



ARTICLE



<https://doi.org/10.1057/s41599-022-01130-7>

OPEN

Global adaptation readiness and income mitigate sectoral climate change vulnerabilities

Samuel Asumadu Sarkodie ¹✉, Maruf Yakubu Ahmed ¹ & Phebe Asantewaa Owusu ¹

Climate change has become a global burden, requiring strong institutional quality and willingness to mitigate future impacts. Though emissions are transboundary and have the tendency of spreading from high emitting countries to low emitting countries, regional exposure, sensitivity, and adaptation readiness determine the extent of climate effects. The existing literature focuses on immediate drivers and damages of emission effects, failing to account for underlying mechanisms occurring via the nexus between emission levels, economic, social, and governance adaptation readiness. Here, this study broadens the scope of previous attempts and simultaneously examines climate change vulnerability across sectors including ecosystem services, food, health, human habitat, infrastructure, and water. We use the Romano-Wolf technique to test multiple hypotheses and present the spatial-temporal severity of climate vulnerability and readiness to combat climate change and its impacts. Besides, we assess the long-term impact of climate change readiness and income expansion on sectoral-climate vulnerabilities. We find that high-income economies with high social, governance, and economic readiness have low climate vulnerability whereas developing economies with low income have high climate change exposure and sensitivity. Our empirical evidence could be used to prioritize limited resources in addressing and managing adaptive actions of extreme climate change vulnerabilities.

¹Nord University Business School (HHN), Post Box 1490, 8049 Bodø, Norway. ✉email: asumadusarkodiesamuel@yahoo.com

Introduction

The global climatic condition is changing—as data collected over four decades show the earth is warming at an unprecedented level (IPCC, 2021). There is high probability that climate change will persist for decades and will continue to hamper humanity (IPCC, 2018). The majority of scientists associate the earth's warming trend with the greenhouse effect caused by greenhouse gas (GHG) emissions (Kerr, 1990; Wigley and Barnett, 1990). The main causes can be attributed to—the burning of fossil fuel such as crude oil, natural gas, and coal to meet the increasing global energy demand—and intensive agricultural practices to meet the growing global food demand. Today, the world is experiencing climate change in the form of extreme weather and variations. For example, the average global temperature and sea level are estimated to rise between 1.8–4.0 °C and 0.09–0.88 m by the end of the 21st century, respectively (SEEFCCA, 2012). Extreme climate events are threat to the considerable progress made on eradicating global hunger and malnutrition in the last decades. The global food market is already experiencing the effect of climate change particularly in rural areas where harvest crops have declined (Gitz et al., 2016). The increase in food supply to meet demand is most often accompanied by deforestation (FAO, 2011). Persistent meteorological drought due to climate change affects water storage, reducing global water supply (Stagge et al., 2015). Global studies indicate one in three people are already facing the threat of water security due to challenges with water shortage (IWMI, 2007; Vörösmarty et al., 2010). Under current climate conditions, the availability of reliable surface water is estimated to decline due to rising variability in river flows triggered by increased variability in precipitation, and reduction in ice storage and snow (Kundzewicz and Doell, 2009). Thus, climate change causes the global average sea level to rise by melting ice sheets and glaciers. Warming of the water from melting ice sheets and glaciers causes ocean volume to expand while declining the number of rivers, reservoirs, lakes, aquifers, and soil moisture (Lindsey, 2021). The degree and frequency of droughts are estimated to increase due to future climate change vulnerability, primarily due to regional decline in precipitation and rising levels in evapotranspiration driven by climate change variability (IPCC, 2013, 2021). Climate change vulnerability and environmental degradation induced human activities have affected the current habitat loss and fragmentation resulting in global biodiversity crisis (Hoffmann et al., 2010).

The Kyoto protocol signed by developed countries in 1997 and Paris Agreement adopted in 2015 by 196 countries and territories with the sole commitment of reducing emissions is stalling, even though many countries are undertaking vigorous emission reduction policies. The GHG emissions emitted today will cause decades of climate change effects. Mitigating GHGs has been unsuccessful due to ineffective governance structures and institutions in creating effective climate policies, however, adaptation to climate change effects is possible (Denton et al., 2014; SEEFCCA, 2012). The barriers to climate change adaptation include lack of human and institutional capacity, lack of awareness and communication, and financial constrain (Bergsma et al., 2012; Stuart-Hill and Schulze, 2010). For example, the \$100 billion broken promise of climate financing by developed nations could hamper trust and effort toward reducing emissions in developing economies (Timperley, 2021). In the last two decades, the world has witnessed extensive studies on the potential impacts of climate change in regional, national, and local development. The existing literature advances the scientific understanding of climate vulnerabilities across sectors including inter alia, economic, ecosystem, food, health, human habitat, infrastructure, and water. Climate change vulnerability can be

classified as three interacting functions of exposure, sensitivity, and adaptive capacity (Smit and Wandel, 2006). Thus, climate vulnerability encompasses a range of methodologies drawn from multi-disciplinary fields offering valuable insights into reducing climate risks (USAID, 2014). Vulnerability to climate change assessment aims to provide insights on developmental policies that reduce the risk associated with the effects of climate change (Schneider et al., 2001). The two primary response options to climate change effects involve mitigation and adaptation. While mitigation aims to reduce GHG emissions—thereby limiting the global climate change, adaptation refers to approaches that moderate adverse effects associated with climate change through a wide range of policies and responses targeted at vulnerable systems (Füssel and Klein, 2006). Climate change adaptation requires knowledge, awareness about exposure, viz. early warning signs, and adaptation options to deal with climate variabilities (Nunfam et al., 2018). The extent of climate change vulnerability and its related risks are location-specific and depends majorly on the effectiveness of governance, quality public healthcare infrastructure, level of material resources, and timely access to critical weather threat information (Mateeva, 2020).

Studies have been conducted to advance the scientific understanding of climate vulnerabilities and adaptation, however, literature on sectoral assessment including food, health, water, ecosystem, infrastructure, and economic activities is sporadic. The existing literature focuses on immediate drivers and damages of emission effects, failing to account for underlying mechanisms occurring via the nexus between emission levels, economic, social, and governance adaptation readiness. The proposed study contributes to the global debate on climate change mitigation and adaptation readiness through the selection of indicators in line with the methodologies and guidelines of the sustainable development goals. Here, we examine:

1. the spatial–temporal severity of climate vulnerability across six sectors namely food, water, infrastructure, human habitat, health, and ecosystem services.
2. the geographical readiness to combat climate change and its impacts.
3. the long-term impact of climate change readiness and income expansion on sectoral-climate vulnerabilities.

Thus, this study broadens the scope of previous attempts by assessing climate change vulnerability across several sectors. We simultaneously test multiple hypotheses of climate vulnerabilities in 192 economies with Romano–Wolf correction technique that controls the over-rejection of null hypotheses. Advantageously, Romano–Wolf correction technique (Clarke et al., 2020) account for the tendency of rejecting the estimated true null hypotheses in contrast to traditional testing techniques. Hence, produces robust and consistent *p*-values via bootstrap resampling of the original climate data—considering the dependence structure of the instrumental-variable-based single-equation test statistics. Because awareness creation is critical to enhancing the knowledge of early warning signs of climate change and its impact, this study proposes the engagement of policymakers and researchers to improve capacity building. Our results could be adopted by environmental agencies in defining the baseline of climate change exposure, sensitivity, and adaptive capacity, before implementing and monitoring adaptive actions.

The subsequent sections of this paper present the conceptual framework, data sources and characteristics, model estimation and validation, empirical results and discussion, summary of findings, and policy implications.

