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Modeling the Links Between Economic Growth, Socio-economic Dynamics and Environmental Dimensions: a Panel VAR Approach

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Modeling the Links Between Economic Growth, Socio-economic Dynamics and Environmental Dimensions: a Panel VAR Approach

Abstract

Damien OUZILLOU
Amundi Investment Institute
damien.ouzillou@amundi.com

Raphaël SEMET
Amundi Investment Institute
raphael.semet@amundi.com

Lauren STAGNOL
Amundi Investment Institute
lauren.stagnol@amundi.com

Takaya SEKINE
Amundi Investment Institute
takaya.sekine@amundi.com

This study delves into the intertwined relationships between demographics, biodiversity, climate change, political stability, and inequality that shaped GDP growth in 166 countries from 2000 to 2020. Combining Granger causality for panel data with causal graph design, we uncover direct and indirect effects, comprehensively assessing the causal dependencies between these dimensions. In particular, we find that extra-financial indicators can rival traditional macroeconomic variables in predicting GDP growth for low-income countries. In contrast, high-income countries benefit from the synergies of both. Impulse response functions derived from panel VAR (PVAR) models allow us to quantify both direct and indirect effects at play between demographics, biodiversity, climate change, political stability, and inequality, shedding light on the mechanisms behind economic growth and offering an investor a new lens to assess potential opportunities and risks across countries.

Keywords: Macroeconomics, economic growth, ESG, extra-financial, Granger causality, VAR modeling, PVAR, Panel data.

JEL classification: O4, C23, Q5.

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About the authors

Damien OUZILLOU

Damien Ouzillou joined Amundi in July 2023 as an intern in the Quant Portfolio Strategy team of Amundi Investment Institute. His work focuses on causality using time series, graph theory, optimization and structural equations. He studied the interlinkages between economic growth, socio-economic dynamics and environmental dimensions.

Damien is an engineering student at the CentraleSupélec engineering school, pursuing a Master degree in applied mathematics and computer science, specialized in probability and statistics. He also holds two Bachelor degrees in mathematics and computer science at Paris-Saclay University (2021).

Raphaël SEMET

Raphaël Semet is a Quant Researcher at Amundi Institute. He works on the social dimensions of ESG, estimating the materiality of social issues at the macroeconomic level and more specifically in financial markets. He joined Amundi in May 2021 in the Quantitative Research team following an internship dedicated to the impact of extra-financial analysis in sovereign credit risk. He holds a Master's degree in Risk and Asset Management from the University Paris Saclay. Currently, Raphaël is pursuing his Ph.D. in Economics at the University Paris Saclay, focusing on the social implications of the environmental transition. His research has led to insightful contributions, particularly regarding the public perception and acceptance of carbon tax policies.

Lauren STAGNOL

Lauren Stagnol, PhD is an Equity Quantitative Researcher at Amundi Investment Institute. She conducts research projects and develops tools and strategies closely linked to portfolio management platforms. She joined Amundi in 2014 as a Fixed-Income Quantitative Researcher for three years. From 2017 to 2020, she was a Bond Portfolio Manager at Candriam in Bruxelles managing euro aggregate and smart beta portfolios. In 2020, Lauren re-joined Amundi as a Quantitative Researcher. Her areas of research cover smart beta, factor investing, sustainable investing, big data based economic and geopolitical narratives in both fixed income and equities.

Lauren completed her Ph.D. thesis entitled "Accounting for risk in the design of fixed-income benchmarks" in Economics at the Université Paris-Nanterre in June 2017, within the doctoral school "Economie, Organisation et Société", co-accredited with les Mines Paris Tech. She also holds a Master of Science in Applied Economics and Econometrics from Université Paris-Nanterre and a Bachelor of Science in Business Economics from Cardiff University (UK).

Takaya SEKINE

Takaya Sekine, CFA is the Deputy Head of Quant Portfolio Strategy within Amundi Investment Institute (formerly known as the Quantitative Research Team of Amundi). In this role, he works on the practical implementation of quant research and alternative data for investment strategies.

He joined Amundi in 2000 and is in his current position since July 2018. Prior to that, he was Deputy CIO at Amundi Japan (between 2011 and 2018) with a focus on global quantitative strategies, Head of Index and Multi-Strategies at Amundi Japan (between 2010 and 2011), Fund Manager (between 2007 and 2010) and Financial Engineer (between 2001 and 2007). He has been involved in macro and policy related investment strategies for both retail and institutional clients. Takaya began his career as an IT Manager at Amundi Japan's predecessor company (between 2000 and 2001).

Takaya is a CFA charterholder since 2005 and an Associate member of the Association of Certified Fraud Examiners since 2010. He received the Ingénieur Civil des Mines degree from Ecole des Mines de Nancy in 2000.

Key takeaways

- Our paper aims at improving our understanding of the interconnections and causal relations between extra-financial metrics and economic growth.
- We quantify such mechanisms in a panel VAR model, revealing the existence of indirect effects.
- The causalities from political stability to economic growth and inequality, and the impact of the latter on demographics, are the most robust relationships identified across our full sample of countries.
- The integration of environmental concerns (either climate change mitigation or biodiversity conservation) in the mechanisms studied varies by income level.
- It is interesting to highlight that progress on the climate change front does not foster significant improvements on other variables in high-income countries. However, in low-income countries, it can substantially mitigate inequalities.
- These findings argue for global improvements in freedom of expression as an essential way to improve economic growth and reduce inequality. A fairer society would also lead to sounder demographic dynamics.
- Our analysis praises for the integration of extra-financial indicators in the design of macro models.

1 Introduction

In the contemporary global economy, the intricate interplay of demographic shifts, climate change, biodiversity loss, political stability and social inequalities constitutes a nexus of risks that looms large on the global stage. Demographic dynamics, shaped by population fluctuations and migration patterns, have profound implications for resource allocation and societal structures. Concurrently, the accelerating impacts of climate change pose unprecedented challenges, disrupting established patterns of economic activity and putting biodiversity under pressure (IPCC, 2021). These threatened ecosystems, vital for the fragile balance of human life, trigger cascading effects that remain the biggest challenge of the century (World Economic Forum, 2023b). Political pressures, entwined with resource competition, introduce additional layers of uncertainty in the economic realm. Social inequality weaves through each dimension, amplifying the consequences for vulnerable communities. The stability and resilience of nations rely directly on each single dimension, but also beyond the conventional economic channel. A comprehensive examination is essential to understand these complexities and their potential impact on growth prospects and financial markets, but also for an effective global strategy in the face of multifaceted risks.

The growing recognition of *a-priori* extra-financial factors' materiality on financial markets underscores the relevance of non-macroeconomic dimensions. For instance, based on an empirical approach, Semet *et al.* (2021) showed that accounting for Environmental, Social, and Governance (ESG) indicators increases by 13.5% the explanatory power of a model explaining sovereign bond yield spreads, compared to a fundamental specification (consisting of macroeconomic variables). In this context, refining our understanding of the mechanisms at play between extra-financial dimensions such as demographic pressures, political stability, inequality, biodiversity loss, accelerating climate change, and their impact on the economy is essential. This paper strives to empirically quantify these interactions across a wide range of countries, providing a framework that enhances our understanding of such mechanisms and allows us to formulate predictions regarding how these dimensions shape future economic growth. The main contribution of our study lies in the global assessment of the direct and indirect mechanisms at play between these dimensions. To illustrate, we found that, for low-income countries, although biodiversity (captured by the proportion of forests) does not cause directly economic growth, it impacts political stability (measured via the freedom of expression), which in turn supports economic growth.

In this paper, we provide causality graphs, using Granger causality analysis to identify which variable causes and/or is caused by other variables. Our results show that extra-financial variables - biodiversity, demography, climate change, political stability, and inequality - are as important as macroeconomic factors in explaining GDP growth in the lower income countries. A combined model of extra-financial and macroeconomic variables for high-income countries outperforms single models (composed only of extra-financial or macroeconomic metrics), showcasing enhanced explanatory power. The most robust relationships we identified across all countries studied are the influence of political stability on economic growth and inequalities and the role of inequalities in driving demographic dynamics. The role of climate change and biodiversity within the dimensions we investigate depends on a country's level of wealth. However, we found that such environmental dimensions can alleviate inequalities overall. Furthermore, alongside political stability and inequalities, demographic dynamics emerge as crucial drivers of economic growth in low-income countries.

The paper is structured as follows. First, in Section 2 we conduct a literature review on the potential relationships between the dimensions covered in our study. Section 3 presents the data and the measures of Granger causality that we will use to derive causality graph. Subsequently, Section 4 introduces the Vector Autoregression (VAR) model employed to address our research question. It enables the evaluation of extra-financial variables' explanatory power to quantify the causalities and analyze the Impulse Response Functions (IRFs). In Section 5, we present the primary findings and the main mechanisms between our variables of interest. Finally Section 6 offers concluding remarks.

2 Literature Review

This section aims to analyze existing research on the relationships between the aforementioned dimensions and economic growth. We focus on extra-financial variables that are measurable, and broadly documented in the literature. Hence we investigate the existing cross-relationships between demographics, biodiversity, climate change, political stability, social inequality, and economic development. In fact, these dimensions are highly reflective of the assumptions behind Shared Socioeconomic Pathways (SSP) (IPCC, 2021), which testifies to their relevance but also strong interconnection. These simplified scenarios translate socio-economic system changes following adaptation to / mitigation of climate change (Le Guenedal, 2019) and are hence tightly linked to GDP projections (Koch & Leimbach, 2023). Mapping academic findings related to relations between these dimensions allows to have economic stylized facts in mind when interpreting our results.

As the interlinkage scope can be wide for some dimensions, we limited the depth of the literature review by focusing only on the empirical literature related to the set of variables we use in this article. As each dimension encompasses multiple aspects (e.g., urbanization, income inequality, gender discrimination, physical risk, transition risk, etc.), generally associated with several strands of the literature (e.g., economics, sociology, physics, etc.), we tried to summarize the effect of one dimension on the other by looking at one dimension at a time and principally relying on empirical studies.

2.1 Demographics

Demographics is the statistical analysis of human population dynamics. Demographics have greatly impacted our societies, notably during the past decades, when unprecedented changes have been possible thanks to population shifts. Indeed, the increase in population over the last 50 years has been greater than in the preceding million (Raleigh, 1999). The population dynamics are constituted of several components such as the size, the structure (i.e., age and sex), and the composition of the population (e.g., rural/urban, education level, etc.), which are affected by fertility, mortality, and migration (Hugo *et al.*, 2008). In what follows, we split the demographic analysis into three components.

2.1.1 The size effect

The role of demographics in economics is paramount and still receives much interest from researchers. Based on a comprehensive literature review, Menike (2018) suggested that population size can negatively or positively affect economic development. The "pessimistic" view establishes that the speed of population growth should be reduced as a country reaches its state of development. Any additional increase in the population beyond this threshold can be economically harmful. For the "optimistic" perspective, the growing population might be recognized as an efficient factor of demand, creating income, which, in turn, initializes the development of technology. This can lead to improvements in health, for example, by increasing life expectancy and human capital, which favors demography (Hugo *et al.*, 2008). However, Kozlovskyi *et al.* (2020) indicated that life expectancy would favor the growth of nominal rather than real GDP per capita. This demographic phenomenon seems even more pronounced for advanced economies.

The growth rate of the population has several implications for the economy and the environment. We partly owe this relationship to Malthus' seminal work on the delicate balance between population and resources. Malthus (1798) points out that resource constraints will sooner or later overtake population growth unless it is curbed by "moral restrictions" or "positive controls" such as plague, famine, and war. Although Malthus shed light on a critical and global mechanism, technological progress allowed to tackle the adverse effects of his theory. Nonetheless, the link between population dynamics and the environment is still particularly thin, notably on biodiversity, as population increase may threaten species conservation (Dietz & Rosa, 1994; Foley *et al.*, 2005; Hanif & Gago-de-Santos, 2017; Smail, 1997). The National Research Council and others (1986) asked a working group to address nine relevant questions on population growth and economic development. Among other results, the authors concluded that rapid population growth can negatively affect access to renewable resources, air and water quality, climate, and species diversity. Moreover, the intensity of devastation depends on the efficiency of social institutions in monitoring resource use and cost distribution. However, the role of institutions, markets, and feedback effects in limiting the impact of demographics on environmental change has to be nuanced (Keyfitz, 1992). According to Luck (2007), there are several significant correlations between population density, species richness, and extinctions. The author highlights the negative correlations between population density and the coverage of protected areas as the areas designated for species conservation tend to be reduced near human settlements. Population growth pressures ecosystems, particularly through expanding agricultural landscapes (Perrings *et al.*, 2006). This expansion will be made at the expense of current unaffected land, reducing the width of the remaining biodiversity (Lambin & Meyfroidt, 2011). In the same vein, deforestation and pressure on fish species are generally associated with increasing demographic trends (Clausen & York, 2008; Murray *et al.*, 1994).

Indisputably, the relationship between population growth and greenhouse gas (GHG) emissions is positive (P. R. Ehrlich & Holdren, 1971; P. Ehrlich & Ehrlich, 1991; O'Neill *et al.*, 2004; Shi, 2001). The intensity and sensitivity of per capita emission following an increase in population may range between 0.75 (Gerlagh *et al.*, 2023) and 1 (M. A. Cole & Neumayer, 2004; O'Neill *et al.*, 2012). The effect could be induced by the growing rate of fertility and urbanization coming from emerging countries, although its role should be nuanced (O'Neill *et al.*, 2012). Using data for 93 countries over the period 1975-1996, Shi, 2003 found that the liability of population change in climate change is more than proportional. The effect is much more pronounced in emerging countries than in developed ones. Casey and Galor (2017) estimated the elasticity of carbon emissions with respect to population and income per capita during the 1950-2010 period. They found that the elasticity with respect to population is approximately seven times larger than the elasticity with respect to income per capita.

2.1.2 The structure and composition effect

A country's demographic structure and composition represent a strength for the economic development (Prskawetz *et al.*, 2007). For instance, Bloom *et al.* (2001, 2007) found that an increasing proportion of the working-age population can substantially improve economic forecasts, something termed as the "demographic dividend". The authors stipulate that the dynamics of the age structure predict economic behaviors and interactions. In other words, young people need education and healthcare spending, adults need work and savings, while the elderly need healthcare and retirement income. For developed countries, Wongboonsin and Phiromswad (2017) found that an increase in the share of the middle-aged working group positively affects economic growth via institutions, investment, and education channels. The result does not hold for developing countries. Meanwhile, the demographic transition[1] may adversely impact the economy due to the contraction of the working-age share of the population. For the U.S., during the 1980-2010 period, Maestas *et al.* (2016) found that population aging reduced the GDP per capita growth rate by 0.3 percentage points per year. Predictions are on the same tracks. Kotschy and Bloom (2023) found that population aging will slow economic growth in the coming decades. This

[1] The demographic transition can be defined as the long-term trend of declining birth and death rates resulting in a shift of the age distribution of the population (Tulchinsky & Varavikova, 2014).

economic slowdown would ultimately permit to save emissions (Dalton *et al.*, 2008; Hassan & Salim, 2015; Shi, 2003), but could increase health inequalities (World Health Organization, 2015).

The rapid development of urban areas has triggered important societal shifts and will remain visible in the coming decades since almost all future population growth will appear in cities (Jedwab *et al.*, 2017). Urban concentration has been found to be conducive to economic growth (Frick & Rodríguez-Pose, 2018; Henderson, 2000; Liddle & Messinis, 2015). However, the relationship appears to be bell-shaped, with the growth rate diminishing after reaching a certain concentration level (Henderson, 2000). For instance, income growth can favor migration from many developing countries (McKenzie, 2017), which can result in poverty hubs in urban areas if not well managed (Tacoli *et al.*, 2015). Additionally, academics pointed out that beyond population increase, urban density growth is one of the leading factors explaining the plant and animal species extinction and represents one of the biggest struggles in biodiversity conservation (Ahmed *et al.*, 2020; McDonald *et al.*, 2008; Shochat *et al.*, 2006). Bai *et al.* (2017) examined the environmental implications of urban density. The article focuses on the relationships within six dimensions: air pollution, ecosystems, land use, bio-geochemical cycles and water pollution, solid waste management, and climate. They concluded that many challenges remain but emphasized the great opportunity of such demographic composition for the construction of sustainable cities. While urbanization can be associated to economic development through education attainment (Ahmed *et al.*, 2020; Guliyeva *et al.*, 2021) and ease the access to water (P. Roberts *et al.*, 2006), it could also generate poverty, regional inequality, health and environmental degradation (Boadi *et al.*, 2005; Liddle, 2017; Moore *et al.*, 2003).

