1939; van der Leeuw 2020). Over the next century, significant uncertainties remain regarding biodiversity, atmospheric chemistry, and climate change (Goudie 1993). Historical data, like HadCRUT (Jones 1994; Jones and Moberg 2003), show that while uncertainties were larger in earlier periods, the temperature increases of the twentieth century were still notable (Brohan et al. 2006). The works of Heal et al. (1998), Ayong Le Kama (2001), and others have explored planning under evaluation criterion uncertainty. Krysiak and Krysiak (2006) noted that uncertainties are eventually resolved and affect both close and distant generations. Thus, Weitzman (1998, 2001, 2010, 2011) emphasized the need for establishing reasonable discount rates to assess future uncertainties effectively.

10. Conclusion

Justified pleas have been made to instead, or also, address climate change from a sustainable development viewpoint (Robinson et al. 2006; Swart et al. 2003; Cohen et al. 1998; Štreimikienė and Mikalauskienė 2021). Linking climate change and development policies can promote sustainability. Climate engineering solutions act as a last resort against unexpected challenges. Research funding for these solutions is important to understand their environmental impacts and related regulatory and governance issues (Fankhauser 2012). The integration of climate and developmental goals has several dimensions. More detailed suggestions for combining climate and non-climate policies can be found in Kok and de Coninck (2004). Today's policy decisions will shape society's future. We may face either a sudden collapse or a gradual shift to sustainability, but unlimited growth in resources is impossible on a finite planet (Meadows et al. 2004; Ayers 2017).

Thus, Fairness to Future Generations relies on a fundamental norm of equality among generations of the human species in relation to the care and use of the natural system (Weiss 1990). Sustainability appears to be at least a necessary condition for justice (Barry 1997). Moral responsibility towards the future, implicit in sustainability, is itself a requirement of justice. Sustainability is a moral commitment to sustaining the conditions in which human well-being can be achieved, both present and the future (Dower 2004).

We explored new methodologies for a sustainable future, emphasizing the need for a different approach. By outlining various authors' perspectives, we aimed to raise important questions to consider in our decision-making for the future (van der Leeuw 2019).

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