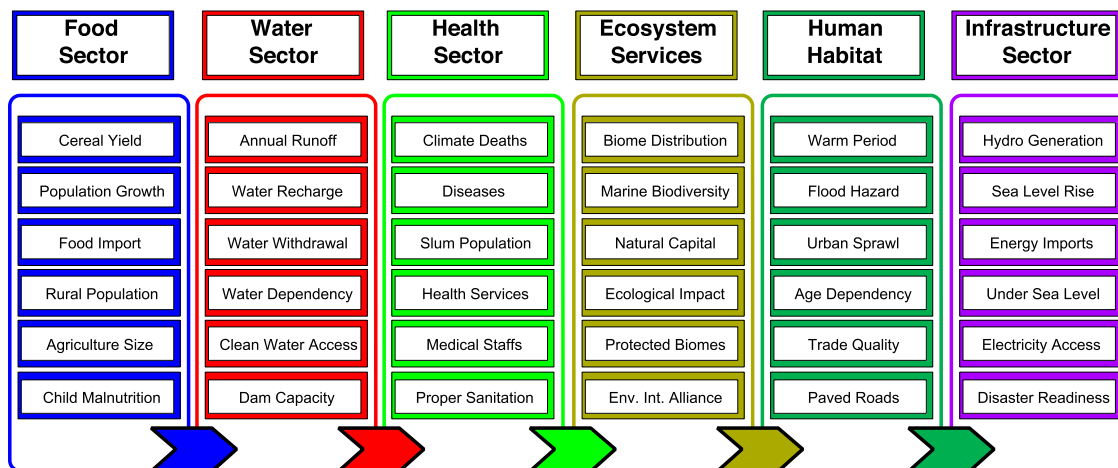


Fig. 1 Conceptual framework of sectoral vulnerabilities to climate change and its impacts. Source: Authors’ construction based on ND-GAIN, 2018 indicators. The first two rows of each column designate climate exposure, the third and fourth rows represent climate change sensitivity whereas the fifth and sixth rows denote adaptive capacity.

Methods

Conceptual framework. The conceptual framework presented in Fig. 1 provides an overview of climate vulnerabilities across sectors namely food, water, health, ecosystem services, human habitat, and infrastructure. Climate change vulnerability entails exposure, sensitivity, and adaptive capacity (Smit and Wandel, 2006), hence, the adoption of ND-GAIN (2018) indicators is crucial to assessing sectoral climate change vulnerabilities. For example, the sectoral exposure to climate change includes variations in cereal yield and population growth, variabilities in annual runoff and groundwater recharge, climate-related vector-borne morbidities and mortalities, modifications in biome and marine biodiversity, changes in temperature and flood hazards, and alterations in hydropower generation and sea-level rise (GFN, 2017; ND-GAIN, 2018; United Nations, 2015; World Bank, 2020). In contrast, sectoral climate change adaptive capacity comprises agricultural production capacity, access to clean and reliable water supplies, access to clean and improved sanitation conditions, biomes protected, trade quality and transportation structure, access to electricity, and disaster readiness (GFN, 2017; ND-GAIN, 2018; United Nations, 2015; World Bank, 2020).

Food sector. Positive strides have been made to address the global impact of climate change in the past decades. For example, global food production (1986–2009) has increased by 121% in South America, 81% in Africa, 58% in Asia, and 57% in North America (D’Odorico et al., 2014). However, based on the estimated 2050 population by United Nations and 2.5% global income growth, global crop production is projected to increase by 100–110% before 2050 (Tilman et al., 2011). Agriculture is an important sector of the economy that provides livelihood to ~36% of the global workforce—particularly, 50% workforce in Asia and Pacific, and 66% of the working population in Sub-Saharan Africa (FAO, 2015). Extreme weather events due to climate change are reported to affect the agricultural sector in developing countries. The post-disaster events of 48 developing countries covering 10 years indicate 25% losses and damages caused by climate hazards such as floods, droughts, and storms (FAO, 2015). The climate change effect from 1981 to 2010 is found to decrease the global mean yield of corn, soybeans, and wheat relative to preindustrial climate (Iizumi et al., 2018). The findings from existing literature suggest a growing strong relationship between crop yield and climate variables—inferring future increase in climate change may have severe impact on crop production (Mavromatis, 2015).

A recent study using the IPCC’s highest climate change scenario shows global crop yields such as wheat, rice, and coarse grains will decline by 17% before 2050—given the scenario remains unchanged (FAO, 2015). The earth’s landmass constitutes 40% dryland which is home to about 2.5 billion people (FAO, 2011). However, the dryland region particularly in developing countries, typically in Africa faces challenges with food security due to challenges to effectively manage and mitigate decreasing crop yield (Nellemann and MacDevette, 2009). Climate variables including temperature above or below a certain threshold by a few days may damage cereal or fruit tree yield (Wheeler et al., 2000). During the 2003 European heatwave, crops yield dropped drastically including 36% of maize harvest in Italy, and 25–30% of fruit and forage harvest in France (SEEFCCA, 2012). The impact of climate change affects the nutritional quality of food products including rice, maize, millet, and cassava—due to elevated CO₂ reducing the concentrated level of vitamins, minerals, or protein (FAO, 2015). The adverse effect of climate change may hamper agriculture production, particularly in developing countries (specifically in Asia and Africa) where the livelihood of rural folks depends majorly on farming, hence, may increase the vulnerability of food insecurity (Nellemann and MacDevette, 2009).

Water sector. Global water resources are already under threat even without climate change. The rise in water scarcity is more pronounced in expanding cities around the globe. The estimated population growth in the next few decades is projected to double in size by an estimated 5 billion from 1995 to 2025 in urban areas (Vörösmarty et al., 2000). It is estimated that climate change variability along with rampant extreme events including flood, drought, storm, and cyclones—will escalate the existing situation in countries already threatened with water insecurity whereas similar problems threaten areas that have not been severely affected (UN, 2020).

Irrigation remains the largest human water usage, accounting for 70% of annual water withdrawal—implying limited water supply is the bottleneck of sustainable agricultural production (Siebert et al., 2010). However, some regions in the Middle East are reported to use water resources as a tool for political leverage (Cartier, 2021). Studies indicate that decrease in participation affects the availability of water resources (Gosling and Arnell, 2016; Hayashi et al., 2010; Lionello and Scarascia, 2018). Climate change is estimated to decrease global groundwater recharge,

thus, affecting renewable groundwater resources (Kundzewicz and Doell, 2009). For example, future water availability in the Maghreb and the Middle East while accounting for demand and supply will lead to a 12% decrease in water supply and a 50% increase in water demand (Droogers et al., 2012). A rise in global temperature could increase permafrost degradation, and runoff from glaciers, affecting soil erosion and sediment loads in colder places (Lu et al., 2010). The rise in temperature in the region is linked to a potential increase in evapotranspiration—which is mostly visible in late spring and early fall seasons—that are responsible for the decline in annual surface runoff (Schilling et al., 2020). Infrastructure improvement and operation practices could help change the volume and timing of water supply systems (Connell-Buck et al., 2011). Addressing the uncertainty associated with climate change variability would require, for example, water resource managers to move from the traditional approach, viz. “predict and provide” towards the adaptation of water resources management approach (Gersonius et al., 2013; Short et al., 2012).