Regarding climate change, the carbon intensity of the population is generally associated with population composition, notably through life expectancy (Jiang & Hardee, 2011; Liddle & Lung, 2010; Rauscher, 2020). To illustrate, Murthy *et al.* (2021) found that among several indicators, such as economic growth, population growth, and health expenditure, life expectancy can be explained by carbon emissions. Chen *et al.* (2022) performed the analysis on the BRICS[2] during the 1990-2019 period. Urbanization and population growth stand out as the most important predictors of carbon emissions. However, there might be nonlinearities between the age of the individual and its level of emissions (O'Neill *et al.*, 2012; Wang & Li, 2021). For instance, Hassan and Salim (2015) estimated that population aging reduces GHG emissions. In addition to age, Chancel, 2014 suggests that generation affiliation can also explain differences in carbon footprint distribution.

[2]The BRICS is an intergovernmental organization comprising Brazil, Russia, India, China, and South Africa.

2.2 Biodiversity

The United Nations Convention on Biological Diversity[3] (UNCBD) defines biodiversity as "the variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems". The abundance of natural capital has permitted humankind to develop and thrive over the ages. Ecosystems are the main source of goods and services (e.g., food, fiber, fuel and energy, medicines, clean water, clean air, flood/storm control, pollination, seed dispersal, pest and disease control, soil formation and maintenance, cultural, and aesthetic and recreational values) required for human survival (Gitay *et al.*, 2002).

Biodiversity cannot be separated from the economic network. In fact, estimates suggest that more than half of the world's GDP (around $44 trillion) is moderately or highly exposed to risks from biodiversity loss (Herweijer *et al.*, 2020). According to the World Economic Forum (2023b), biodiversity loss and ecosystem collapse represent the fourth most concerning risk over the last ten years. However, economic development is generally accountable for biodiversity stress through increasing demand for resources, the exploitation and destruction of species, unsustainable land use, soil, water, and air pollution, diversion of water, fragmentation, and unification of landscapes and urbanization (Gitay *et al.*, 2002). The impacts of biodiversity loss are numerous, but the intensity of the repercussions remains uncertain. Indeed, a small perturbation of an ecosystem can substantially hamper the structure and functioning of the whole ecosystem irreversibly (Cardinale *et al.*, 2012). For instance, Hooper *et al.* (2012) concluded that species loss had a similar impact on primary productivity as disastrous climate hazards such as drought, ultraviolet radiation, climate warming, acidification, or fire. Mechanically, biodiversity loss will primarily affect the production of foods, fuels, and fibers, which might impede food security (Perrings *et al.*, 2006). Combined with climate change, these two interdependent dimensions can have a snowball effect, as biodiversity helps to stabilize ecosystem productivity and services after climate events (Isbell *et al.*, 2015).

Researchers have also highlighted concerns about inequality raging from biodiversity loss. People suffering from these impediments rely directly and indirectly on ecosystem services such as food production, including agriculture, livestock, and hunting (Delang, 2006; Millennium Ecosystem Assessment, MEA, 2005; Perrings *et al.*, 2006). For instance, Pimentel *et al.* (1997) found that around 300 million people have an economical dependence on forests. Farnsworth *et al.*, 1988 reported that around 80% of the developing countries' population relies on biodiversity for primary health care. Additionally, 85% of the drugs produced by traditional medicine originate in nature. Alongside the shortcomings in health supply, biodiversity loss jeopardizes human health through the transmission of infectious diseases (Keesing *et al.*, 2010; Marselle *et al.*, 2021). As demonstrated by Adams *et al.* (2004), these resources are vital to humankind, and the consequences of their dysfunction are

[3]The Convention was signed at the 1992 Earth Summit in Rio de Janeiro by 168 countries.

directly linked to poverty threat, political instability, and social inequality.

Biodiversity constitutes a pool of economic resources that maintain the standard of living of many individuals. One could assume that the risk of biodiversity loss should initiate incentives to protect the environment. However, Smith *et al.* (2003) showed that rich biodiversity areas are generally located in countries with lower governance scores than other nations. This would limit the global effect of conservation policies since biodiversity conservation should be embedded in public decision-making (Patrick, 2022). The findings of Hanson *et al.* (2009) indicate that 90% of armed conflicts in the second half of the twentieth century occurred within countries containing biodiversity "hotspots". Furthermore, threatened ecosystems can affect social relations and even result in conflicts, notably through the impact of biodiversity loss on well-being, health, and security (Millennium Ecosystem Assessment, MEA, 2005). Similarly, species extinction gives rise to violent practices for protecting areas using military tactics. For instance, Orta-Martínez and Finer (2010) illustrated the case of biodiversity degradation and the resistance of indigenous groups in Peru. The emergence of "green wars" against poaching also echoes the increasing pressure on ecosystems (Büscher & Fletcher, 2018; Duffy, 2014). To summarize, biodiversity is the keystone of our economic network and might be the source of growing poverty and raging conflicts if not sustainably managed.

2.3 Climate Change

Climate change is defined as the "statistically significant variation in either the climate's mean state or its variability, persisting for an extended period (typically decades or longer)" (Masson-Delmotte *et al.*, 2022). The United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as "a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods". The UNFCCC's definition stresses the human liability in the environmental issue. Concretely, global warming is the human-driven change of CO_2 concentration in the atmosphere. This accumulation implies an increase in the mean atmospheric temperature through the greenhouse gas effect. Average temperature shifts alter the natural system's functioning. Consequently, the amplification of environmental hazards impacts, directly or indirectly, each of the dimensions studied in this article and beyond. According to World Economic Forum (2023b), global warming has been the major global risk in the last decade and will still be influenced by the capacity of economies to initiate decarbonization. The climate change dimension is thus confronting two risks: the physical and the transition risk. While the former is related to the physical impacts of climate change, the latter is associated with the adjustment to a low emission economy. This distinction advocates short-term reactions to curb GHG emissions using mitigation policies and the medium-term adaptation measures required to curb the repercussions of physical damages. We keep this distinction throughout the article.

2.3.1 The physical risk

Scientists and economists have worked together to estimate the economic repercussions of the intensification and recurrence of climate hazards. Integrated Assessment Models (IAM) have been used to compute the social cost of carbon[4] through the optimization of the benefit-cost trade-off. Estimating the economic cost[5] of physical risks is paramount in IAMs but greatly uncertain (Diaz & Moore, 2017). To illustrate, Newell *et al.* (2021) estimated that the regional impacts on GDP will range between -4% and $+359\%$ in 2100. A 1% loss of global GDP amounts to $800 billion today but can be 5 to 12 times greater by 2100. On the empirical side of the literature, academics have particularly investigated the temperature effect on economic growth. Regardless of development level, M. Burke *et al.* (2015) advocated for a nonlinear relationship between economic productivity and temperature, which might peak at 13°C and then sharply decline. Specifically for the European Union (EU), Ciscar *et al.* (2011) suggested that the discounted impact of climate change may halve the annual welfare growth in the long run. However, these impacts vary substantially across countries. For instance, Dell *et al.* (2012) found that a 1°C increase in temperature will impact economic growth by 1.3 percentage points in developing countries. Conversely, climate change tends to hurt relatively less developed countries (Dell *et al.*, 2012; Diffenbaugh & Burke, 2019; Newell *et al.*, 2021). Therefore, we understand the difficulty of quantifying climate change's impact on economic growth and whether it has a positive or negative effect overall (Tol, 2018).

The uncontrolled temperature rise would ultimately devastate ecosystems [6], strengthening the link between climate change and biodiversity. For instance, Warren *et al.*, 2018 estimated that for a 4°C increase in the global mean temperature, the loss of biodiversity's areas will be reduced by 40%, ranging between 30% and 80% for mammals and insects, respectively. Flannigan *et al.* (2000) conclude that global warming significantly and immediately impacts ecosystems in the U.S. - one of the megadiverse countries - notably due to wildfires becoming more severe and affecting larger areas. D. Jacob and Winner (2009) note that if trends in GHG emissions keep up, global air quality will decline dramatically. This air quality degradation may have consequential impacts on ecosystems (Greaver *et al.*, 2012; Lovejoy, 2006). In particular, sulfur and nitrogen emissions can cause acid rain, which damages fauna and flora. From these few references, we understand that climate change acts as a biodiversity loss multiplier, creating uncontrollable cascading effects with sometimes irreversible repercussions.

The distribution of climate change damages across the global population also

[4] The social cost of carbon is the "shadow price" of an efficient carbon tax, allowing to balance current costs and future benefits of such pathway of decarbonization.

[5] While current generations endorse the cost of the carbon tax through carbon price mechanisms, the benefits of such policy implementation are represented by the discounted economic cost of avoided damages.

[6] As climate change is a natural science subject, the empirical approach of researchers can encompass a much broader set of notions than those emphasized here.

receives much interest from academics. The emergence of the climate justice argument[7] echoes asymmetries in the liability and repercussions of climate change. Ravallion *et al.* (2000) argue that developed countries have predominantly emitted large amounts of GHG to grow at the expense of vulnerable countries, predominantly affected by damages, whose liability in the environmental issue would then be almost nonexistent[8]. As a consequence, most of the climate-induced damages are disproportionately borne by poor countries (Mendelsohn *et al.*, 2006; Tol *et al.*, 2004), mainly explained by geographic factors (Mendelsohn *et al.*, 2006) and agricultural dependency (Palagi *et al.*, 2022). According to the United Nations[9] (UN), around 50% of least developed countries are at high levels of natural risk incidents. Over the last 15 years, around 12% of these countries were hit by five major disasters. N. Islam and Winkel (2017) explained that at least three main factors explain the rise in inequalities caused by climate change: the increased exposure of disadvantaged groups to damage, their heightened vulnerability, and their reduced capacity to adapt. Due to the relative decline in economic growth in the hottest and poorest countries, it is estimated that the level of inequality between countries, weighted by population, has increased by 25% over the last fifty years (Diffenbaugh & Burke, 2019). In a business-as-usual setup, M. Burke *et al.* (2015) estimated that global income loss will average 23% by 2100 with strong income inequality implications. This would make more than 77% of countries poorer on a per capita basis. Tol *et al.* (2004) tried to measure this effect by implementing an environmental Gini coefficient. Results point to the sharply skewed distribution of impacts across countries soon. Additionally, climate change pushes poverty and inequality levels upward due to food insecurity (Leichenko & Silva, 2014; Paglialunga *et al.*, 2022). Furthermore, climate change will limit the availability of several services, increasing the inequality of opportunities regarding access to resources (Arnell, 1999; J. T. Roberts & Parks, 2006), health (Archibong & Annan, 2023; S. A. R. Khan *et al.*, 2016), education (Drabo & Mbaye, 2015) or gender gap reduction (Andrijevic *et al.*, 2020; Demetriades, Esplen, *et al.*, 2010; Pearse, 2017; Perez *et al.*, 2015).

Many articles have also focused on the implications of climate change for governance. We acknowledge two main directions. First, climate change impacts should increase the risks of political instability. Second, political instability strengthens the repercussions of climate change. For instance, the report of Halden (2007) analyzed how climate change may impact international security in the long run. The author suggested that climate change's impacts on international relations and political risk are inextricably bound to socio-political contexts. Therefore, we cannot state that climate change impacts will directly trigger social and political events. However, if climate change repercussions are surging quickly, the international system could face

[7] The notion establishes that equity and human rights aspects must be central in the decision-making and action on climate change rather than solely environmental or physical considerations.

[8] Holdren (2007) estimated that around 75% of the world's annual CO_2 emissions are coming from the Global North, which represents only 15% of the global population. In parallel, J. T. Roberts and Parks (2006) estimated that the contribution of the poorest 10% of the world's population is roughly 1% of CO_2 emissions.

[9] https://www.un.org/en/conferences/least-developed-countries/brussels2001.

major issues, arising from geopolitical decisions linked to mitigation and adaptation measures. In this regard, Sofuoğlu and Ay (2020) found a causal relationship between climate change and political instability in sixteen countries from the Middle East and North Africa (MENA) region. Findings stipulate that climate change can exacerbate instability in regions at risk of political instability and conflicts. Reverse causality should also be considered. Indeed, countries with political instability are much more exposed and vulnerable to natural hazards (Dupont, 2008; Link *et al.*, 2015). For these unstable countries, climate change might provoke social tensions, leading to political instability. Forsyth and Schomerus (2013) interpreted pathways of these cascading effects. According to their analysis, climate change hazards such as sea level rise, weather extremes or temperature rise deteriorate natural resources. The degradation of ecosystems leads to the loss of biological diversity, water scarcity, and inefficient soil. These losses mechanically hinder basic needs such as water, food, energy, and health access. Climate change provokes intense resource scarcity, which may propel global and local competition and conflict for securing common resources (Huntjens & Nachbar, 2015). In this regard, Sakaguchi *et al.* (2017) conducted a meta-analysis to understand the empirical relationships between climate change and violence. Findings indicate that there might be a positive link between the two variables, mediated by a complex set of indirect processes. M. B. Burke *et al.* (2009) emphasized the strong historical linkages between civil war and temperature variations in Africa. Authors affirm that warmer years in the coming decades will significantly increase the likelihood of war. Given climate projections of future temperature trends, they estimated that the number of armed conflicts is likely to increase by 54% by 2030. However, the link between natural disasters and social conflict is not obvious. For example, Nardulli *et al.* (2015) analyzed empirically the effect of floods and storms on the intensity of civil unrest: their results do not show intensified civil unrest in light of such events. Conversely, Devlin and Hendrix (2014) acknowledged the intensification of conflicts following precipitation scarcity.

Soil degradation, chronic drought, progressive crop failure, extreme natural disasters, and drinking water shortages directly impact food security and health risks. Their accumulation will be the source of forced migration over the coming decades (Dupont, 2008). Increasing mortality and mass migration will impact the distribution of the world's population. According to the World Bank (2000), between 1990 and 1998, around 97% of natural hazard-related deaths occurred in developing countries. Casale and Margottini (2004) estimated that in a business-as-usual scenario, the death toll can amount to 100,000 lives per year. Hutton (2008) explains that the population's age structure is also relevant to understand climate change vulnerability. For example, heatwaves disproportionately affect older people due to respiratory or heart disease exposure. Beyond the size, the demographic structures will be moving due to climate change. For instance, Drabo and Mbaye (2015) found evidence that climate-induced disasters amplify the migration of highly skilled people in developing countries. For a median scenario with a +2°C increase in global mean temperature, Burzynski *et al.* (2018) found that the impact of climate change will induce voluntary and forced migration of around 120 million workers over the next decades. In addition, mass migration could facilitate the spread of infectious diseases (Archibong & Annan, 2023).

2.3.2 The transition risk

If the physical risk is the direct consequence of climate change, the transition risk is more related to the countries' inaction in curbing GHG emissions in a compatible time frame. The energy transition depends on the stabilized reduction of fossil fuel dependency and, thus, the mitigation of GHG emissions, endorsed by more or less restrictive measures (e.g., carbon price mechanisms or carbon tax). Therefore, the transition risk can be gauged by the carbon footprint[10] and the energy demand of a country. Although several international agreements on climate change have been adopted since the 80s, not all countries have complied with or implemented them. These include the Montreal Protocol on the protection of the ozone layer (1987), the Kyoto Protocol (first binding international agreement in 1997) which aims to reduce the onset of global warming by reducing the concentration of greenhouse gases in the atmosphere, and the 21^{st} Conference of the Parties to the UNFCCC (COP21) where participants committed on their economic pathway to limit global warming to "well below 2°C" compared to pre-industrial levels. According to the latest climate action tracker report[11], in late 2023, around 145 countries had announced or are considering net-zero targets. This is covering almost 90% of global emissions. Pledges to become carbon neutral in the next decade would require critical shifts of economic, social, and political structures to reduce fossil fuel dependency globally. However, these major steps toward decarbonization are still under scrutiny since emissions trends are not decreasing globally (Global Carbon Budget, 2023).

Starting with the economic effects induced by this environmental transition, we notice that much of the literature has primarily focused on the economic cost of the transition. If some studies call for a prolific effect of the transition on the economic outlook, others are more skeptical. For instance, I. Khan *et al.* (2021) examined the interlinkages between energy transitions, energy consumption, and sustainable economic growth based on historical data for 38 countries. They found a positive relationship between the energy transition and sustainable economic growth, but only in the long run. Similarly, Garcia-Casals *et al.* (2019) expect a positive global GDP growth induced by reducing GHG emissions. A relative increase in employment favors the growth rate. Capros *et al.* (2008) estimated that the total cost of the EU plan to reduce GHG emissions by 20% in 2020 compared to 1990, approximated to 0.4% of GDP. A large part of the transition will be made possible only if energy consumption patterns shift from fossil fuel to renewables. Therefore, the link between energy consumption and economic growth should be analyzed. In this regard, Markandya *et al.* (2016) estimated that the shift of the energy structure away from carbon-intensive sources favored the net employment generation of $530,000$ jobs in

[10] We assume that the carbon footprint represents the sum of all GHG emissions generated within a country.

[11] The climate action tracker report is available at https://climateactiontracker.org/global/cat-net-zero-target-evaluations/.

European countries during the period 1995 - 2009. Yet, in their seminal paper, Kraft and Kraft (1978) found no causality between gross energy demand and gross national product (GNP). Still, economic activity has been found to drive energy demand. Controlling for development levels, Komarova *et al.* (2022) examined the link between energy demand and GDP. Results confirm a stronger relationship between energy consumption and GDP for non-OECD countries than for OECD countries. Alternatively, using panel data, Inglesi-Lotz (2016) found a significant and positive influence of renewable energy consumption on economic growth in OECD countries. Based on a set of 171 countries, Hannesson (2009) suggested that energy use impacts GDP growth but not necessarily proportionally. Focusing on G-7 countries, Soytas and Sari (2006) analyzed the impact of a change in energy consumption on income. Based on Granger causality tests, they found that the direction of causality seems to differ across countries. Using panel data on 24 middle- and high-income countries over the period 1990-2011, Tiba *et al.* (2016) investigated the interrelationship between renewable energy, environment, foreign trade, and growth. For high-income countries, the results confirm a bidirectional relationship between renewable energy and growth, between CO_2 emissions and economic growth, between foreign trade and growth, and between renewable energy and CO_2 emissions. The relationship between foreign trade and renewable energy and between emissions and trade seems to be unidirectional. For middle-income countries, there is a bidirectional causality between renewable energy and growth, between CO_2 emissions and growth, between trade and growth, between trade and renewable energy, and between CO_2 emissions and trade.

One pervasive issue in the transition is the unequal distribution of environmental policies' costs and benefits across individuals and countries. As summarized by Dwarkasing (2023):

"*[...] multifaceted inequalities are treated as ex-ante phenomena that interact with climate and low-carbon transition policies. This interaction then determines social outcomes in terms of energy access, health, employment, essential goods affordability and livelihoods. Each of these outcomes then feed back into the inequality filter where existing inequalities are either amplified or diminished.*"

In contrast to some stylized ideas, the green transition of the economy can harm poor people (Dercon, 2014). Therefore, the social justice argument should be at the core of emissions reductions and climate adaptation policies. For instance, carbon taxes are generally regressive (i.e., predominantly impacting the relative standard of living of people with lower income levels), provoking public opposition (Cabrita *et al.*, 2021; Cludius, 2015; Semet, 2024) which could freeze advances in the transition. Flues and Thomas (2015) examined the distributional effects of energy taxes in OECD countries. Despite large heterogeneity across countries, taxes on transport fuels are not regressive on average, but taxes on heating fuels and electricity appear slightly regressive. This regressive trend in the carbon tax depends largely on the use of revenue collected (Alvarez, 2019). Moreover, evidence shows that the highly exposed population to climate change's negative impacts are also the most vulnerable to the adverse effects of unsuitable mitigation policies (Markkanen & Anger-Kraavi, 2019).

As stated earlier, the green transition is a synonym for shifting energy from hydrocarbon resources to clean energy. If fossil fuel is carbon-intensive, clean technologies are substantially more metal-intensive than existing power generation (Kleijn *et al.*, 2011). Therefore, developing clean technologies depends on essential components from which a large source is bound to critical minerals (e.g., copper, lithium, nickel, cobalt, and rare earth elements) (Stagnol *et al.*, 2023). As a result, a substantial rise in global demand for critical minerals and metals is associated with the transition (Gielen, 2021). According to IEA (2021), demand for these minerals is estimated to increase by a factor of four to six by 2040. Additionally, Hund *et al.* (2023) suggests that high-impact minerals (e.g., graphite, lithium, and cobalt) require an increase of roughly 500% of their production by 2050 from 2018 levels (Sonter *et al.*, 2020). Unfortunately, the extraction and processing of critical minerals have substantial environmental and social consequences (Durán *et al.*, 2013; Hofmann *et al.*, 2018). For instance, Santangeli *et al.* (2016) confronted protected area network and renewable energy expansion of solar, wind, and bioenergy sources. While energy sources have varying impacts on biodiversity, Central and Latin America appears to be at high risk of renewable energy expansion. Durand (2012) estimated that more than 40% of major metal mines in Africa are located inside or close to protected areas. Rehbein *et al.* (2020) examined the overlap between renewable energy infrastructures and conservation areas. They notice that the renewable electricity facilities under development overlap with conservation areas in Southeast Asia. This could increase the share of compromised wilderness by 60%. Yet, a positive relationship between biodiversity preservation and mitigation progress exists. To illustrate, Usman and Makhdum, 2021 demonstrated a bidirectional causality between the use of renewable energies and forest areas in the BRICS. While forests can store substantial carbon amounts, renewable energy consumption represents an alternative to non-renewable forest products, preserving forest cover and biodiversity (Ponce *et al.*, 2021).

This race for raw materials is redrawing international relations in the geopolitics of critical materials (Gielen, 2021). Some countries, notably China, which provides nearly 90% of all rare earth metals globally (Jaroni *et al.*, 2019), are in full possession of certain critical materials, comforting a dominant position in the global supply. Leaders of the mineral industry hence stand in an advantageous position, potentially controlling the price and supply at a global scale. As a result, the competition for the control of natural resources reshapes the world relationships and politics (Rasmussen & Lund, 2018), which might also be the consequence of declining hydrocarbon revenue in oil exporting countries (Pistelli, 2020). The criticality of the minerals rests on this notion of supply disruption risks for political, geographical, and trade reasons (Hofmann *et al.*, 2018; Zepf, 2020). However, the link between governance indicators and mining events is debatable. While evidence shows that mining events occurring in countries with political risk can trigger conflicts, endangering international relations and human rights abuses (Church & Crawford, 2018, 2020), the direct impact is not so clear (Kühnel *et al.*, 2023).

2.4 Political Stability

In this study, we focus principally on the governance quality of countries (e.g., political stability, rule of law, corruption control, freedom of expression, and government effectiveness). Therefore, we more or less disregard international relationship analyses.

Political stability is intrinsically linked to economic growth. Undoubtedly, sound governance quality is a fertile ground for economic development. Using data for 125 countries during the period 1960-1985, Helliwell, 1994 found a bidirectional and positive relationship between democracy and economic growth, notably in developed countries. Education and investment channels are prominent factors linking the two indicators. Based on a sample of 113 countries for the period 1950-1982, Alesina *et al.* (1996) found that countries highly at risk of government collapse tend to have economic growth substantially lower than others. Cooray (2009) tested the impact of government quality and government expenditure on economic growth for 71 countries. Findings reveal that both indicators are important for economic growth. AlBassam (2013) examined the relationship between governance and economic growth during economic crises. The results highlight a dim influence on the relationship between governance and economic growth. Different levels of development affect the relationship in various ways during times of crisis. Otherwise, Baklouti and Boujelbene (2020) demonstrated that political stability has a virtuous feedback loop: political stability leads to economic growth, and growth favors the development and maintenance of democratic systems. Conversely, shreds of evidence showed that governance of bad quality jeopardizes economic projections. Using more than 450 estimates from 41 different countries, Campos *et al.* (2010) made a meta-analysis on the relationship between corruption and growth. Findings inform that 32% of these estimates support a significant and negative impact of corruption on growth, 62% are statistically insignificant, while only 6% support a positive and significant relation. Mauro (1995) explained that the negative link between corruption and growth is related to investment levels. Mo (2001) emphasized the critical role of political instability in corruption-growth relations. He estimated that a 1% increase in the corruption index reduces the growth rate by around 0.72%.

Biodiversity conservation is also linked to political stability, although this link is likely indirect. As long as the biodiversity hubs are located in developing countries, more at risk of political instability, nature conservation projects have a lower rate of success (Smith *et al.*, 2003). Similarly, in studying 55 countries during the period 1981-1985, Didia (1997) found a strong negative correlation between the level of democracy and the rate of tropical forest exploitation. Enlarging to other governance indicators, Afawubo and Noglo (2019) showed that improvement of the control of corruption, political stability, government effectiveness, and the rule of law reduces deforestation. The results are significant for a sample of low- and middle-income countries. All indicate that countries suffering from political corruption are less likely to implement environmental protection measures (Al-Mulali & Ozturk, 2015).

Democratic states are also more likely to engage with the environmental transition. For instance, Chou and Zhang (2020) find a positive correlation between improving democratic institutions and the awareness of environmental conservation. This benefits the structure of energy consumption and strengthens energy efficiency. Similarly, Chou and Zhang (2020) stated that democracy quality significantly impacts energy efficiency for the 35 European countries they analyze. Gani (2012) tried to explain emissions trends with governance indicators in 99 developing countries. The author found a negative relationship between political stability, the rule of law, and corruption control concerning CO_2 emissions per capita. Millock *et al.* (2008) investigated globally the historical link between economic transition and emissions reduction. Findings advocate for the negative effect of political instability and corruption on environmental law implementation in developing countries. They add that strong institutions are critical for the transition and may be linked to pollution reduction. However, the impact of governance quality on the environment is not systematic. Using non-parametric estimators, Halkos and Tzeremes (2013) analyzed the historical relationship between CO_2 emissions and conventional governance indicators. G-20 countries might have a nonlinear relationship between CO_2 emissions and governance performance. In other words, high governance quality is not systematically associated with reducing CO_2 emission levels.

The association of sustainable development with governance quality is generally accepted. Authoritarian states are likelier to have high levels of inequality and poverty (Chetwynd *et al.*, 2003; M. N. Islam, 2016; Muller, 1988). One recurrent link between these two dimensions is due to corruption issues. For instance, Li *et al.* (2000) related that corruption affects income distribution and that an important proportion of the Gini differential between developing and developed countries can be explained by corruption alone. Using panel vector error correction models, Apergis *et al.* (2010) showed that corruption and income inequality Granger cause each other in the short and long run. Policardo *et al.* (2019) also found a bidirectional causality link between corruption and income inequality, but they add that this link is country-based. Gupta *et al.* (2002) explained this link through the reduction of economic growth, a less progressive tax system, low level and effectiveness of social spending, and the loss of human capital. In the same vein, many empirical findings support good governance as an important factor of poverty and income inequality reduction (Coccia, 2021; M. R. Islam & McGillivray, 2020; Sarkodie & Adams, 2020). For instance, Gorus and Ben Ali (2023) found that among governance factors, voice and accountability, regulatory quality, the rule of law, and the control of corruption play a major role in income inequality. Political stability and government effectiveness are less accurate for predicting income inequality in these countries. Conversely, Kunawotor *et al.* (2020) found that governance quality indicators such as government effectiveness, voice and accountability, regulatory quality, and political stability do not impact income inequality in African countries. Additionally, the effect of government spending on income inequality tends to be moderate and negative (Anderson *et al.*, 2017).

2.5 Inequality

The notion of social inequality gathers many concepts that are often mixed up. The most pervasive idea of inequality is related to income inequality, which is illustrated by the income gap across individuals. However, if income inequality unveils the generic and aggregated view of social inequality, the sources of this aftermath are plentiful. For Crossman (2021), "social inequality is characterized by unequal opportunities and rewards for different social positions or statuses within a group or society. It contains structured and recurrent patterns of unequal distributions of goods, wealth, opportunities, rewards, and punishments". Therefore, we can distinguish the "inequality of conditions" from the "inequality of opportunities". While the former refers to the unequal distribution of income, wealth, and assets, the latter is related to the unequal distribution of chances across individuals. It gathers several aspects such as the gender gap, right to education, health status, and justice treatment. Generally, inequality of opportunities strongly influences inequality of conditions (Jean-Paul, Martine, *et al.*, 2018).

2.5.1 Inequality of conditions

The unequal distribution of conditions across individuals is a raving debate in economics. However, its broad impact on growth is still unclear. Empirical findings are generally associated with the work of Kuznets (1955) and the Kuznet's Curve (KC). Kuznets stated that industrializing nations experience a rise and subsequent decline in economic inequality as economic growth increases, yielding an inverted-U-shaped curve. While modern economists opposed to the empirical KC in developed countries (Milanovic, 2016; Piketty, 2013; Stiglitz, 2016) and developing countries (Ram, 1988), others shed light on a potential KC in developing countries (Ota, 2017; Stiglitz, 2016; Younsi & Bechtini, 2020). Overall, we recognize that KC's validity depends on many specific characteristics. For instance, Desbordes and Verardi (2012) found evidence of an inverted-U relationship between inequality and economic development in a panel of 113 countries over the 1960-2000 period. However, according to the authors, this relationship is not causal and vanishes once endogenous factors are accounted for. On BRICS countries, Younsi and Bechtini (2020) analyzed the validity of the KC during the period 1990-2015. While their results support the KC, Granger's causality test confirms a unidirectional causality between all financial development indicators and income inequality and a unidirectional causality between income inequality and economic growth. Regarding wealth, M. R. Islam and McGillivray (2020) found that wealth inequality is negatively associated with economic growth.

Social inequality plays a central role in climate change, as it is both a cause and a consequence of global warming. As demonstrated by Cappelli *et al.* (2021), a bidirectional relationship between climate-related disasters and income inequality levels might exist. Countries with higher levels of income inequality are hit harder by natural disasters, and climate change pushes inequality up by predominantly affecting poor people. Similarly, Cevik and Jalles (2022) shed light on a positive relationship between climate change vulnerability and income inequality, but only in developing countries. Mechanically, reducing income inequality is positively associated with environmental quality (Baek & Gweisah, 2013; Torras & Boyce, 1998). As originally stated by Boyce (1994), the study of Mikkelson *et al.* (2007) also confirms a positive relationship between the number of threatened species and the level of economic inequality (i.e., Gini ratio). A 1% increase in the Gini ratio (implying rising inequalities) results in almost a 2% increase in the number of threatened species. However, biodiversity conservation tends to be closely related to wealth level (Jacobsen & Hanley, 2009; Mirza *et al.*, 2019).

Grossman and Krueger (1991) introduced the concept of the Environmental Kuznets' Curve (EKC). It is a U-shaped or inverted-U curve describing the relationship between two variables. The term "environmental" is quite general, and can include both climate change and biodiversity variables. In its application, Grossman and Krueger (1991) stated that for two air pollutants (i.e., sulfur dioxide and "smoke"), concentration first increases with GDP per capita, and then decreases inversely with GDP per capita. This gives the inverted-U-shaped curve. This hypothesis shows that there is a relationship between economic growth and pollution. Ehrhardt-Martinez *et al.* (2002) identified that there is a clear EKC between GDP per capita and deforestation, in the form of an inverted-U curve. They noticed that the threshold is around $1,150 per capita, "a fairy low threshold" in their words. Conversely, Clausen and York (2008) demonstrate that economic growth increases the likelihood of fish species becoming threatened within a country, but that the EKC does not exist for aquatic biodiversity. They find no significant GDP per capita threshold above which the number of threatened fish species decreases. The EKC is therefore not always proven, which explains the debate on the subject.

Regarding GHG emissions, the effect of income inequality on emissions seems to be unsteady across time and countries. While Baloch *et al.* (2020) support the increasing effect of income inequality and poverty on emission, Grunewald *et al.* (2017) found that the relationship between income inequality and per capita emissions depends on the income level. Moreover, Ravallion *et al.* (2000) found that a higher level of inequality between and within countries tends to reduce emissions. Bae (2018) adds that income inequality directly raises CO_2 emissions while indirectly reducing it via the negative impact of climate change on economic growth. In addition, findings support the weakening of the mitigation policies with rising levels of inequality. Finally, Masud *et al.* (2020) examined the link between income inequality and environmental sustainability using Granger causality and panel regression methods on the Association of Southeast Asian Nations (ASEAN) members. Findings support a bi-directional causality relationship between income inequality and environmental sustainability but only among the poorest 40% of nations.