Health sector. The effects of climate change exposure on global health vary between countries. For instance, the loss of healthy life years in low-income countries in Asia and Africa is estimated to be 500 times more severe than that in Europe and the United States (McMichael et al., 2008). The climate warming of 1.5 °C is considered hazardous to human lives, which is expected to exacerbate the physical and mental health of the vulnerable and poor population. Extreme poverty is reported to affect health outcomes (viz. morbidity and mortality) and health equity (Murray, 2006). Hence, individuals with lower economic status have higher risks of poor health (WHO, 2018b). Thus, climate change is considered an indicator of the poverty multiplier, which is estimated to force 100 million vulnerable populations into severe poverty by 2030 (WHO, 2018a). Evidence from literature is becoming increasingly clear that climate change variabilities have a severe impact on human health (WorldBank, 2018). An increase in warmer temperatures is associated with the rise in morbidity across countries (Campbell et al., 2018). Prolong exposure to heat may exacerbate pre-existing cardiovascular and chronic respiratory diseases among the aged and people with underlying health conditions (McGeehin and Mirabelli, 2001). Socioeconomic factors such as income, housing, education, and employment are highly sensitive to climate change vulnerability and exposure, which may result in uneven access and distribution of health facilities. For instance, the Chicago heatwave saw a vulnerable community experience high rate of heat-related deaths than community residents that felt secure and safe (Pasquini et al., 2020). Large-scale environmental changes are reported to unlikely cause entirely new disease outbreaks, but rather alter the intensity, range, and seasonality of existing health diseases (McMichael et al., 2008). Evidence shows the necessity of optimizing the health infrastructure, improving the know-how, and technical competence of health professionals to curb climate-induced health risks through treatment, and monitoring (Mateeva, 2020; McMichael et al., 2008).

Ecosystem services. Climate change affects individual species and how different organisms interact with others, hence, changing the structure and functioning of the ecosystem, benefits, and services provided to society (Weiskopf et al., 2020). The periodic evaluation of the current and potential future impact of climate change on the ecosystem can allow society to better anticipate, plan, manage and adapt to the necessary changes (West et al., 2009). The duration, degree, and frequency of extreme climate events including heatwaves, drought, flood, and forest fires are altered by long-term climate change (USGCRP, 2018). Recent studies indicate a 66% probability of increasing the impact of

habitat loss and fragmentation in 18.5% of global ecoregions—with an estimated 54.1% of all known biodiversity including birds, mammals, reptiles, and terrestrial amphibians (Segan et al., 2016).

Ecosystem and biodiversity provide vital regulation services including easing the impact of extreme events, soil and air quality maintenance, sequestering carbon, and controlling the spread of diseases. With the accelerated increase in climate change, carbon storage remains threatened. Given the increase in forest area in the last decades, it is still unclear whether the afforestation rate will continue to outweigh the rate of deforestation (Weiskopf et al., 2020). The climate-driven threat to forestry production varies depending on forest type and may likely decrease in forests where soil water supply is limited in planting seasons (Halofsky et al., 2020; Latta et al., 2010). Existing studies remain unclear whether the use of fertilization is still effective as forest ages (Latta et al., 2010). Additionally, human-induced climatic events enhance the introduction and spreading of non-native species—that capitalizes on the changing environment to colonize native species. The non-native species may dominate by reproduction, and in some cases lead to the extinction of native species (Schmitt et al., 2019; Yeruham et al., 2020). Climate change is predicted to exacerbate the impact of species invasion, with a global economic cost estimated at \$1.4 trillion (Burgiel et al., 2014).

Climate change adaptation and proactive techniques based on scientific methods to meet the emerging, anticipated, and extreme weather events are required to sustain the ecosystem and enhance biodiversity (Holsman et al., 2019). For instance, the scientific-based data system employed by the US to capture and detect changes in fish productivity, catch, and abundance. This approach provides adequate information for decision-making and management of fisheries including seasonality, annual quota, stock rebuilding policies, and spatial closures (Weiskopf et al., 2020). In creating adaptive climate change strategies, institutional managers could determine relative risks exposure, sensitivity, and adaptability through climate change vulnerability assessment of species, and exposure to non-climate stressors (Glick et al., 2011; Spencer et al., 2019).

Human habitat. Drought and heat waves are significant climate events that increase risks associated with wildfire. The destructive wildfire that occurred in California in 2017–2018 is reportedly caused by extreme summertime forest fire (Williams et al., 2019). Similarly, Macedonia in the summer of 2007 experienced wildfire which destroyed an estimated 40,000 acres of forest whereas severe drought in 2003 caused an economic loss of \$330 million in Croatia (SEEFCCA, 2012). Climate change exposure such as flooding has become a global phenomenon with varying degrees. For instance, long heavy rain that occurred in early 2000 caused the Nzoia river to flood western Kenya, affecting over 800,000 people, killing 237 people, and destroying properties (Cartier, 2021). The climate change effect extended beyond Africa, with heavy floods in the Middle East that ruined farmlands, particularly in Iran, affecting crop yield (Cartier, 2021).

Global Urbanization is one of the 21st-century megatrends which cannot be stopped or adjusted. Urbanization is considered one of the most sensitive sectors to climate change vulnerability. The 55% of the world's population constituting 4.2 billion (i.e., est. 2018) of the total 7.6 billion lives in urban cities. The estimate of urban settlement in the future reveals 60%, and 66.4% of the total world's population of 8.6 billion by 2030 and 9.8 billion by 2050, respectively (UN, 2020). The majority of urban dweller population growth is estimated to occur in developing countries within East Asia, South Asia, and Sub-Saharan Africa (UNDESA, 2019). Urban sprawl is expected to increase, affecting the already limited resources such as energy, water, sanitation, and waste

management—that can further spur climate change effects (Sarkodie et al., 2020). Unstable and rapid urbanization with slums proliferation and overcrowding often exposes people to related health risks due to lack of clean and safe water, poor sanitary conditions, among others. Thus, population growth and economic development are dominant contributing factors influencing the increase in the number of people affected by coastal and river floods (PBLNEAA, 2014).

Infrastructure sector. It is reported that 8 of the world's largest top 10 cities are located near coastal areas. In the US alone, about 40% of the population lives in densely populated coastal provinces prone to rising sea levels—leading to shoreline erosion, flooding, and storms (Lindsey, 2021). The rising sea level has a direct impact on humanity by increasing sea floods and coastal erosions unless costly climate change adaptation including sea defense and relocation of communities is undertaken. The sea level has risen at a rate averaging 0.11–0.14 inches yearly since 2013—which is relatively twice faster than the projected long-term trend (EPA, 2016a). For instance, significant coastal areas sensitive to climate change vulnerability in European countries (including Denmark, England, Germany, The Netherlands, and Italy) are already below normal high tide levels and prone to flooding from storm surges (McCarthy et al., 2001). A projected 9% of all European coastal zones are below 5 m elevation, particularly in The Netherlands and Belgium where 85% of the coastal areas are below the 5 m elevation level. These areas below the 5 m elevation level are potentially vulnerable to sea-level rise and inundations (EEA, 2005). The effect of rising sea level on groundwater may result in a short-term and long-term decrease in terrestrial water resources, ecosystem, and infrastructure (Kirwan and Gedan, 2019; Knott et al., 2018; Nicholls et al., 2011).

Climate change effect is certain, but adverse impacts or exposure on the water sector are uncertain. The energy sector is estimated to take 10% of the world's freshwater (IEA, 2016). The dependence of industry and energy sectors on global freshwater is predicted to grow to 24% by the end of 2050, specifically in Europe and Asia (UN, 2020). The global freshwater withdrawal for energy sectors is projected to grow more than 2% by 2040, with a 60% increment in consumption (IEA, 2016). The global plan to accelerate the agenda towards switching from fossil fuel consumption to renewable energy is critical to climate change mitigation. The global installed renewable power generation capacity is dominated by 70% hydropower resources (Trace, 2019). While hydropower is considered a sustainable, clean, and low-carbon source of renewable energy, climate change variability threatens the future of hydropower. Extreme climate change events including high recorded temperature and drought could have exacerbated the already threatened arid and semi-arid areas in Africa (IPCC, 2007). For instance, the impact of climate change is estimated to decline hydropower generating capacity from the Zambezi river basin over the next 60 years (Yamba et al., 2011). Similarly, the increase in temperature is reducing the Nile river basin, which is projected to negatively affect the Aswan dam (Beyene et al., 2010). Besides the impact of climate change variability, the expansion of hydropower reservoirs has a potential threat to the indigenous settlement, loss of habitat and fragmentation, and transboundary conflicts (Ferreira et al., 2014; Zarfl et al., 2015).