For the links between income inequality and political stability, we mainly find studies on the effect of governance quality and income inequality. Income inequality is critical in explaining political violence and regime instability (Muller, 1985, 1988; Muller & Seligson, 1987). However, less can be said about the reverse relationship. Perotti (1996) investigated the interlinkages between income inequality, democracy, and economic growth. They gave evidence on the potential propagation of income inequality and political instability.

2.5.2 Inequality of opportunities

Generally speaking, inequality of opportunities is related to individual characteristics such as age, gender, family background, disability, socioeconomic factors such as education systems, geographic location, health care protection, or national security (Jean-Paul, Martine, *et al.*, 2018). As a consequence, every dimension studied in this paper is related to the concept of social inequality through the channel of inequality of opportunities. From the retained variable list, we are particularly interested in the inequality of opportunities regarding gender, health, and resource access (e.g., water and energy).

Starting with the gender aspect, we acknowledge a vast empirical literature on this topic. Many articles advocate for the positive impact of women's empowerment on economic outlooks, particularly in education and employment (Hill & King, 1995; Kabeer & Natali, 2013; Morrison & Morrison, 2007; Ramanayake, Ghosh, *et al.*, 2017; Thévenon & Del Pero, 2015). Several channels may explain the links between women's inclusiveness and economic growth. For instance, Martin (1995) and Galor and Weil (1993) showed that increasing wage and educational attainment lowers fertility rates. It affects the female labor market participation and boosts economic growth (Cavalcanti & Tavares, 2016). However, according to the latest gender gap report (World Economic Forum, 2023a), estimates from 2023 suggest that at the current rate of progress, it will take 131 years to reach full parity. As in the case of women's representation in business leadership, gender gaps in political leadership are also to blame. Although there is a low number of women holding political decision-making posts worldwide, pieces of evidence stipulate that they tend to constrain corruption (Rivas, 2013; Swamy *et al.*, 2001), aspire to democratic systems (Hinojosa, Kittilson, *et al.*, 2020; Inglehart *et al.*, 2003), peace (Caprioli, 2003; Caprioli & Boyer, 2001), and promote gender equality (S. Jacob *et al.*, 2014; Wängnerud, 2009).

Woman empowerment is also intensely linked to environmental outcomes. First, women are likely to be disproportionately vulnerable (Cutter, 2017; Denton, 2002). For instance, Bechtel (2010) highlighted that more than 70% of the population subject to chronic poverty are women. Consequently, women appear to be more concerned by environmental risks than men (Bechtel, 2010; Blocker & Eckberg, 1989; Bord & O'Connor, 1997; McCright, 2010; Mohai, 2014). They also seem more engaged than men in favor of the climate (L. M. Hunter *et al.*, 2004; Norgaard & York, 2005; Zelezny *et al.*, 2000). To illustrate, Neumayer and Plümper (2007) examined the link between natural disasters and gender gaps in 141 countries during the 1981-2002 period. Findings support a greater impact of natural disasters on women's life expectancy than men's, but it could be substantially diminished if women's socioeconomic status improves. Furthermore, gender gaps in access to assets, public goods, and services hamper their prospect of well-being. In certain regions, women are unlikely to own land, making them even more dependent on common property or open-access resources. Consequently, environmental and ecosystem degradation disproportionately affects women. However, including women in political decisions regarding climate change and environmental pressures is also substantially beneficial. For instance, the increasing number of women in parliaments can increase forest preservation (Salahodjaev & Jarilkapova, 2020) and support environmental treaties ratification (Norgaard & York, 2005).

A large part of the literature hypothesized that there are several interlinkages between poverty reduction, economic growth, and health equality (Rivera & Currais, 2003; Sachs & Warner, 1997; Weil, 2014). This stipulates that without health standards, the economic growth of a country is endangered. Evidence shows that bad health hampers income creation through employment channels and human capital acquisition (O'Donnell *et al.*, 2015; Weil, 2014). The reversal causality, stipulating that weak economic growth can increase health inequality, has also been demonstrated empirically. For instance, Preson (1975) showed that the effect of income on health tends to be significant in low-income countries but insubstantial in developed countries. Specifically, income inequality is a dominant factor in health outcomes in the poorest countries. As Weil (2014) demonstrated, loss of income can impact health through the standard of living (e.g., nutrition), infrastructure (e.g., sanitation or water supply), and medical technology. Furthermore, reduction in child mortality, or more generally, improvements in life expectancy, tend to be associated with gains in GDP per capita (P. R. Hunter *et al.*, 2010; Ray & Linden, 2018). Conversely, increasing level of income inequality leads to infant mortality in developed countries. Finally, Wildman (2003) emphasized that health policies aiming to reduce health inequality can increase health inequality if not considering income inequality.

Access to resources is paramount in the explanation of inequality of opportunities. A lot of articles seek the link between access to natural resources such as water use (Barbier, 2004; M. J. Cole *et al.*, 2018; Yang *et al.*, 2013) or energy (Aristondo & Onaindia, 2018; Sinha *et al.*, 2022; Stern *et al.*, 2019). Concerning electricity access and consumption, Yoo and Lee (2010) found a statistically significant inverted-U-shaped relationship between per-capita electricity consumption and per-capita income. While Bakehe (2020) showed that increasing access to electricity reduces the rate of deforestation in many African countries, Baek and Gweisah (2013) found that increasing energy consumption harms the environment. Still in African countries, Wolde-Rufael (2006) tests the long-run and causal relationship between electricity consumption and GDP per capita during the 1971-2001 period. Results indicate a long-run relationship between electricity consumption and GDP for only nine countries and Granger causality for twelve countries. A positive uni-directional causality from GDP to electricity consumption was found in six countries, while the reversal relationship appears in only three countries. The relationship between water use and access seems to be positive with economic growth through productivity channels. This yields an inverted-U relationship between economic growth and water use (Barbier, 2004; M. A. Cole, 2004; Katz, 2015; Shafik, 1994).

With abundant literature documenting the network of relationships between economic growth, inequalities, climate change, biodiversity loss, political stability and demographic dynamics, we now shift the focus toward indicators that are widely variable to translate these different dimensions.

3 Data

3.1 Data Description and Transformation

We construct a dataset of 57 variables over the period 2000-2020. The data is reported annually. For any given country and variable, the resulting time series comprises a maximum of 21 values (one per year from our period). As our interest lies in 166 countries, our dataset contains $166 \times 21 = 3486$ rows. We removed the majority of small islands with small populations but also some larger countries, such as Taiwan, South Sudan, Palestine, Kosovo, North Korea, Somalia, Turkmenistan, and Puerto Rico, because these territories lack data. Variables are classified according to 6 dimensions: demographics, biodiversity, climate change, political stability, inequalities and economics. Indeed the latter is an essential dimension of our study since we aim to measure the interrelationships between socio-economic dynamics, environmental dimensions, and economic growth.

Table 1: Demographic Variables

Full Variable Name	Unit	Source
Total Population	Number of people	WB
Working-age Population	%	WB
0-14 Age Population	%	WB
65+ Age Population	%	WB
Fertility Rate	children/women	WB
Urban Population	%	WB
Rural Population	%	WB
Population Density	people/km^2	WB
Female Population	Number of people	WB
Male Population	Number of people	WB
Net Migration	Nb of immigrants-emigrants	WB

Source: Amundi Institute.

Our dataset covers various aspects of demographics, such as urbanization, fertility, gender, migration, and population age structure. Demographic data is retrieved from the World Bank (WB) website[12], with the World Development Indicators database. The demographic variables are presented in Table 1. Total population, female and male population, and net migration are expressed in millions. Furthermore, the working-age population corresponds to the 15-64 age.

[12] https://databank.worldbank.org/source/world-development-indicators

Variables related to biodiversity are presented in Table 2. The crop production index shows yearly agricultural production relative to the base period 2014-2016. We also cover natural resources, cereal yields, protected places, forests, and agriculture. The share of important terrestrial biodiversity sites that are protected, which we call more concisely protected biodiversity sites, comes from the website Our World In Data (OWID)[13].

Table 2: Biodiversity Variables

Full Variable Name	Unit	Source
Forest Rents	% of GDP	WB
Proportion of Forest	%	WB
Cereal Yield	kg/ha	WB
Natural Resources Rents	% of GDP	WB
Protected Biodiversity Sites	%	OWID
Crop Production Index	2014-2016=100	WB
Agricultural Land (km^2)	km^2	WB
Agricultural Land (%)	%	WB

Source: Amundi Institute.

Table 3 presents the climate change variables. Our focus is on temperature change, CO_2 emissions, and energy. To begin with, the temperature anomaly represents the difference in temperature compared with the average temperature over the period 1901-2000. The data is sourced from the National Centers for Environmental Information (NCEI). Renewable energy consumption refers to the proportion of total energy consumption that comes from renewable sources. The metric top 10% carbon emitters per capita refers to the average amount of CO_2 emissions per person of the top 10% of emitters in a given country. The data derives from the World Inequality Database (WID)[14]. Furthermore, change in primary energy consumption represents the year-to-year variation in primary energy consumption within a given country.

Table 4 is dedicated to the metrics employed to assess political stability. Government effectiveness precisely describes public and civil services' independence from political pressures and the government's capacity to implement its commitments that affect their quality. Corruption control measures the extent to which public power is used for private purposes, including major forms of corruption and petty bribes. Freedom of expression measures the degree to which individuals can freely express themselves and how much the media can present varying political opinions. It ranges from 0 (low freedom) to 1 (high freedom).

The aim is also to analyze potential relationships between Total GDP, the unemployment rate of the 15+ population, adjusted net national income, inflation,

[13]https://ourworldindata.org/grapher/protected-terrestrial-biodiversity-sites
[14]https://wid.world/data/

Table 3: Climate Change Variables

Full Variable Name	Unit	Source
CO_2 Emissions/ Capita	tons	WB
Temperature Anomaly	°C	NCEI
Renewable Energy Consumption	% total energy	WB
Top 10% Carbon Emitters/capita	CO_2 tons PPP	WID
Energy use/ Capita	kWh	OWID
Change Primary Energy Consumption	%/year	OWID

Source: Amundi Institute.

Table 4: Political Stability Variables

Full Variable Name	Unit	Source
Political Stability	-3.5 - 3.5	WB
Rule of Law	-3.5 - 3.5	WB
Military Expenditure	% of PIB	WB
Corruption Control	-3.5 - 3.5	WB
Government Effectiveness	-3.5 - 3.5	WB
Freedom of Expression	0 - 1	OWID

Source: Amundi Institute.

GDP/capita, and annual GDP growth as illustrated in Table 5. The unemployment rate of the 15+ population data comes from the International Labour Organization[15] (ILO). Consumer price inflation is a common measure of inflation. Adjusted net national income is calculated by subtracting fixed capital consumption and natural resource depletion from Gross National Income (GNI). Total GDP and adjusted net national income are expressed in billions.

Table 5: Economic Variables

Full Variable Name	Unit	Source
Total GDP	US \$	WB
Unemployment 15+ Population	%	ILO
Adjusted Net National Income	US \$	WB
Adjusted Net National Income/ Capita	US \$	WB
Inflation Consumer Prices	%	WB
GDP/ Capita	US \$	WB
Annual GDP Growth	%	WB

Source: Amundi Institute.

We study various inequalities as depicted in Table 6, such as gender, health, education, infrastructure, and income. In addition, the Human Development Index

[15] https://ilostat.ilo.org/data/

(HDI) is a statistic that measures various countries' levels of social and economic development, from 0 (underdeveloped) to 1 (most developed). Data is measured by the United Nations Development Programme (UNDP)[16]. Every category of inequality comprises multiple variables. As far as gender inequality is concerned, women's political empowerment measures the extent to which women can enjoy civil liberties and participate in civil society and the political life of a country. It varies from 0 (least empowered) to 1 (most empowered). Additionally, there are health inequalities evident through factors such as life expectancy at birth, the proportion of individuals reaching age 65, or expenditure on current healthcare. Infrastructure inequalities consist of indicators such as water and electricity access and the number of people with telecommunication subscriptions per 100 individuals. Finally, the Palma ratio measures income inequality within a country by comparing the share of national income received by the top 10% in income with that received by the bottom 40%. An index of x means that the top 10% receive x times what the bottom 40% receive, so the higher the ratio, the greater the inequality. Likewise, we consider wealth per adult, which is more general than just income, as it includes property. On this aspect, we also look at the share of total wealth held by the richest 1%, the richest 10%, and the poorest 50%. We also choose the same variables, but this time for income instead of wealth.

Table 6: Inequality variables

Full Variable Name	Unit	Source
Women's Political Empowerment	0 - 1	OWID
Electricity Access	%	WB
HDI	0 - 1	UNDP
Life Expectancy at Birth	Nb of years	WB
Palma Ratio	$0 - \infty$	OWID
Water Access	%	WB
Top 1% Share Income	%	WID
Top 10% Share Income	%	WID
Bottom 50% Share Income	%	WID
Per Adult National Wealth	€ PPP	WID
Top 1% Share Wealth	%	WID
Top 10% Share Wealth	%	WID
Bottom 50% Share Wealth	%	WID
Current Health Expenditure	% of PIB	WB
Current Health Expenditure / Capita	PPP (internat. $)	WB
Survival to Age 65, Female	%	WB
Survival to Age 65, Male	%	WB
Gender Inequality Index	0 - 1	OWID
Fixed Telephone Subscriptions	Nb subscr./100 ppl	OWID

Source: Amundi Institute.

[16] https://hdr.undp.org/data-center/human-development-index#/indicies/HDI

Finally we check the stationarity of raw time series, 1^{st} and 2^{nd} difference using Dickey-Fuller test and proceed with series in 1^{st} difference owing to the lowest proportion of non-stationary time series (namely 5.6%, compared to 11.72% for raw data and 6.08% for 2^{nd} difference). However, inflation (consumer prices), GDP growth, and annual change in primary energy consumption are already variables that represent a difference between two consecutive years. Therefore, and only for these three variables, we leave them as raw data.

3.2 Granger Causality

The Granger causality test is a statistical method employed to assess whether a given time series can predict another time series. If we want to verify a possible Granger causality between two time series X and Y, an important assumption is that X and Y must be stationary (Granger, 1969). In cases where any series lacks stationarity, the initial step involves rendering it stationary, usually through techniques like differencing, as we implemented above. The test's null hypothesis (H0) posits that the lagged values of X (with the number of lags typically user-specified) do not account for the variability observed in Y. In other words, H0 asserts that the lags of X do not exhibit Granger causality on Y. Granger causality can be expressed as an attempt to model Y using the lagged values of both Y itself and the X variable. The coefficients for the lagged Y values are denoted as alphas, while the coefficients for the lagged X values are represented as betas. All of this can be written as follows:

$$Y_t = \alpha_0 + \sum_{j=1}^{k} \alpha_j Y_{t-j} + \sum_{j=1}^{k} \beta_j X_{t-j} + \varepsilon_t \tag{1}$$

With $k \in \mathbb{N}^*$, the maximum number of lags, and ε_t the error term at time t. The null hypothesis H0 is as follows:

$$H_0 : \beta_1 = \beta_2 = \ldots = \beta_k = 0 \tag{2}$$

Since we are working with panel data, Granger causality operates slightly differently from the standard Granger test (Granger, 1969). Dumitrescu and Hurlin (2012) provide an extension to detect Granger causality between two variables in panel data. Let $i = 1, \ldots, N$ be the countries (in our case, $N = 166$ is the number of countries) and $t = 1, \ldots, T$ be the years ($T = 20$ is the number of years in our period since we are using differentiation). So the Equation (1) is rewritten as follows:

$$Y_{i,t} = \alpha_{i,0} + \sum_{j=1}^{k} \alpha_{i,j} Y_{i,t-j} + \sum_{j=1}^{k} \beta_{i,j} X_{i,t-j} + \varepsilon_{i,t} \tag{3}$$

where $X_{i,t}$ and $Y_{i,t}$ are the observations of two stationary variables in year t for country i. The associated coefficients may now vary from country to country (hence the addition of i as an index). In addition, the panel must be balanced without missing data. Thus, in the DH (Dumitrescu and Hurlin) Test, hypothesis H0 becomes:

$$H_0 : \beta_{i,1} = \beta_{i,2} = \ldots = \beta_{i,k} = 0 \qquad \forall i = 1, \ldots, N \tag{4}$$

This corresponds to the fact that there is no significant causality at the determined threshold in the panel, regardless of the country. As for the alternative hypothesis, the DH Test assumes that there may be causality for some countries but not necessarily for all, hence H1:

$$\begin{aligned} H_1 : \beta_{i,1} = \beta_{i,2} = \ldots = \beta_{i,k} = 0 \qquad & \forall i = 1, \ldots, N_1 \\ \beta_{i,1} \neq 0 \text{ or } \ldots \text{ or } \beta_{i,k} \neq 0 \qquad & \forall i = N_1 + 1, \ldots, N \end{aligned} \tag{5}$$

Where $N_1 \in [0, N-1]$ is unknown and strictly less than N, otherwise H1 is strictly identical to H0. Furthermore, if $N_1 = 0$, causality at the chosen threshold is verified for all the countries in the panel. We do not employ the DH test, but instead, a very similar one that shares the same null hypothesis, H0. Indeed, for each pair of variables, we calculate the number of countries with causality in each direction. If the result is 0 it implies that causality never occurs, regardless of the country, which brings us back to Equation (4).

In addition, Granger causality requires sufficiently distinct values and variance in the time series being studied. We have chosen to use a first difference dataset so that we only drop a small number of non-stationary time series. However, several time series do not vary from year to year. For example, access to electricity in developed countries has been at 100% for many consecutive years. As a result, the time series in difference consists almost entirely of zeros, making it impossible to use it to investigate possible Granger causality. Therefore, we perform an additional sorting operation, removing the time series with too low variability.

Finally, we create causality matrices, country by country, for our 57 variables. These are composed entirely of 0s and 1s. Let $(i, j) \in [[1, 57]] \times [[1, 57]]$ and $M = (m_{i,j}) \in M_{57,57}(\mathbb{R})$ the matrix such that the element $(m_{i,j})$ equals 1 if the variable j Granger causes the variable i, and 0 otherwise. Then, for certain pairs (i, j), it is possible that $(m_{i,j}) = (m_{j,i}) = 1$. In this case, we use the p-value to determine which variable Granger causes the other with the greatest likelihood. To do this, we calculate the p-value for each of the four lags and the smallest one is assigned to $(m_{i,j})$ for this specific Granger causality. We assume that beyond four years, it becomes challenging to attribute a meaningful interpretation to the idea that the variation in one variable has caused the variation in another variable. In a scenario where $(m_{i,j}) = (m_{j,i}) = 1$, where it seems that the two variables Granger cause each other, we retain the causality associated with the lowest p-value. This approach allows to keep only the most persistent links, and avoid two variables Granger causing each other.

We divide our 166 countries into two country groupings: low-income (71 countries) and high-income (95 countries) in the spirit of Semet *et al.* (2021). We use the World Bank classification of countries according to their income[17]. It contains four country groupings: low-income (22 countries), lower middle-income (49 countries), upper-middle-income (43 countries) and high-income (52 countries). All the countries in the "upper middle-income" category are placed in the "high-income" group,

[17] https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups

while the "lower middle-income" countries are considered as "low-income". Based on our two-country grouping scheme, we can aggregate the causality matrices of all the countries belonging either to the low-income or the high-income group. Since our causality matrices are composed of 0s and 1s, with causalities that can only run in one direction, summing up all these matrices enables us to determine for how many countries one variable causes another within the same group of countries. We analyze the results obtained in the next section.

3.3 Causal Relationships Results

3.3.1 Theory and first causality graphs

Firstly, we aim to identify the most important dimensions for each income group. As we have a graph $G = (V, E)$ with $V = [[1, 57]]$ a set of vertices (also called nodes) and $E \subseteq \{(x, y) \mid x, y \in V \text{ and } x \neq y\}$ a set of edges (also called links). Then, given that an edge connects two distinct nodes, $2n$ nodes are connected by n edges. So, to quantify the extent to which a dimension D contributes to an income group while controlling for the number of variables per dimension, we calculate the contribution as follows:

$$contribution_D = \frac{\text{Number of links containing a node of D}}{\text{Number of nodes of D}} \tag{6}$$

We obtain the number of links per node, the "connection density" of each dimension, available in Table 7.

Table 7: Weighted Contribution of Each Dimension per Income Group

	High-income	Low-income
Demographics	111.18	111.81
Biodiversity	108.87	110.88
Climate change	108.00	109.67
Political Stability	107.33	111.17
Inequalities	110.79	110.63
Economics	108.71	108.29

Source: Amundi Institute.

First, each variable can cause at most $\text{Card}(V) - 1$ other variables and be caused by at most $\text{Card}(V) - 1$ other variables too. Hence, the maximum possible number of links per node is:

$$\text{MaxLinks} = 2 \times [\text{Card}(V) - 1] = 2\ \text{Card}(V) - 2 \tag{7}$$

In our case, $\text{Card}(V) = 57$. Therefore, the maximum number of links per node possible in our configuration is $\text{MaxLinks} = 2 \times 57 - 2 = 112$. However, if we look again at Table 7, we witness that all the values are close to MaxLinks. We can deduce that causality graphs, for both high-income and low-income, should be very dense graphs whose vertices are practically all interconnected. To have interpretable graphs, we aim to retain one variable per dimension, keeping GDP growth for the economic dimension.

3.3.2 Identifying the best combination of variables through optimization

Our objective is to identify the combination of 6 variables, one for each dimension, such that the sum of the two-by-two causalities between each pair of variables is maximal. In other words, the objective would be to find the submatrix of size 6×6 with the largest sum of coefficients and then extract the variables in question. Hence for a given dimension, we might not select the variable with the maximum number of causalities, but one that - when combined to other dimensions - maximizes the sum of coefficients. A collective optimum could then be reached, not necessarily aligned with each dimension's individual optimum.

Let $M = (m_{i,j}) \in M_{6,6}(\mathbb{R})$ be the matrix such that the element $(m_{i,j})$ corresponds to the number of countries in which the variable j causes the variable i. Let $\{D_1, D_2, \dots, D_6\}$ be the six dimensions of our study. Finally, let $v = (v_1, v_2, \dots, v_6) \in \prod_{i=1}^{6} D_i$ be a vector of 6 variables, with $v_i \in D_i$, $\forall i = 1, \dots, 6$. We now write $M^{[v]} = (m_{i,j}^{[v]}) \in M_{6,6}(\mathbb{R})$ to specify the variables corresponding to the rows and columns of the matrix. Then, the optimization problem mentioned above is written as:

$$\begin{aligned} \underset{v}{\text{maximize}} \quad & \sum_{i=1}^{6}\sum_{j=1}^{6} m_{i,j}^{[v]} \\ \text{subject to} \quad & v_i \in D_i, \ \forall i = 1, \dots, 6. \end{aligned} \tag{8}$$

Such optimization allows to determine which variables in our dataset are most likely to have a causal relationship with each other, with the highest probability. Furthermore, it enables us to compare the combinations of variables obtained for p-value thresholds of 1%, 5%, and 10%. Table 8 presents our results for each income group and threshold. At the 1% threshold, the combinations are nearly identical between the low and high-income groups, barring a difference of only one variable (on the climate change dimension, energy use per capita is selected for high-income, while renewable energy consumption is retained for low-income). Furthermore, within each income group, the optimal combinations differ only by one variable between the 5% and 10% thresholds. In Figure 1, we present Granger causality graphs with the optimal variable combinations found at the 1% threshold. For ease of reading, we remove the bottom least significant (33%) causal relationships removed. For both low - Figure 1a - and high-income - Figure 1b - groups, the most robust causal relationship is the same: the proportion of forest causing rural population (in 26 countries for high-income and 23 for low-income).

After performing the causality graphs, we now aim to define equations and coefficients that represent the variables in relation to each other. The subsequent section outlines the construction of VAR models using the optimized variable combinations.

Table 8: Variable Combination per Income Group and per Threshold with GDP growth

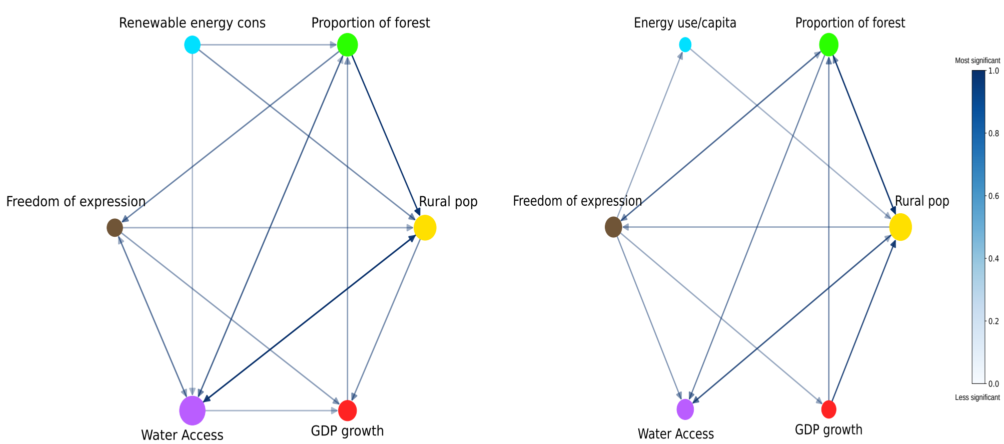
Income level	Threshold	Variable combination
High-income	1%	rural population, proportion of forest, energy use per capita, freedom of expression, water access
High-income	5%	population above 65, agricultural land (%), top 10% carbon emitters/capita, corruption control, fixed telephone subscription
High-income	10%	population between 0 - 14, agricultural land (%), top 10% carbon emitters/capita, corruption control, fixed telephone subscription
Low-income	1%	rural population, proportion of forest, renewable energy consumption, freedom of expression, water access
Low-income	5%	active population, agricultural land (%), renewable energy consumption, freedom of expression, water access
Low-income	10%	active population, agricultural land (%), renewable energy consumption, corruption control, water access

Source: Amundi Institute.

Figure 1: 1% Threshold Granger Causality Graphs with Optimized Variable Combination

(a) Optimized Combination for Low-income

(b) Optimized Combination for High-income



Source: Amundi Institute.

4 Vector Autoregression Model (VAR)

4.1 Origins and Presentation of the Model

4.1.1 Classical VAR

In 1980, Christopher Sims introduced VAR models as a pivotal tool for capturing and analyzing the interrelated dynamics and causal connections within a collection of macroeconomic variables (Sims, 1980). It extends the principles of univariate autoregressive modeling to dynamic multivariate time series analysis. Comprehensive reviews of VAR methodologies can be found in the works of Watson (1994), Waggoner and Zha (1999) and Peña *et al.* (2001), as well as Lütkepohl (2013). According to Zivot and Wang (2006), VAR appears highly effective, flexible, and user-friendly for analyzing multivariate time series data, yielding strong predictive capabilities, notably for financial and economic series. They add that it frequently outperforms univariate time series models and complex simultaneous theory-based equations models in forecasting.

Let $\mathbf{Y}_t = (y_{1,t}, y_{2,t}, \ldots, y_{n,t})^T \in M_{n,1}(\mathbb{R})$ be a vector of time series variables with n the number of variables in the considered model, $\mathbf{c} = (c_1, c_2, \ldots, c_n)^T \in M_{n,1}(\mathbb{R})$ be a vector containing constants and $\boldsymbol{\varepsilon}_t = (\varepsilon_{1,t}, \varepsilon_{2,t}, \ldots, \varepsilon_{n,t})^T \in M_{n,1}(\mathbb{R})$ an error vector.

Finally, let $\mathbf{\Pi}_k = \begin{pmatrix} \pi_{1,1}^{(k)} & \pi_{1,2}^{(k)} & \cdots & \pi_{1,n}^{(k)} \\ \pi_{2,1}^{(k)} & \pi_{2,2}^{(k)} & \cdots & \pi_{2,n}^{(k)} \\ \vdots & \vdots & \vdots & \vdots \\ \pi_{n,1}^{(k)} & \pi_{n,2}^{(k)} & \cdots & \pi_{n,n}^{(k)} \end{pmatrix} \in M_{n,n}(\mathbb{R})$ be the coefficient matrices.

Thus, the p-lag VAR(p) model for n time series variables can be generalized as follows:

$$\mathbf{Y}_t = \mathbf{c} + \sum_{k=1}^{p} \mathbf{\Pi}_k \mathbf{Y}_{t-k} + \boldsymbol{\varepsilon}_t, \qquad for\ t = 1, \ldots, T \tag{9}$$

Which is equivalent to:

$$\begin{pmatrix} y_{1,t} \\ y_{2,t} \\ \vdots \\ y_{n,t} \end{pmatrix} = \begin{pmatrix} c_1 \\ c_2 \\ \vdots \\ c_n \end{pmatrix} + \sum_{k=1}^{p} \begin{pmatrix} \pi_{1,1}^{(k)} & \cdots & \pi_{1,n}^{(k)} \\ \pi_{2,1}^{(k)} & \cdots & \pi_{2,n}^{(k)} \\ \vdots & \vdots & \vdots \\ \pi_{n,1}^{(k)} & \cdots & \pi_{n,n}^{(k)} \end{pmatrix} \begin{pmatrix} y_{1,t-k} \\ y_{2,t-k} \\ \vdots \\ y_{n,t-k} \end{pmatrix} + \begin{pmatrix} \varepsilon_{1,t} \\ \varepsilon_{2,t} \\ \vdots \\ \varepsilon_{n,t} \end{pmatrix} \tag{10}$$

Henceforth, we derive a set of n equations, each corresponding to an individual variable within the system. In each equation, each variable depends on the other lagged variables. Such formulation allows us to systematically analyze the intricate network of interdependencies and causal links that may be at play among the time series within a model. VAR modeling also allows the examination of impulse responses of specific variables to shocks created by other variables. It would enable us to observe the macro variable's responses over time and, therefore, to understand how certain variables would react to sudden changes in other variables. Finally, a VAR model offers the advantage of being devoid of any economic theory, adopting a purely statistical approach. This ensures that the model remains impervious to the influence of any specific ideological paradigm or school of thought (Bourbonnais *et al.*, 2015; Sims, 1980).

4.1.2 Panel VAR

A Panel VAR (PVAR) is a VAR adapted to panel data, where each specific entity's effect is considered. In our case, the entities are the countries. Thus, we indicate that each time series is expressed differently depending on the country concerned. Mathematically, we obtain an equation very similar to Equation (9):

$$\mathbf{Y}_{i,t} = \mathbf{c}_i + \sum_{k=1}^{p} \mathbf{\Pi}_{i,k}\mathbf{Y}_{i,t-k} + \boldsymbol{\delta}\boldsymbol{d}_{i,t} + \boldsymbol{\gamma}\boldsymbol{s}_{i,t} + \boldsymbol{\varepsilon}_{i,t} \qquad t = 1, \ldots, T \tag{11}$$

Where $\boldsymbol{d}_{i,t} \in M_{n,1}(\mathbb{R})$ represents a vector of predetermined variables that may potentially correlate with past errors, and $\boldsymbol{s}_{i,t} \in M_{n,1}(\mathbb{R})$ is a vector of exogenous variables. Moreover, $\boldsymbol{\delta} = (\delta_{i,j}) \in M_{n,n}(\mathbb{R})$ and $\boldsymbol{\gamma} = (\gamma_{i,j}) \in M_{n,n}(\mathbb{R})$ are respectively the coefficients matrices associated with $\boldsymbol{d}_{i,t}$ and $\boldsymbol{s}_{i,t}$.

To determine p, the number of lags, in Equation (11), we use several criteria: log-likelihood, sequential modified LR test statistic at 5% level (LR), Final Prediction Error (FPE), Akaike Information Criterion (AIC), Schwarz information Criterion (SC) and Hannan-Quinn information criterion (HQ). Based on all these criteria, we observe that the optimal value for low-income countries is $p = 5$, whereas it is $p = 6$ for high-income countries (see Table 12 and Table 11, both in Appendix A.2): indeed the criteria's values are minimized for these lags. Hence, we proceed with these lag lengths.