Existing studies showed the impact of extreme climate change on energy demand (Bradshaw, 2010; Sailor, 2001). For instance, extreme temperature affects the daily peak of energy demand in Eastern European countries, due to the intensive use of air condition during the summer season, and this trend is expected to continue (EEA, 2004). For climate change vulnerability adaptive strategy of an engineering-based solution, existing

literature suggests an expansion of hydropower dams, management of wetland ecosystems and floodplains with improved coordinated policies and legislations (Watts et al., 2011). Other effective adaptation strategies in reducing the vulnerability of hydropower include increasing power plant efficiency, cohesive management of dams, and renewable energy diversification such as wind, solar, and bioenergy (Guerra et al., 2019; Owusu and Asumadu, 2016). Climate change uncertainty could be considered in planning hydropower projects including location, dam type, integrated energy development, and water management policies (Cole et al., 2014).

Data. This study employs time-frequency data spanning 1995–2017 from the Emission Database for global atmospheric research (EDGAR, 2020), development indicators database of the World Bank (2020), and Notre Dame global adaptation index (ND-GAIN, 2018). The selection of data series for subsequent empirical assessment incorporates the concept and indicators of the sustainable development goals into the hypotheses. Our data include: greenhouse gas emissions per capita (ton CO₂eq/cap)—used as a proxy for climate change while accounting for population dynamics, GDP per capita (US\$)—used to examine the role of income level in climate change, climate change readiness (measured in scores)—consist of economic, social and governance investment for climate change mitigation and adaptation mechanisms, and climate change vulnerability (measured in scores)—comprising of ecosystem services, food sector, health sector, human habitat, infrastructure sector, and water sector (ND-GAIN, 2018). Economic readiness involves easiness of doing business—a form of climate financing, whereas governance readiness incorporates political stability, corruption control, regulatory quality, and rule of law. In contrast, social readiness includes social inequality, innovation, ICT, and education (World Bank, 2020). Based on the ND-GAIN pre-defined indicators (Fig. 1), the six categories of climate change vulnerability consist score generated aggregated inputs of two adaptive capacity indicators for each category (6 × 2), two sensitivity indicators for each category (6 × 2), and two exposure indicators for each category (6 × 2). Thus, each of the six categories of climate change vulnerability consists of 6 input indicators (6 × 6).

Model estimation. The empirical procedure presented herein follows a linear panel regression model with six target variables regressed on several individual regressors separately in multiple models. For brevity, the model specification can be expressed as (Clarke et al., 2020):

$$y_{i,t}^a = \beta_0^a + \beta_1^a x_{i,t} + \varepsilon_{i,t}^a \quad (1)$$

where $y_{i,t}^a$ denotes the multiple target variables $a = 1, \dots, 6$ namely ecosystem services, food sector, human habitat, health sector, infrastructure sector, and water sector across countries $i = 1, \dots, 192$, in annual period $t = 1995, \dots, 2017$; β_0^a represents the constant across multiple target variables, $x_{i,t}$ represents the regressors including economic readiness, governance readiness, social readiness, income level, and GHG emissions as control variable; β_1^a is the estimated parameter of regressors across the 6 target variables, and $\varepsilon_{i,t}^a$ denotes 6 stochastic white noise from a normal distribution with multivariate specification. To examine the long-term relationship between climate change vulnerabilities and readiness to combat climate change and its impacts, we test several multiple hypotheses.

The Romano–Wolf correction technique is employed to investigate the multiple hypotheses using the baseline model specification (Eq. 1)—following the instrumental-variable based single-equation via two-stage least squares estimator, expressed

as:

$$\text{Ecosystem services}_{i,t} = \beta_0 + \beta_1 Z_{i,t} + \lambda \text{GHG}_{i,t} + \varepsilon_{i,t} \quad (2)$$

$$\text{Food sector}_{i,t} = \beta_0 + \beta_1 Z_{i,t} + \lambda \text{GHG}_{i,t} + \varepsilon_{i,t} \quad (3)$$

$$\text{Human habitat}_{i,t} = \beta_0 + \beta_1 Z_{i,t} + \lambda \text{GHG}_{i,t} + \varepsilon_{i,t} \quad (4)$$

$$\text{Health sector}_{i,t} = \beta_0 + \beta_1 Z_{i,t} + \lambda \text{GHG}_{i,t} + \varepsilon_{i,t} \quad (5)$$

$$\text{Infrastructure sector}_{i,t} = \beta_0 + \beta_1 Z_{i,t} + \lambda \text{GHG}_{i,t} + \varepsilon_{i,t} \quad (6)$$

$$\text{Water sector}_{i,t} = \beta_0 + \beta_1 Z_{i,t} + \lambda \text{GHG}_{i,t} + \varepsilon_{i,t} \quad (7)$$

where Ecosystem services_{*i,t*} (Sector 1), Food sector_{*i,t*} (Sector 2), Human habitat_{*i,t*} (Sector 3), Health sector_{*i,t*} (Sector 4), Infrastructure sector_{*i,t*} (Sector 5), and Water sector_{*i,t*} (Sector 6) denote the outcome variables, *Z* represents the regressors, viz. economic readiness, governance readiness, and social readiness, respectively. Equations (2)–(7) are run simultaneously with income level as endogenous variable used as instruments alongside country-specific resampling clusters, GHG_{*i,t*} denotes greenhouse gas emissions—implemented as control variable.

$$\text{Ecosystem services}_{i,t} = \beta_0 + \beta_1 \text{Income level}_{i,t} + \lambda \text{GHG}_{i,t} + \varepsilon_{i,t} \quad (8)$$

$$\text{Food sector}_{i,t} = \beta_0 + \beta_1 \text{Income level}_{i,t} + \lambda \text{GHG}_{i,t} + \varepsilon_{i,t} \quad (9)$$

$$\text{Human habitat}_{i,t} = \beta_0 + \beta_1 \text{Income level}_{i,t} + \lambda \text{GHG}_{i,t} + \varepsilon_{i,t} \quad (10)$$

$$\text{Health sector}_{i,t} = \beta_0 + \beta_1 \text{Income level}_{i,t} + \lambda \text{GHG}_{i,t} + \varepsilon_{i,t} \quad (11)$$

$$\text{Infrastructure sector}_{i,t} = \beta_0 + \beta_1 \text{Income level}_{i,t} + \lambda \text{GHG}_{i,t} + \varepsilon_{i,t} \quad (12)$$

$$\text{Water sector}_{i,t} = \beta_0 + \beta_1 \text{Income level}_{i,t} + \lambda \text{GHG}_{i,t} + \varepsilon_{i,t} \quad (13)$$

where income level denotes the independent variable across country *i* and time *t*, whereas $\varepsilon_{i,t}$ is the white noise. Similarly, Eqs. (8)–(13) are run simultaneously with economic readiness, governance readiness, and social readiness as treatment variables used as instruments beside country-specific resampling clusters. The Romano–Wolf multiple-hypothesis testing procedure incorporates model specifications in Eqs. (2)–(13) as baseline models whereas λ is the estimated parameter for control variable GHG_{*i,t*} with country-specific resampling clusters based on bootstrapping technique for null distributions.