4.2 Coefficients of the Panel VAR Model and Estimation

We employ a panel VAR model to fit our dataset's structure. For its specification, we need to choose which will be our endogenous and exogenous variables, and the optimal lag (respectively the $\boldsymbol{d}_{i,t}$, $\boldsymbol{s}_{i,t}$ and p in Equation (11)). We also add a constant term to our specifications. Considering the non-causal relationships identified between some variables (see Figure 1a and Figure 1b) we also adjusted the model to restrict certain coefficients to 0. By doing so we impose the structure of the VAR. Considering the fairly small size of our sample, it also allows to preserve degree of freedom by decreasing the number of coefficients to estimate. It represents 96 restrictions for high-income out of 222 coefficients and 45 out of 186 for low-income countries compared to unrestricted 6 dimensions VAR. For the low-income, renewable energy is turned exogenous since it is not Granger caused by other variables as depicted in Figure 1a: it decreases the dimension of the VAR to 5, implying the estimation of 155 coefficients in the unrestricted version[18]. The number of coefficients is thus drastically reduced for both samples. This approach avoids over-parameterization and preserves the degree of freedom while reducing noise in the relationships between variables. Such restricted linear VAR specification implies iterate Generalized Least Square (GLS) weighting for estimation instead of Ordinary Least Squares (OLS) that are not asymptotically inefficient (Luetkepohl *et al.*, 2007). The OLS method is normally estimated for each equation separately in an unrestricted specification.

4.2.1 High-income countries

Firstly, as indicated in Table 11 in Appendix A.2, we choose a number of lags $p = 6$ for countries classified as high-income. Then, looking at Figure 1b, we observe that each variable is caused by at least one other variable. We consider all our variables to be endogenous. Finally, we choose **c**, the constant, as our only exogenous variable. Then, we look at Figure 1b to restrict the coefficients of the non-causal relationships to 0. For example, freedom of expression is caused by the rural population, but the reverse is not true. Thus, we automatically set the effect of freedom of expression on the rural population to 0. Based on these specifications, we carry out the panel VAR estimations. We obtain the results shown in Table 13 (in Appendix A.2). It demonstrates the interrelationships between the variables and their significance (measured with a Student's t-test). Moreover, it allows us to quantify the intensity and signs of the causalities. In addition, the residual correlation matrix for high-income countries, presented in Figure 6 in Appendix A.2, consists solely of weak correlations, demonstrating a sound goodness-of-fit of our model. The most interesting result is the coefficient of determination (R^2) of GDP growth: its interpretation is that for high-income countries, 7.12% of GDP growth's variance is explained by only five non-financial variables. Thus, even in the category of the most developed countries, we see that GDP growth cannot be explained solely by economic/financial considerations. Other dimensions need to be considered, and their impact is significant.

4.2.2 Low-income countries

For low-income countries, the optimal number of lags is p = 5 (see Table 12 in Appendix A.2). Furthermore, in Figure 1a, we witness that all the variables are caused at least once by another variable except renewable energy consumption. Thus, we consider all the variables endogenous except renewable energy consumption, which is exogenous, and the constant **c**. Once the model is specified, we set all the coefficients of the non-causal relationships to 0, as in the previous subsection. The

[18]With k the number of dimensions in the VAR, p the number of lags and d the number of intercept terms, the number of coefficients to be estimated for a VAR is $k + pk^2$. Hence, the unrestricted high-income VAR implies the estimation of 222 coefficients and 186, respectively, for the unrestricted low-income VAR. When renewable energy is turned exogenous, the latter figure drops to 155.

resulting panel VAR estimates are presented in Table 14 (in Appendix A.2), and the residual correlation matrix in Figure 7 in Appendix A.2. The latter showcases the absence of strong correlations among the variables of interest. The R^2 of the GDP growth equation - explained by five extra-financial variables - stands at 23.05% for this sample of countries, which is much higher than for countries classified as high-income. It can be seen that non-financial macro variables have a decisive influence on fluctuations in GDP growth, particularly in low-income countries. Moreover, according to Table 14 (in Appendix A.2), GDP growth is a function of its past values, rural population, freedom of expression, and renewable energy consumption, while for high-income countries, GDP growth was mainly responsive to its lagged values and freedom of expression (see Table 13 in Appendix A.2). So, the phenomena causing a variation in GDP growth are significantly more diversified for the least developed countries, whereas for the most developed countries, the economic and political stability dimensions dominate.

4.2.3 Explanatory power beyond macroeconomic variables

In the spirit of Semet *et al.* (2021), we are interested in evaluating the explanatory power of our model, which consists only of extra-financial variables, compared to a more traditional macroeconomic framework. The juxtaposition of different specifications (the first two consisting of either macroeconomic or only extra-financial variables, and one including both extra-financial and macroeconomic variables) allows us to evaluate the relevance of extra-financial variables in addition to traditional macroeconomic indicators in explaining GDP growth. We chose standard measures such as inflation (consumer prices) (Fischer, 1993), current account balance (Divya & Devi, 2014), and claims on central government (Reinhart & Rogoff, 2010) because of their importance in driving economic expansion. The three variables are taken from the World Bank website, from the World Development Indicators database[19]. The comparison is made using the adjusted R^2, which penalizes the number of variables used in the model, and we use Ordinary Least Squares (OLS) estimation. To avoid autocorrelation of each variable between the different lags and thus multicollinearity problems, we use a specification with one lag ($p = 1$). Finally, we consider models with fixed effects, applied both in the cross-section (i.e., countries) and the period (i.e., years). The results are shown in Table 9.

Table 9: Adjusted R^2 Coefficients from OLS Regressions for GDP Growth Prediction

Variables	Low-income	High-income
ESG	0.2817	0.2917
Macroeconomic	0.2737	0.3183
Macroeconomic + ESG	0.2814	0.3203

Source: Amundi Institute.

[19] https://databank.worldbank.org/source/world-development-indicators/

Looking at the adjusted R^2 for low-income countries, societal factors (politics, demographics, etc.) appear to be as important as macroeconomic indicators in explaining economic growth. For high-income countries, the model that includes both extra-financial and macroeconomic information outperforms the models that contain only societal or macroeconomic variables, which calls for a close analysis of these two dimensions together when assessing the growth prospects of these countries.

5 Results

This section provides, for both low and high-income, the interpretations of impulse response functions (IRFs) that describe the response of the variable to shocks in other variables from the VAR system. The IRFs we interpret in this section are obtained from the sparse panel VARs (Table 13 and Table 14 in Appendix A.2), i.e., those that take into account restrictions on non-causality between certain pairs of variables. In practice, if we observe causality between two variables in a small number of countries (compared to our arbitrary threshold), we can set a coefficient of 0 between these two variables. Response standard errors are derived from Monte Carlo simulations replicated 1000 times and estimated using Cholesky decomposition. We choose a horizon length of 10 years. The year-by-year responses are available in the appendix (see Figure 8 in A.3.1 and Figure 9 in A.3.2). The next sections provide insight into the most significant and robust causalities identified for each sample of countries.

5.1 Underlying Mechanisms for High-income Countries

First, the impulse response presented in Figure 2a highlights a positive causality from GDP growth to the energy used per capita. However, as explained in a previous section, the coefficient associated with this causal relationship (from GDP growth to energy use/capita) was set to 0 (see Figure 1b), implying the existence of indirect causal effects. For example, GDP growth has a significant causal effect on the rural population, which in turn causes freedom of expression, which itself causes energy use/per capita. Moreover, it can be observed that - at least during the first ten consecutive years - after a positive shock of 1% in GDP growth, energy use/capita cumulatively increases by 900-1200 kWh. The year-by-year impulse response (see Figure 8a in Appendix A.3.1) shows that it is primarily the instantaneous effect in the first two years that is very positive and then the response to the GDP growth shock declines strongly and rapidly. This result echoes the work of Dedeoğlu and Kaya (2013), who also found a positive causality of GDP growth on energy use. Indeed, the total energy use increases to meet the demand from economic activity, which implies a rise in energy use per capita. Furthermore, these results indicate that overall, and as of today, our panel of developed countries has not yet reached the turning point of the EKC, which implies a fall in environmental pollution (or resource use) once countries achieve a certain level of wealth. However, we do not control for the consumption of renewable energy, which might be concealed within the more generic "energy use" metric.

Second, freedom of expression has a predominantly positive effect on GDP growth. Indeed, looking at the impulse response showing the cumulative effect in Figure 2b, we observe a strong and positive effect in the very short run (about 0.5% growth during the first two years) following a 1% increase in freedom of expression, but also a persistent long term impact. This result confirms Voerman-Tam *et al.* (2023)'s finding of a positive relationship between freedom of expression and countries' wealth, but also the more generic relationship between political stability and economic growth, as highlighted by Alesina *et al.* (1996). The latter argues that political instability creates economic inefficiencies and uncertainty in productive economic decisions (e.g., investment) and policies.

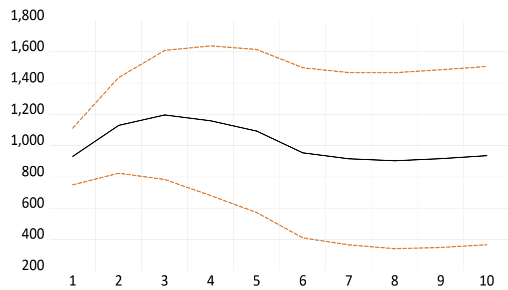
The impulse response 2e in Figure 2b shows that as GDP growth increases, so does water access. However, since there is no direct causal relationship at play (we assign a coefficient of 0 due to the causality graph in Figure 1b), it implies the existence of indirect effects. GDP growth causes rural population and proportion of forest, which in turn causes water access, which explains its relatively small increase for a 1% increase in GDP growth. In fact, Shafik (1994) indicates that access to water is an environmental problem generally solved when incomes improve. Furthermore, the year-by-year impulse response 8e (in Appendix A.3.1) shows that the effect of a positive shock of GDP growth on water access is positive for at least ten consecutive years, and is particularly significant in the first two years.

In Figure 2, impulse responses 2c and 2f represent a two-way causality between rural population and water access. This result appears in many countries as observed in Figure 1b. The year-by-year impulse responses 8c and 8f (in Appendix A.3.1) illustrate that a 1% positive shock for one variable hurts the other. These negative effects persist for at least ten years, with a stronger impact on the rural population's water access. The cumulative effects observed in Figure 2c and Figure 2f are significant at the 95% level for at least 6 and 10 years, respectively. These two dimensions are highly intertwined. According to P. Roberts *et al.* (2006), rural populations experience limited access to social and economic services compared to urban areas, which increases poverty and inequalities (such as poor water access). However, demographics can alter migratory movements (McKenzie, 2017) and pressure access to basic resources in certain areas, amplifying inequalities (Tacoli *et al.*, 2015).

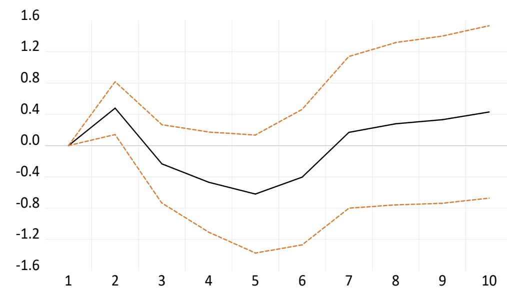
Finally, the cumulative 2d impulse response showcases that a positive shock of 1% in freedom of expression significantly increases water access in the long term, at the 5% threshold. Indeed, water access rises each year for ten years, although the effect becomes statistically significant at the 5% threshold after nine years. Otherwise, if we look at the year-by-year effect (Figure 8d in Appendix A.3.1), we see that the effect due to the freedom of expression shock increases as the years pass: after six years, its impact becomes statistically significant at the 5% level. M. N. Islam (2016) states that in democratic countries, an increase in political freedom causes a decrease in income inequality. Also, egalitarian countries are more likely to have higher access rates to natural resources (including water), thanks to better redistribution. Freedom of expression is generally associated with democracy. Results corroborate

Figure 2: Accumulated Impulse-response Functions for High-income Countries Data

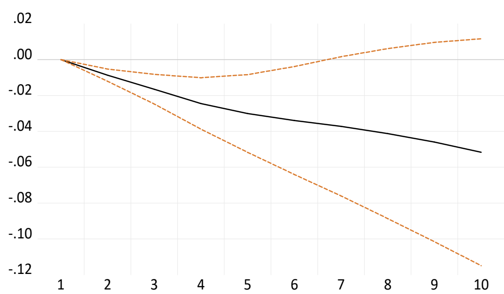
(a) Response of Energy use/Capita to GDP Growth



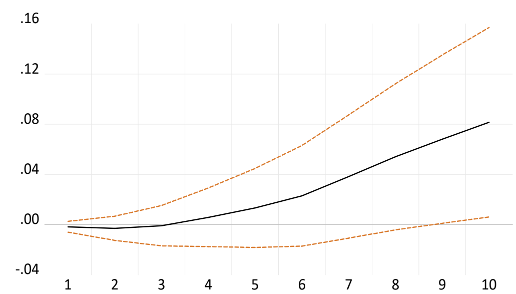
(b) Response of GDP Growth to Freedom of Expression



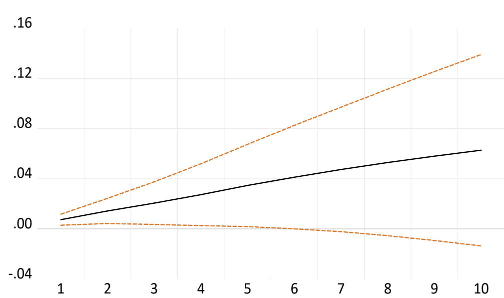
(c) Response of Rural Population to Water Access



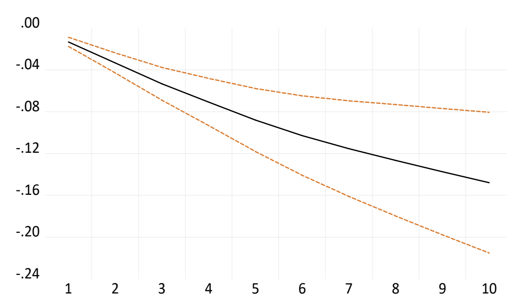
(d) Response of Water Access to Freedom of Expression



(e) Response of Water Access to GDP Growth



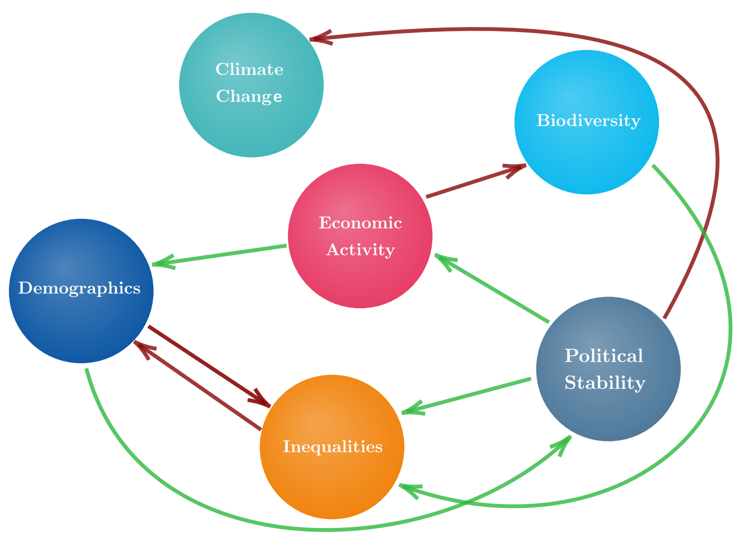
(f) Response of Water Access to Rural Population



such an impact on income inequality (measured by water access).

Figure 3 summarizes our results based on the strongest causal relationships identified for our panel of high-income countries. It is worth noting that climate change and biodiversity do not respond in the expected way to improvements in economic prospects or political stability. Our results show that high-income countries may not have reached the turning point on the Environmental Kuznets Curve in 2000-2020. This conclusion is consistent with Kaya Kanlı and Küçükefe (2023)'s findings using CO_2 emissions and could be explained by the heterogeneity within our sample of high-income countries. The authors argue that the EKC hypothesis does not hold for all high-income countries but also sheds light on a rebound effect with income growth that would lead to an N-shaped curve instead of an inverted-U, as demonstrated by Germany recently reaching a second inflection point (Kaya Kanlı & Küçükefe, 2023).