Model validation. The 24 estimated baseline models are validated graphically using the Romano–Wolf multiple-hypothesis correction expressed as (Clarke et al., 2020):

$$\max_{t,j}^{*,k} := \max\{t_{(j)}^{*,k}, \dots, t_{(A)}^{*,k}\} \text{ for } j = 1, \dots, A \text{ and } k = 1, \dots, K \quad (14)$$

where $\max_{t,j}^{*,k}$ is the max value of vector $\{t_{(j)}^{*,k}, \dots, t_{(A)}^{*,k}\}$. Here, we test six hypotheses H_a (i.e., $a = 1, \dots, A$) each for the specified Eqs. (2)–(7), and (8)–(13). Each of the six hypotheses has corresponding coefficient of interest ∂_a , an estimator of $\hat{\partial}_a$ with standard error $\hat{\sigma}_a$. The alternative hypothesis using the instrumental-variable-based single-equation via two-stage least-squares estimator is based on two-sided tests expressed as: $H_a^0 : \partial_a \neq 0$ assuming $\partial_a^0 = 0$, for $a = 1, \dots, A$. Studentization of the test statistic based on data (*D*) resampling using bootstrapping

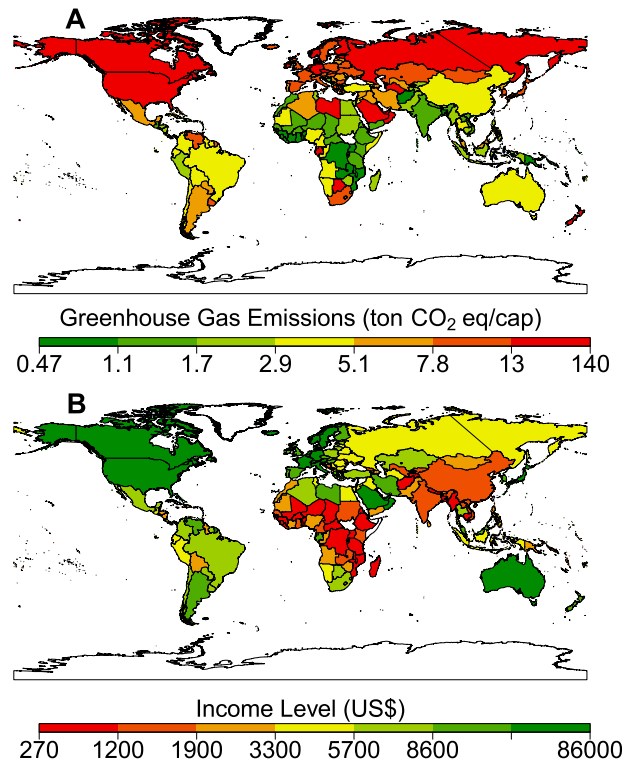


Fig. 2 Geographical distribution of (A) GHG Emissions (B) Income Level. From green to red in **A** denotes low to high GHG emissions, whereas from red to green in **B** denotes low to high-income level. The method of country-level data categorization was based on quantiles, used to capture continuous intervals with uniform distribution. **A**—mean: 7.95, min: 0.49, and max: 105.58 ($N = 192$); measured in ton CO₂eq/cap. **B**—mean: 14,423, min: 616, and max: 106,471 ($N = 183$); measured in US\$.

technique can be expressed as (Clarke et al., 2020):

$$c_a^{*,k} := \frac{\hat{\partial}_a^{*,k} - \hat{\partial}_a}{\hat{\sigma}_a^{*,k}} \quad (15)$$

where $c_a^{*,k}$ is the test statistics centered around zero assuming the resampled estimate $\hat{\partial}_a^{*,k}$ minus the baseline (original) estimate $\hat{\partial}_a$, k denotes each resample of the original data for each H_a , and $\hat{\sigma}_a^{*,k}$ represents the standard errors of resampled estimates. Thus, each null hypothesis is rejected if the multiple-testing adjusting probability value is <5% significance level.

Results

Geographical trends. The spillover effect of GHG emissions is undeniable, however, varies in concentrations across global economies as depicted in Fig. 2A (i.e., $N = 192$, mean = 7.95, median = 4.01, min = 0.49, and max = 105.58, measured based on average in ton CO₂eq/cap). The geographical distribution of GHG emissions presented in Fig. 2A accounts for country-specific population growth dynamics, identifying Palau (105.58 ton CO₂eq/cap) as the highest emitter of GHG emissions whereas DR Congo (0.49 ton CO₂eq/cap) is the lowest GHG emitter. It is noteworthy that while Palau is a high-income country in the East Asia & Pacific region, DR Congo is classified as low-income country in Sub-Saharan Africa. The other top 5 GHG emitters include Qatar (79.23 ton CO₂eq/cap), Falkland Islands (58.28 ton CO₂eq/cap), Curaçao (43.18 ton CO₂eq/cap), Kuwait (79.23 ton CO₂eq/cap), and Botswana (79.23 ton CO₂eq/cap). In contrast, other 5 low emitters aside DR Congo includes Burundi (0.49 ton CO₂eq/cap), Malawi (0.53 ton CO₂eq/cap),

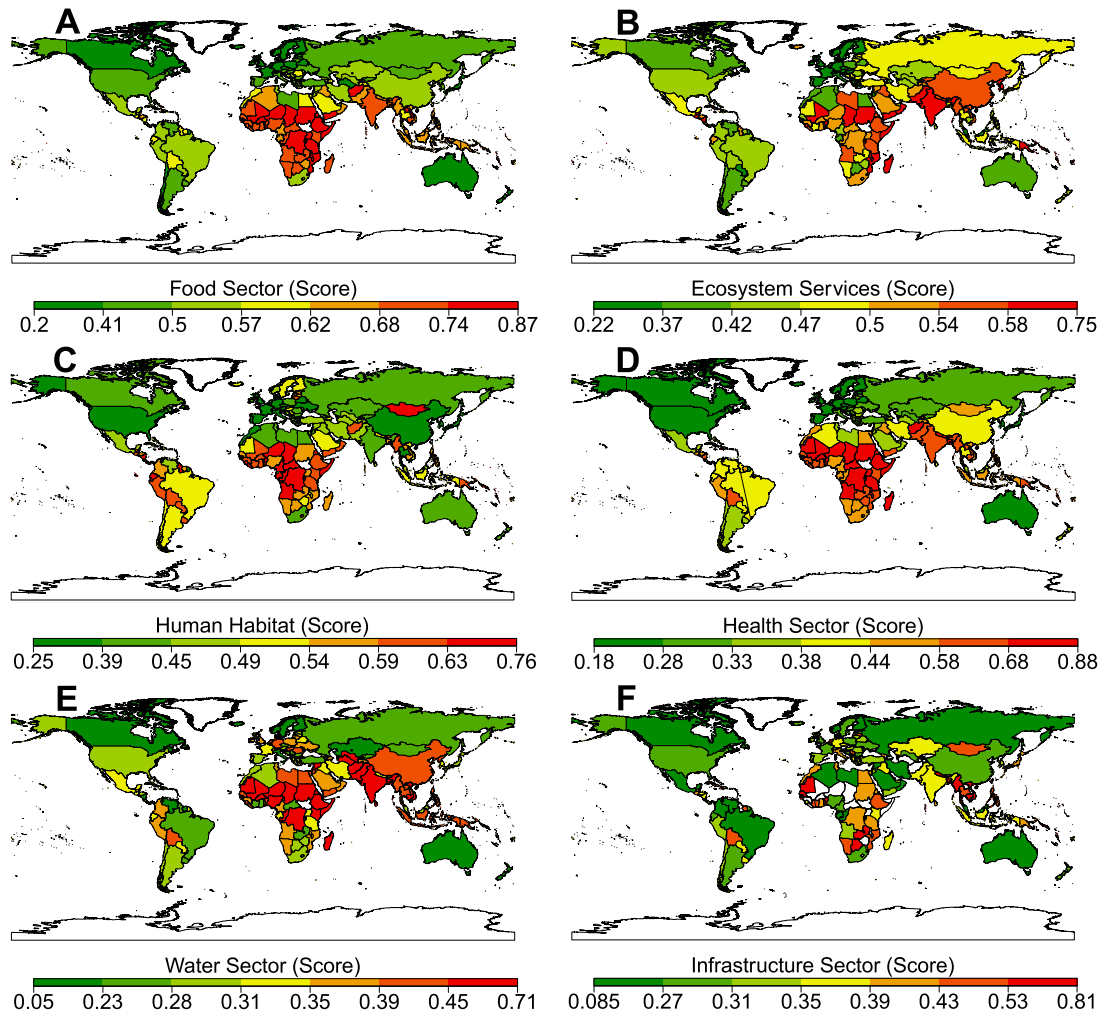


Fig. 3 Vulnerability of (A) Food Sector (B) Ecosystem Services (C) Human Habitat (D) Health Sector (E) Water Sector (F) Infrastructure Sector—to climate change and its impacts. From green to red denotes low to high vulnerability. The method of country-level data categorization was based on quantiles, used to capture continuous intervals with uniform distribution. A—mean: 0.57, min: 0.20, and max: 0.84 ($N = 188$); measured in scores, dimensionless. B—mean: 0.47, min: 0.22, and max: 0.74, ($N = 181$); measured in scores, dimensionless. C—mean: 0.50, min: 0.26, max: 0.75, ($N = 178$); measured in scores, dimensionless. D—mean: 0.46, min: 0.18, max: 0.84 ($N = 188$); measured in scores, dimensionless. E—mean: 0.33, min: 0.05, max: 0.69 ($N = 177$); measured in scores, dimensionless. F—mean: 0.37, min: 0.08, max: 0.79 ($N = 152$); measured in scores, dimensionless.

Rwanda (0.54 ton CO₂eq/cap), Faroes (0.57 ton CO₂eq/cap), and Solomon Islands (0.65 ton CO₂eq/cap). Aside from both GHG concentration limits (i.e., min: 0.49 ton CO₂eq/cap, and max: 105.58 ton CO₂eq/cap), the average global GHG emissions is pegged at 7.95 ton CO₂eq/cap—of which 60 economies exceed the average while 132 economies are below average. Thus, economies with considerably low GHG emissions are concentrated in Sub-Saharan Africa and Southern Asia whereas high emitting countries are found in North America, Europe, Central Asia, Middle East & North Africa, and Central Asia (see Fig. 2A).

The environmental Kuznets curve (eKc) hypothesis underscores the importance of income level in assessing emission concentrations across economies. The geographical disparities of income distribution are evident in Fig. 2B (i.e., $N = 183$, mean = 14,423, min = 616, and max = 106,471, measured based on average in US\$). The top 5 countries with high average income level comprise Qatar, Brunei Darussalam, Luxembourg, United Arab Emirates, and Kuwait. It is evident that majority of low-income economies are geographically located in Sub-Saharan Africa, Eastern Asia, and Southern Asia—however, DR Congo, Burundi, Central African Republic, Mozambique, and Niger are 5 hotspot countries with low-income distribution (Fig. 2B).

The climate change vulnerability presented herein indicates the tendency of economies to experience the negative impacts of climate risks. We examined the geographical risk distribution of sectoral climate vulnerabilities across economies presented in Fig. 3. As shown in Fig. 3, countries with high sectoral climate vulnerabilities are mostly located in Sub-Saharan Africa, Southern Asia, Eastern Asia, and South-East Asia. The top 5 countries with high food sector vulnerability (i.e., $N = 188$, mean = 0.57, min = 0.20, and max = 0.84, measured in scores—dimensionless) include Niger, Timor-Leste, Burkina Faso, Chad, and Eritrea—whereas Denmark, United Kingdom, Germany, Iceland, and Luxembourg represent 5 principal economies with low food sector climate vulnerability (Fig. 3A). Figure 3B (i.e., $N = 181$, mean = 0.47, min = 0.22, and max = 0.74, measured in scores—dimensionless) shows that while Spain, Germany, Hungary, Switzerland, and Denmark are 5 leading countries with low ecosystem service vulnerability, Kiribati, North Korea, Sudan, Tonga, and Solomon Islands are the top 5 countries with high ecosystem service vulnerability. In terms of human habitat climate vulnerability (i.e., $N = 178$, mean = 0.50, min = 0.26, and max = 0.75, measured in scores—dimensionless), Congo, Solomon Islands, Gabon, Timor-Leste, and Central African

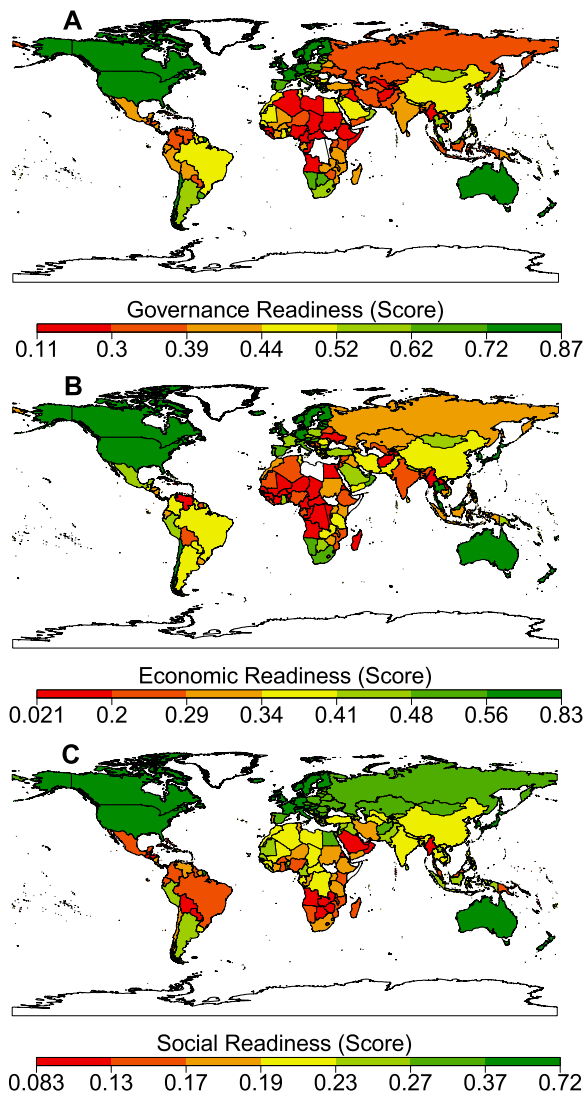


Fig. 4 Mitigation of climate change (A) Governance Readiness (B) Economic Readiness (C) Social Readiness. From red to green denotes low to high readiness. The method of country-level data categorization was based on quantiles, used to capture continuous intervals with uniform distribution. A—mean: 0.50, min: 0.08, and max: 0.88, ($N = 188$); measured in scores, dimensionless. B—mean: 0.39, min: 0.03, max: 0.81, ($N = 178$); measured in scores, dimensionless. C—mean: 0.31, min: 0.09, max: 0.74, ($N = 180$); measured in scores, dimensionless.

Republic are the top 5 countries with high-risk whereas Spain, Switzerland, Barbados, United Arab Emirates, and Germany are low-risk countries (Fig. 3C). The principal 5 countries with high health sector vulnerability (i.e., $N = 188$, mean = 0.46, min = 0.18, and max = 0.84, measured in scores—dimensionless) include Somalia, Ethiopia, Guinea-Bissau, Tanzania, and Chad whereas Monaco, Denmark, Netherlands, Iceland, and Switzerland are low-risk economies (Fig. 3D). Figure 3E (i.e., $N = 177$, mean = 0.33, min = 0.05, and max = 0.69, measured in scores—dimensionless) shows that while Niger, Sudan, Pakistan, Somalia, and Turkmenistan are high-risk countries with water vulnerability, Suriname, Dominica, Saint Vincent, and the Grenadines, Djibouti, and Bahamas are low-risk economies. The top 5 economies with high infrastructure sector vulnerability (i.e., $N = 152$, mean = 0.37, min = 0.08, max = 0.79, measured in scores—dimensionless) include Guinea-Bissau, Marshall Islands, Maldives, Zambia, and Micronesia—whereas Norway, Libya,

Algeria, Saudi Arabia, and Colombia are five major economies with low infrastructure sector climate vulnerability (Fig. 3F).