Figure 3: Strongest Causalities Identified for High-income Countries



Notes: Economic activity improves demographic dynamics (i.e., the share of rural population decreases), which reduces inequalities (i.e., the share of the population with access to water). However, inequalities can also worsen demographic dynamics. In our sample, economic growth is generally associated with biodiversity loss (share of forests). However, biodiversity conservation can help mitigate inequalities. A sound political environment (i.e., freedom of expression) is a determinant of economic activity and inequality reduction. Nonetheless, our analysis shows that it acts as a drag on climate change since energy consumption per capita rises following an improvement in freedom of speech.

5.2 Underlying Mechanisms for Low-income Countries

In Figure 4, impulse responses 4a and 4b highlight a two-way causality between GDP growth and freedom of expression. However, following the observation of the causality graphs (see Figure 1a), the coefficient associated with the causality from GDP growth to freedom of expression was set to 0, revealing indirect effects. Indeed, GDP growth causes proportion of forest, which in turn causes freedom of expression, likely to explain the small move in freedom of expression following a 1% increase in

GDP growth. The mechanism of political instability undermining growth (Alesina *et al.*, 1996; Voerman-Tam *et al.*, 2023) presented for high-income countries remains valid for low-income countries: we find that freedom of expression positively causes GDP growth, and significantly so at the 5% level (see Figure 4b). Nevertheless, our results also showcase a relationship going the other way around. Baklouti and Boujelbene (2020) highlight the existence of a bidirectional causal relationship between economic development and democracy, the latter being typically associated with a higher education level and a more diverse society. Such as society generally requires institutions that promote pluralism and education, fostering pluralistic values and tolerance. Therefore, GDP growth leads to a rising demand for democratic governance, likely implying more freedom of expression. We observe a strong effect of this mechanism in our impulse response 4a, which is significantly positive at the 5% threshold at least for the first two years, as the lower bound of the confidence interval is higher than zero.

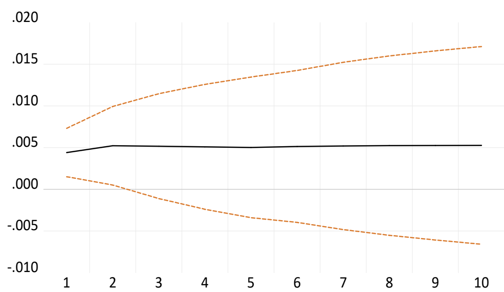
The curve 4c in Figure 4 illustrates the impulse response of GDP growth to a positive shock of 1% in the share of rural population in low-income countries. Firstly, it can be seen that GDP growth decreases over the years. However, the effect diminishes over time, as also exhibited by the year-by-year Figure 9b in Appendix A.3.2. The results are significant at the 5% threshold over a decade. After six years, a 1% increase in the rural population leads to a significant fall of 1.2% in GDP growth. These results confirm the strong causality from rural population to GDP growth previously identified in Figure 1a and corroborates the positive relationship between urban concentration and economic development before a certain level of income, pointed at by Henderson (2000).

On the causality of water access on GDP growth in low-income countries, Figure 4d, presenting the cumulative effects, depicts a monotonic increase over at least the first ten years. This becomes statistically significant at the 5% level in the long term, particularly after 9-10 years, where we observe an increase of around 1.5% in GDP growth after a 1% increase in water access. Such a result is in line with P. R. Hunter *et al.* (2010)'s study, showcasing that better access to drinking water leads to a fall in the infant mortality rate by reducing disease but is also conducive to an improvement of GDP per capita owing to time saved by households with close access to water. Moreover, a reduction in the infant mortality rate and diseases might increase life expectancy, which in turn can foster higher GDP per capita (Weil, 2014) (see subsection 2.5 for more details). The increase in GDP growth we observe following a positive shock to water access authenticates such mechanisms.

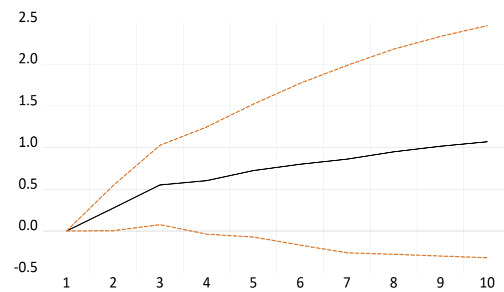
For low-income countries, climate change is measured by renewable energy consumption (for the sample of high-income countries, the variable retained in the optimization process for this dimension was Energy Use/ Capita). It is set as exogenous in the VAR model, following the analysis of Figure 1a. Table 14 in Appendix A.2 exhibits how renewable energy consumption translates into a higher forest level, in line with (Ponce *et al.*, 2021)'s findings. It testifies to the "climate biodiversity nexus" particularly how climate change is responsible for biodiversity loss (Cherief *et al.*, 2022). In addition, climate change mitigation (measured in our model by

Figure 4: Accumulated Impulse-response Functions for Low-income Countries Data

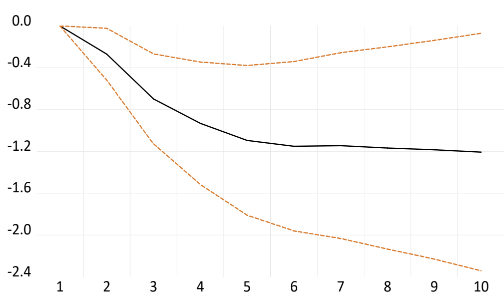
(a) Response of Freedom of Expr. to GDP growth



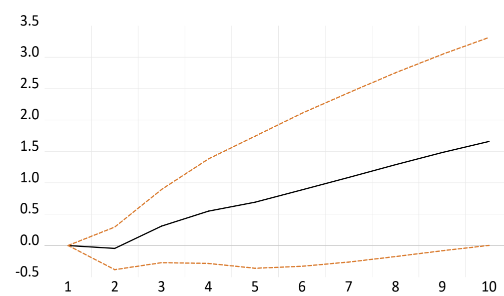
(b) Response of GDP Growth to Freedom of Expr.



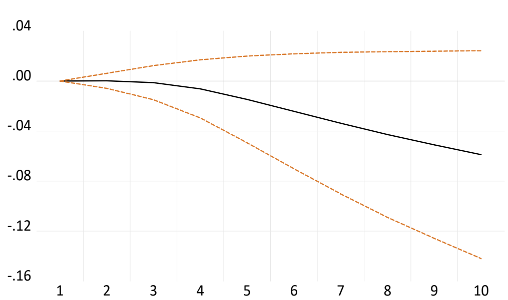
(c) Response of GDP Growth to Rural Population



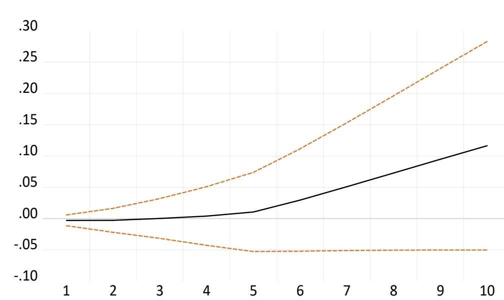
(d) Response of GDP growth to Water Access



(e) Response of Rural Population to Water Access



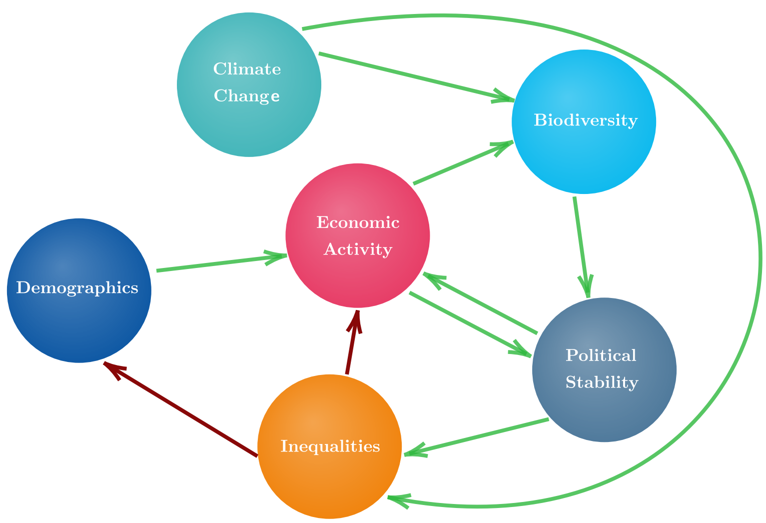
(f) Response of Water Access to Freedom of Expression



renewable energy consumption) also leads to greater access to water for the population, thereby reducing inequalities. For instance, N. Islam and Winkel (2017) highlight that climate change increases the likelihood of droughts, which can cause water scarcity. He explains that this mechanism is also closely linked to demographic dynamics, particularly the importance of the rural population, which is also reflected in our analysis.

Finally, the underlying mechanisms for the causalities of water access on rural population (Figure 4e) and freedom of expression on water access (Figure 4f) are very similar for high and low-income (see subsection 5.1 for more details). Hence, we rather focus on the differences in impulse responses between High and Low-income for the same causalities. First, we witness the increase in water access in low-income countries following an upturn in freedom of expression. Such difference might be driven by high-income countries' overall strong performance on these two metrics, leaving less magnitude for improvement. However, it is interesting to note that the share of the rural population responds similarly to a water access shock in all countries, regardless of income group.

Figure 5: Strongest Causalities Identified for Low-income Countries



Notes: Economic activity leads to biodiversity conservation (i.e., proportion of forest), which in turn improves the political environment (i.e., freedom of expression). The latter is conducive to economic growth, and the causality goes both ways, as an increase in economic activity results in improvements in political stability. Inequalities (i.e., the share of the population with access to water) also benefit from a stable political environment. However, widening inequalities can worsen both economic growth and demographics. A decline in the share of the rural population, which in our model translates into worsening demographic dynamics, may hinder economic activity. Finally, although treated as exogenous in our specification, climate change mitigation (captured by renewable energy consumption) is conducive to biodiversity conservation and inequality reduction.

The causalities from political stability to economic growth and inequalities and the impact from the later on demographics are the most robust relationships identified across our full sample of countries. These results advocate for global improvements in freedom of expression as a substantial way to improve economic growth and mitigate inequalities. A fairer society would also lead to sounder demographic dynamics. Inequalities can also be alleviated by conserving biodiversity in high-income countries or climate change mitigation in low-income countries. Economic growth has a differentiated impact on biodiversity depending on a country's level of development: GDP growth tends to improve forest cover in low-income countries while reducing it in wealthier countries. Finally, on top of political stability, we witness that inequalities and demographics are also essential drivers of economic growth for low-income countries.

6 Conclusion

This paper explores the potential linkages between six dimensions: demography, biodiversity, climate change, political stability, inequalities, and economics. In particular, we seek to identify which phenomena are significant drivers of variation in GDP growth and to quantify these effects. To do this, we first reviewed the literature and assumed that all the dimensions are interrelated. We then constructed from available data a dataset of 57 variables covering 2000-2020 for more than 160 countries worldwide to assess their causal dependencies, controlling for income levels.

Using Granger causality for panel data, we examined the causality between each pair of variables and estimated the strength of these relationships across countries. After identifying the strongest relationships between all dimensions through optimization, we built causality graphs, which allowed us to identify which variables cause each other and in which direction, also identifying the most recurrent relationships worldwide. Next, we constructed a panel VAR, structured according to previously established causality graphs, constraining some mechanisms. We then obtained coefficients to quantify both the intensity and the direction (positive or negative) of the causal effects between each pair of variables. Decomposing GDP growth's variance allows us to assess the explanatory power deriving from extra-financial and macroeconomic variables. More precisely, these two dimensions are equally important for low-income countries, while for high-income nations, their combination yields superior results in explaining economic growth.

The IRFs derived from our panel VAR estimations provide some insights into the mechanisms at play between extra-financial dimensions and economic growth. First, some direct relationships hold regardless of a country's income level. In particular, the impact of political stability - captured by freedom of expression - on economic growth and inequality stands out, as does the link between inequality and demographics. In low-income countries, a 1% increase in freedom of expression leads to GDP growth of 0.5% after three years and 1% after ten years, while a 1% increase in access to water leads to a 1.5% increase in GDP growth after ten years. The integration of environmental concerns (either climate change mitigation or biodiversity conservation) in the mechanisms studied varies by income level. It is interesting to highlight that improvement on the climate change front does not foster significant improvements on other variables in high-income countries. However, in low-income countries, it can substantially mitigate inequalities. Still, we must bear in mind that development of renewable energy infrastructure comes with a significant entry cost in these countries. We also found that for high-income countries, a 1% increase in GDP growth leads to an increase in annual energy consumption per capita of 1200kWh after three years. If this result *a priori* rejects the EKC hypothesis, further analysis should be carried out, particularly considering the use of renewable energy. In comparison, biodiversity plays a more central role in low-income countries. Our study sheds light on the existence of indirect mechanisms. For example, biodiversity does not directly affect economic growth or inequality in low-income countries. Still, it does drive inequality, which in turn is a determinant of GDP growth and inequality.

A refined understanding of the drivers, but most importantly of the - direct and indirect - mechanisms conducive to growth, is essential from the viewpoint of policymakers. It showcases the role of extra-financial factors and motivates their integration within policy designs. Moreover, the IRFs we derived from our panel VAR model can be employed to evaluate "what ifs" scenarios and the impact of extra-financial dimensions on future growth. From a portfolio manager's or analyst's perspective, such analysis could be incorporated into government bond valuations. To illustrate, from our empirical results, we identify that a country whose freedom of speech has declined - for example, following a change of government - could see its growth prospects for the next decade undermined. Finally, this framework could be enriched to reveal new dynamics between extra-financial and macroeconomic data.

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A Appendix

A.1 Income Groups

Table 10: List of Countries Within Each Income Group

	Countries
Low-income	Afghanistan, Angola, Burundi, Benin, Burkina Faso, Bangladesh, Bolivia Bhutan, Central African Republic, Cote d'Ivoire, Cameroon, Congo, Dem. Rep., Congo, Rep. Comoros, Cabo Verde, Djibouti, Algeria, Egypt Arab Rep., Ethiopia, Ghana, Guinea Gambia, The, Guinea-Bissau, Honduras, Haiti, India, Iran, Islamic Rep., Jordan, Kenya Kyrgyz Republic, Cambodia, Lao PDR, Lebanon, Liberia, Sri Lanka, Lesotho, Morocco Madagascar, Mali, Myanmar, Mongolia, Mozambique, Mauritania, Malawi, Niger, Nigeria Nicaragua, Nepal, Pakistan, Philippines, Papua New Guinea, Rwanda, Sudan, Senegal, Sierra Leone Sao Tome and Principe, Eswatini, Syrian Arab Republic, Chad, Togo, Tajikistan, Timor-Leste Tunisia, Tanzania, Uganda, Ukraine, Uzbekistan, Vietnam, Yemen, Rep., Zambia, Zimbabwe
High-income	Albania, United Arab Emirates, Argentina, Armenia, Australia, Austria Azerbaijan, Belgium, Bulgaria, Bahrain, Bahamas The, Bosnia and Herzegovina, Belarus, Belize Brazil, Brunei Darussalam, Botswana, Canada, Switzerland, Chile, China, Colombia, Costa Rica Cuba, Cyprus, Czechia, Germany, Denmark, Dominican Republic, Ecuador, Spain, Estonia, Finland France, Gabon, United Kingdom, Georgia, Equatorial Guinea, Greece, Guatemala, Guyana, Hong Kong Croatia, Hungary, Indonesia, Ireland, Iraq, Iceland, Israel, Italy, Jamaica, Japan Kazakhstan, Korea, Rep., Kuwait, Libya, Lithuania, Luxembourg, Latvia, Moldova, Maldives Mexico, North Macedonia, Malta, Montenegro, Mauritius, Malaysia, Namibia, Netherlands Norway, New Zealand, Oman, Panama, Peru, Poland, Portugal, Paraguay, Qatar, Romania Russian Federation, Saudi Arabia, Singapore, El Salvador, Serbia, Suriname, Slovak Republic Slovenia, Sweden, Thailand, Trinidad and Tobago, Turkiye, Uruguay, USA, Venezuela, South Africa

Source: Amundi Institute.