Climate change readiness underpins long-term climate change mitigation and impact reduction strategies across global economies. The geographical distribution of the three forms of readiness viz. governance (i.e., $N = 188$, mean = 0.50, min = 0.08, and max = 0.88, measured in scores—dimensionless), economic (i.e., $N = 178$, mean = 0.39, min = 0.03, max = 0.81, measured in scores—dimensionless) and social (i.e., $N = 180$, mean = 0.31, min = 0.09, max = 0.74, measured in scores—dimensionless) are presented in Fig. 4. The top 5 economies with high governance readiness comprise Finland, New Zealand, Denmark, Switzerland, and Sweden whereas Myanmar, Sudan, Iraq, Afghanistan, and Somalia are countries with very low governance readiness (Fig. 4A). Governance readiness entails stable investment and institutional environment that reassures investors of growth and sustained invested capital devoid of governance and institutional disruptions—hence, stimulates climate adaptation actions (Chen et al. 2015). Countries with low governance have similar characteristics of political instability, high perceived levels of public corruption, low regulatory quality, and lack of rule of law (TI, 2022). Poor governance, social unrest, and terrorism are found to have a negative impact on economic development and vice versa (McGowan, 2006). Evidence from Fig. 4B shows the top 5 countries with high economic readiness include Norway, Singapore, New Zealand, United States, and Iceland while 5 hotspot countries with low economic readiness comprise Myanmar, Chad, Central African Republic, Eritrea, and DR Congo. Economic readiness involves the investment environment that makes it easy to do business and facilitates private sector capital mobilization for climate adaptation strategies (Chen et al., 2015). Countries with high economic readiness have similar characteristics of good governance, high regulatory quality, political stability, and rule of law, hence, creating a conducive environment for investment and ease of doing business. The top 5 economies with high social readiness comprise South Korea, Finland, Denmark, Norway, and New Zealand, however, countries with low social readiness include Lesotho, Equatorial Guinea, Samoa, Eritrea, and Zimbabwe (Fig. 4C). Social readiness captures societal conditions that enable the effectiveness, equitable use, and profitability of investments that facilitate climate change adaptation (Chen et al., 2015). Hence, countries with low social readiness have either high social inequality, low literacy rates, or low innovation/ICT integration.

Empirical relationships. The nexus between sectoral climate vulnerabilities and climatic drivers are examined and reported in Table 1. Because GHG emissions, specifically CO_2 have transboundary effects, the empirical assessment presented herein accounted for spillover effects and heterogeneity across 192 countries and territories. We used novel panel estimation techniques capable of solving the complexities of emissions and cross-country time series data. Following standard econometric standards, we validated the estimated parameters using error metrics and multiple hypotheses testing via Romano–Wolf technique (see the “Methods” section). The resampled p -values and Romano–Wolf p -values in Fig. 5 confirm the null hypothesis of the estimated p -values of multiple models, hence, validating the instrumental-variable-based single-equation model via two-stage least squares. This implies the model specifications and estimated parameters are robust to make unbiased statistical inferences.

We observe differing effects of anthropogenic GHG emissions, income, and climate change readiness on health sector, food sector, human habitat, ecosystem services, infrastructure sector, and water sector (Table 1). The empirical results presented in

Table 1 Parameter estimates.

Parameters	Economics	Governance	Social	Income
Ecosystem	-0.5026*** [0.0152]	-0.5135*** [0.0140]	-0.5429*** [0.0151]	-0.0658*** [0.0017]
Food	-0.7834*** [0.0166]	-0.7885*** [0.0183]	-0.9902*** [0.0214]	-0.1180*** [0.0021]
Habitat	-0.5985*** [0.0169]	-0.5963*** [0.0182]	-0.6492*** [0.0180]	-0.0815*** [0.0002]
Health	-1.1857*** [0.0211]	-1.2079*** [0.0246]	-1.4752*** [0.0329]	-0.1510*** [0.0021]
Infrastructure	-0.3467*** [0.0195]	-0.3898*** [0.0213]	-0.4218*** [0.0226]	-0.0211*** [0.0027]
Water	-0.2801*** [0.0158]	-0.2798*** [0.0156]	-0.3073*** [0.0188]	-0.0338*** [0.0023]
GHG → Ecosystem	0.0013*** [0.0002]	0.0015*** [0.0002]	-0.0002 [0.0002]	0.0032*** [0.0002]
GHG → Food	-0.0004** [0.0002]	-0.0001 [0.0002]	-0.0012*** [0.0002]	0.0025*** [0.0002]
GHG → Habitat	0.0002 [0.0002]	0.0003 [0.0003]	-0.0019*** [0.0002]	0.0025*** [0.0025]
GHG → Health	0.0005*** [0.0002]	0.0012*** [0.0003]	-0.0008*** [0.0003]	0.0033*** [0.0002]
GHG → Infrastructure	0.0007*** [0.0002]	0.0010*** [0.0002]	0.0003* [0.0002]	0.0005** [0.0002]
GHG → Water	0.0008*** [0.0002]	0.0011*** [0.0002]	-0.0001 [0.0002]	0.0014*** [0.0003]
Constant → Ecosystem	0.6497*** [0.0055]	0.7070*** [0.0064]	0.6262*** [0.0044]	1.0206*** [0.0143]
Constant → Food	0.8749*** [0.0063]	0.9553*** [0.0087]	0.8688*** [0.0065]	1.5893*** [0.0180]
Constant → Habitat	0.7242*** [0.0060]	0.7839*** [0.0082]	0.7020*** [0.0053]	1.1966*** [0.0178]
Constant → Health	0.9130*** [0.0081]	1.0441*** [0.0118]	0.9058*** [0.0099]	1.7686*** [0.0178]
Constant → Infrastructure	0.5013*** [0.0079]	0.5579*** [0.0106]	0.4943*** [0.0072]	0.5511*** [0.0233]
Constant → Water	0.4286*** [0.0057]	0.4561*** [0.0071]	0.4231*** [0.0056]	0.6167*** [0.0195]
Obs (N) ¹	3676	3697	3676	3550
Obs (N) ²	3739	3760	3697	3571
Obs (N) ³	3634	3655	3655	3529
Obs (N) ⁴	3739	3760	3697	3571
Obs (N) ⁵	3088	3088	3109	3004
Obs (N) ⁶	3592	3613	3592	3466
p-value ¹	0.0000***	0.0000***	0.0000***	0.0000***
p-value ²	0.0000***	0.0000***	0.0000***	0.0000***
p-value ³	0.0000***	0.0000***	0.0000***	0.0000***
p-value ⁴	0.0000***	0.0000***	0.0000***	0.0000***
p-value ⁵	0.0000***	0.0000***	0.0000***	0.0000***
p-value ⁶	0.0000***	0.0000***	0.0000***	0.0000***
R-square ¹	-	0.1412	0.1154	0.3749
R-square ²	0.3228	0.2081	0.2755	0.4747
R-square ³	0.1603	0.0449	0.2212	0.4000
R-square ⁴	0.2980	0.0779	-	0.6741
R-square ⁵	-	-	-	0.0914
R-square ⁶	0.0680	0.0948	-	0.0922

***, **, * denote statistical significance at 1%, 5%, and 10%; 1, ..., 6 represent Sector 1, ..., Sector 6; [.] denotes the estimated standard errors, and → represents the causal effect relationship across 192 countries and territories.