A.2 Supplementary materials for VAR

Table 11: Lag Length Criteria (High-income)

Lag	Log-likelihood	LR	FPE	AIC	SC	HQ
1	-12507	12215.3	0.125	14.95	15.08	15.0
2	-11366.4	457.97	0.073	14.41	14.68*	14.51*
3	-10688.4	121.81	0.075	14.43	14.84	14.58
4	-9973.1	95.29	0.072	14.40	14.96	14.61
5	-9329.5	82.73	0.078	14.47	15.21	14.75
6	-8583.4*	75.29*	0.071*	14.39*	15.31	14.74

Log-likelihood: maximize
Sequential modified LR test statistic at 5% level: minimize
Final prediction error (FPE): minimize
Akaike, Schwarz, and Hannan-Quinn information criterion (AIC, SC, HQ): minimize

Source: Amundi Institute.

Table 12: Lag Length Criteria (Low-income)

Lag	Log-likelihood	LR	FPE	AIC	SC	HQ
1	950.8	8568.7	1.62×10^7	-1.45	-1.29	-1.39
2	1054	204.32	1.43×10^7	-1.57	-1.31	-1.47
3	1018.6	58.43	1.45×10^7	-1.56	-1.15	-1.40
4	1284	25.86*	8.61×10^8	-2.08	-1.52	-1.87
5	1538.8*	89.74	4.86×10^8*	-2.65*	-1.92*	-2.37*
6	1370.6	40.20	6.02×10^8	-2.44	-1.51	-2.08

Log-likelihood: maximize
Sequential modified LR test statistic at 5% level: minimize
Final prediction error (FPE): minimize
Akaike, Schwarz, and Hannan-Quinn information criterion (AIC, SC, HQ): minimize

Source: Amundi Institute.

Figure 6: Correlation Matrix of Residuals for High-income Countries

	GDP Growth	Rural Pop.	Prop. of forest	Energy use/cap.	Freedom expr.	Water access
GDP growth	1	-0.015	-0.006	0.287	0.071	0.094
Rural pop	-0.015	1	0.010	-0.020	0.003	-0.173
Prop. of forest	-0.006	0.010	1	0.004	-0.019	0.008
Energy use/cap.	0.287	-0.020	0.004	1	-0.010	0.056
Freedom of expr.	0.071	0.003	-0.019	-0.010	1	-0.018
Water access	0.094	-0.173	0.008	0.056	-0.018	1

Source: Amundi Institute.

Figure 7: Correlation Matrix of Residuals for Low-income Countries

	GDP Growth	Rural Pop.	Prop. of forest	Freedom expr.	Water access
GDP growth	1	0.040	0.041	0.094	0.037
Rural pop	0.040	1	-0.006	0.006	-0.058
Prop. of forest	0.041	-0.006	1	0.008	0.003
Freedom of expr.	0.094	0.006	0.008	1	-0.018
Water access	0.037	-0.058	0.003	-0.018	1

Source: Amundi Institute.

Table 13: High-income Panel VAR

	GDP Growth	Rural Pop.	Proportion of forest	Energy use per capita	Freedom of expression	Water access
GDP growth(-1)	0.0738**	0.0008**	-0.0003	0	0	0
GDP growth(-2)	0.0555*	-0.0006	-0.0004	0	0	0
GDP growth(-3)	0.0590**	-0.0005	0.0002	0	0	0
GDP growth(-4)	0.0511*	0.0003	0.0009*	0	0	0
GDP growth(-5)	0.0697**	0.0004	-7.30E-05	0	0	0
GDP growth(-6)	0.0053	0.0003	-0.0004	0	0	0
Rural pop.(-1)	0	1.1399***	0.0189	0	0.0240	-0.1306***
Rural pop.(-2)	0	-0.2172***	-0.0624	0	-0.0253	0.1308**
Rural pop.(-3)	0	0.03934	0.0512	0	-0.0255	0.0205
Rural pop.(-4)	0	0.0529	-0.0555	0	0.0269	-0.0351
Rural pop.(-5)	0	-0.1745***	0.0125	0	-0.0139	0.0434
Rural pop.(-6)	0	0.1128***	0.0354	0	0.0151	-0.0347
Prop. of forest(-1)	0	-0.0017	0.3978***	0	0.0078	0.0196
Prop. of forest(-2)	0	0.0045	0.3023***	0	-0.0218**	-0.0450*
Prop. of forest(-3)	0	-0.0105	0.1974***	0	0.0159	0.0256
Prop. of forest(-4)	0	-0.0010	-0.2152***	0	-0.0063	-0.0250
Prop. of forest(-5)	0	-0.0097	0.0790**	0	0.0039	0.0217
Prop. of forest(-6)	0	0.0089	0.1242***	0	-8.99E-06	0.0092
Energy use/cap.(-1)	0	-5.55E-07	0	0.2024***	0	0
Energy use/cap.(-2)	0	-2.23E-07	0	0.0421	0	0
Energy use/cap.(-3)	0	2.14E-07	0	-0.0654***	0	0
Energy use/cap.(-4)	0	-9.95E-08	0	-0.0464*	0	0
Energy use/cap.(-5)	0	-2.68E-07	0	-0.1216***	0	0
Energy use/cap.(-6)	0	-1.52E-07	0	0.0110	0	0
Freedom of expr.(-1)	13.6422***	0	0.0294	4087.01	0.2695***	0.0131
Freedom of expr.(-2)	-24.9896***	0	-0.0978	-5857.17**	-0.1349***	0.0896
Freedom of expr.(-3)	1.6568	0	0.0061	2167.07	0.1087***	0.1166
Freedom of expr.(-4)	-6.2442	0	-0.0376	-2885	-0.0344	0.0027
Freedom of expr.(-5)	10.2346*	0	-0.0298	2239.20	-0.0352	0.0732
Freedom of expr.(-6)	14.5887***	0	0.0751	2086.64	-0.0454	0.1449**
Water access(-1)	0	-0.1144***	0	0	0	0.9343***
Water access(-2)	0	0.1336***	0	0	0	-0.0014
Water access(-3)	0	-0.0355	0	0	0	0.0300
Water access(-4)	0	0.0409	0	0	0	0.0310
Water access(-5)	0	-0.0036	0	0	0	-0.0792
Water access(-6)	0	-0.0386	0	0	0	0.0217
Constant	1.1906***	-0.0114***	-0.0034	-233.09**	-0.0015	0.0026
R-squared	0.0712	0.9693	0.7302	0.0844	0.0833	0.9403
Sum squared resids	35754.38	4.1646	11.4732	1.24E+10	1.4720	7.0955

*** : 1%
** : 5%
* : 10%
Number of coefficients: 126
Number of restrictions: 96

Source: Amundi Institute.

Table 14: Low-income Panel VAR

	GDP Growth	Rural Pop.	Proportion of forest	Freedom of expression	Water access
GDP growth(-1)	0.4198***	0	0.0001	0	0
GDP growth(-2)	0.0024	0	6.69E-05	0	0
GDP growth(-3)	0.0583*	0	0.0010	0	0
GDP growth(-4)	0.0385	0	-0.0008	0	0
GDP growth(-5)	0.0669**	0	-0.0003	0	0
Rural pop.(-1)	-3.5736**	1.0684***	0	0	-0.0046
Rural pop.(-2)	-0.0194	-0.1297***	0	0	0.0211
Rural pop.(-3)	3.0314	0.0445	0	0	0.0072
Rural pop.(-4)	-0.3340	-0.2594***	0	0	0.0052
Rural pop.(-5)	0.5174	0.2156***	0	0	-0.0161
Prop. of forest(-1)	0	-0.0155	0.8618***	-0.0104	0.0079
Prop. of forest(-2)	0	0.0508***	0.0458**	0.0163	-0.0034
Prop. of forest(-3)	0	-0.0253	0.0324	-0.0078	0.0005
Prop. of forest(-4)	0	0.0102	0.0058	0.0087	-0.0301
Prop. of forest(-5)	0	-0.0115	-0.0107	-0.0046	0.0214
Freedom of expr.(-1)	5.8021**	0.0102	0	0.1934***	0.0630
Freedom of expr.(-2)	2.5903	0.0152	0	-0.0404	0.0522
Freedom of expr.(-3)	-1.8841	0.0176	0	-0.0014	0.0119
Freedom of expr.(-4)	2.1452	0.0169	0	-0.0134	0.0473
Freedom of expr.(-5)	-0.2043	0.0211	0	0.0163	0.2581**
Water access(-1)	-0.3320	0.0007	-0.0088	0.0004	0.9964***
Water access(-2)	3.0119*	-0.0123	0.0501	-0.0104	0.0235
Water access(-3)	-2.0181	-0.0113	-0.0704*	0.0069	0.0160
Water access(-4)	-0.4519	-0.0027	0.0432	0.0067	-0.0597
Water access(-5)	0.3162	0.0208	-0.0123	-0.0020	0.0041
Renew. energy cons.(-1)	0	0.0012	-0.0004	0	0.0044**
Renew. energy cons.(-2)	0	-0.0006	0.0049***	0	-0.0030
Renew. energy cons.(-3)	0	0.0005	0.0003	0	0.0018
Renew. energy cons.(-4)	0	0.0006	0.0015	0	0.0022
Renew. energy cons.(-5)	0	0.0002	0.0011	0	-0.0013
Constant	0.8345***	-0.0203***	-0.0061	-0.0018	0.0040
R-squared	0.2305	0.9332	0.8601	0.0422	0.9606
Sum squared resids	19446.87	5.9317	9.3425	2.2479	19.9726

*** : 1%
** : 5%
* : 10%
Number of coefficients: 110
Number of restrictions: 45

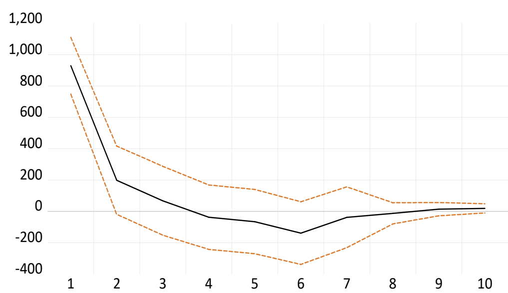
Source: Amundi Institute.

A.3 Year-by-year Impulse Response

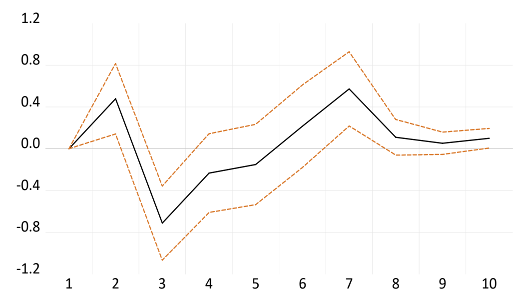
A.3.1 High-income

Figure 8: Year-by-year Impulse-response Functions for High-income Countries Data

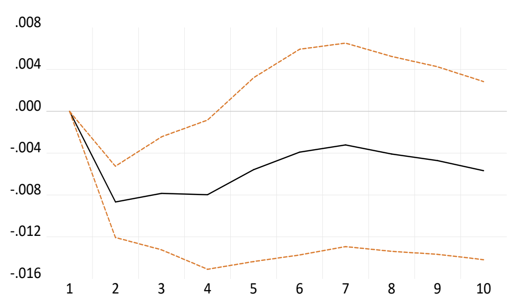
(a) Response of energy use/capita to GDP growth



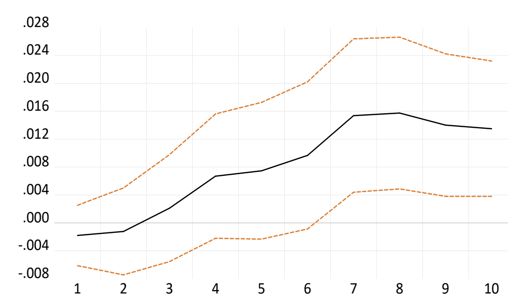
(b) Response of GDP growth to freedom of expression



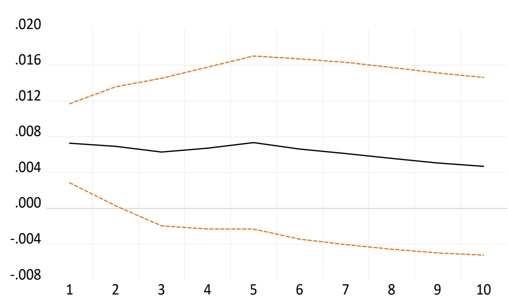
(c) Response of rural population to water access



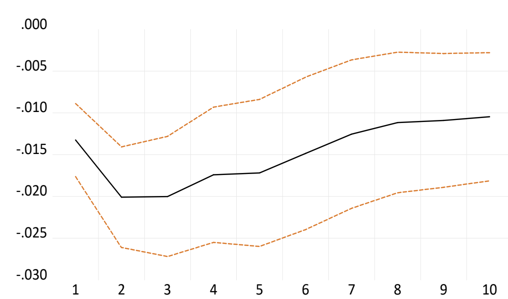
(d) Response of water access to freedom of expression



(e) Response of water access to GDP growth



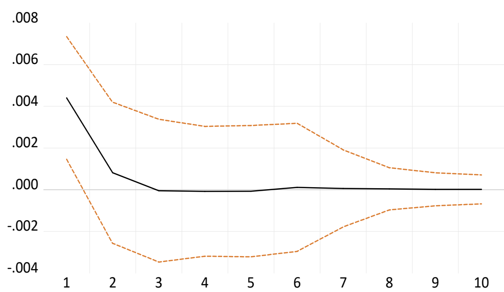
(f) Response of water access to rural population



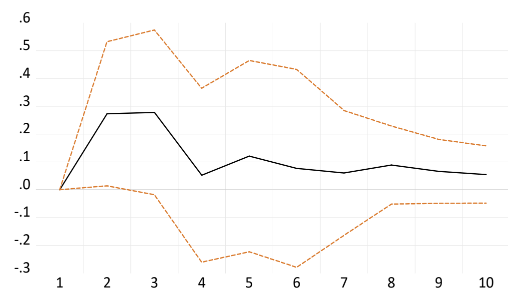
A.3.2 Low-income

Figure 9: Year-by-year Impulse-Response Functions for Low-income Countries Data

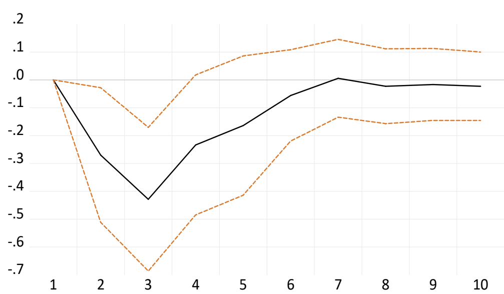
(a) Response of Freedom of Expr. to GDP growth



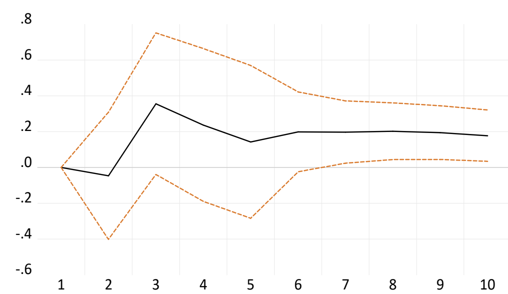
(b) Response of GDP growth to freedom of expression



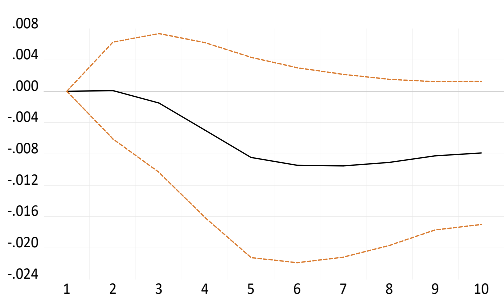
(c) Response of GDP growth to rural population



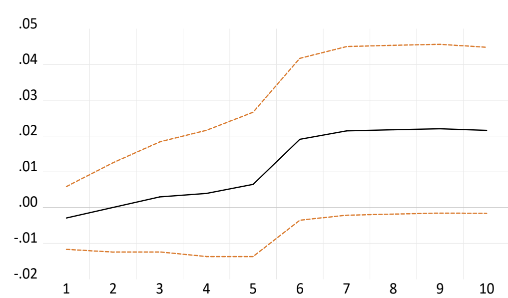
(d) Response of GDP growth to water access



(e) Response of rural population to water access



(f) Response of water access to freedom of expression



Important Information

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