Table 1 show improvements in economic, governance, and social readiness across countries decline sectoral climate vulnerability of ecosystem services by 0.28–1.48%. However, the mitigation effect of social readiness across sectors is relatively high compared to governance and economic readiness. Similarly, rise in income level mitigates sectoral climate vulnerability by 0.02–0.15%. The empirical assessment is confirmed by the linear relationship between income and climate change vulnerability presented in Fig. 6. In accounting for income convergence, vulnerability falloff as countries move up the ranks from low income → lower middle income → upper middle income to high income. For example, low-income countries, predominantly in Sub-Saharan Africa, comprising Niger, Sierra Leone, Eritrea, Madagascar, Burkina Faso, Ethiopia, Uganda, Chad, Rwanda, Guinea, and Mali have high climate vulnerability whereas developed economies namely Luxembourg, Denmark, Sweden, Finland, Norway, the US, Iceland, Austria, Singapore, Qatar, UAE, and New Zealand exhibit low climate vulnerability (Fig. 6). Thus, as income level increases across economies in long term, climate change vulnerability declines. In contrast, rising levels of anthropogenic GHG emissions intensify climate vulnerability across sectors. Among various sectors, the climate reduction effect of readiness and income is fairly high on health services compared to water services. Thus, the climate reduction effect is in the order health > food > habitat > ecosystem services > infrastructure >

water. This infers high income level, social, governance, and economic readiness minimizes climate change exposure and sensitivity but improves adaptive capacity across vulnerable sectors, predominantly in climate-prone regions. For example, long-term climate readiness and sustainable income improve the health sector by reducing climate-related deaths and diseases caused by warm periods and flood hazards. Sustainable economic readiness reduces dependency on foreign aids for health service delivery, especially in developing countries but strengthens domestic capacity to lessen climate-related sensitivity in the health sector. Thus, strengthening adaptive capacity of the health sector involves improving health and sanitation facilities, increasing the quantity and quality of medical staff, and healthcare access for slum and poor population.

Country-specific linking of climate drivers. As presented in Figs. 7–11, we graphically investigated country-specific effects of climate and its related drivers by accounting for either income or regional convergence. Figure 7 reveals the nexus between anthropogenic GHG emissions and income across income groups. We observe a positive monotonic relationship with lower emission levels for low-income countries, typically Sub-Saharan Africa, and high emission levels for high-income economies, predominantly North America, Europe, and Central Asia. While the eKc hypothesis highlights decline in environmental pollution

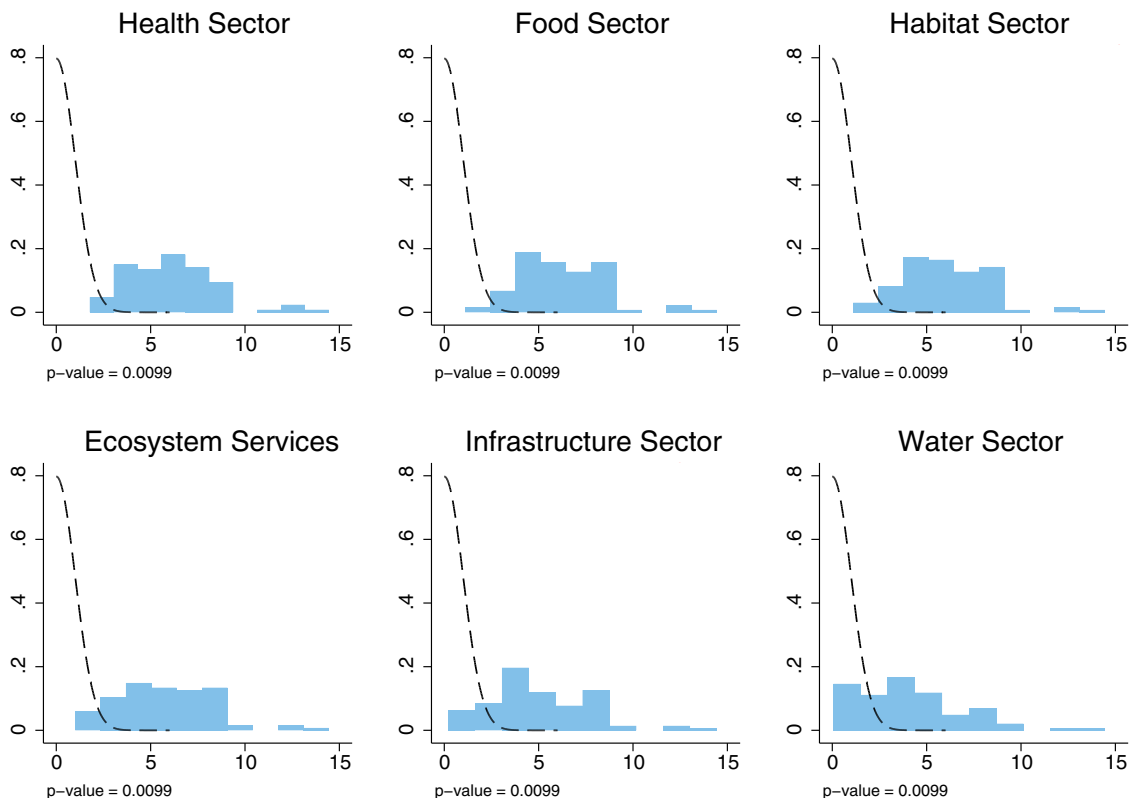


Fig. 5 Model validation of estimated parameters. Multiple-hypotheses testing of sectoral vulnerability vs. economic readiness using Romano-Wolf p -value.

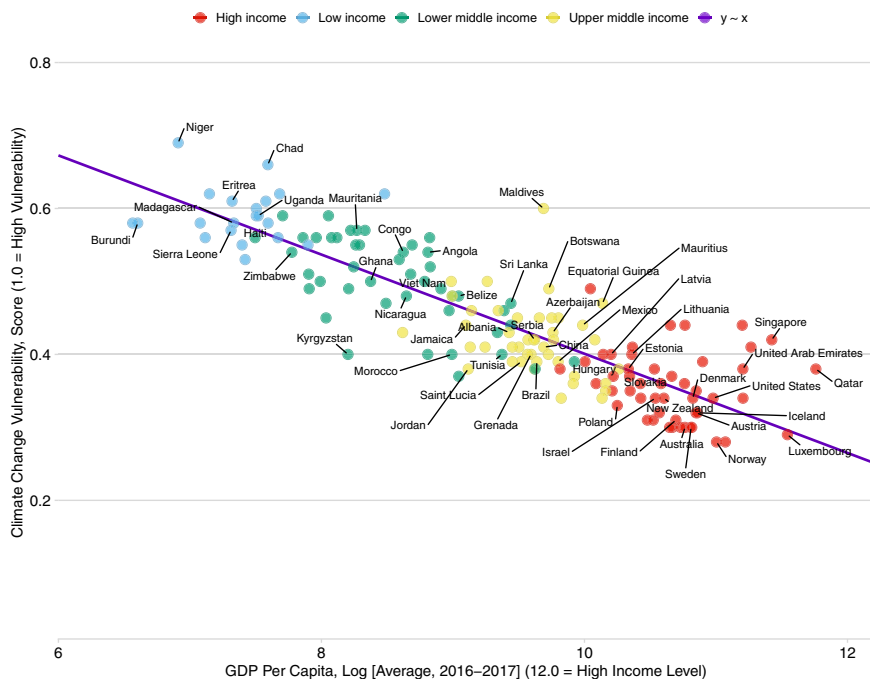


Fig. 6 Linear relationship between GDP per capita and climate change vulnerability. This plot captures income convergence (i.e., high income, low income, lower middle income, and upper middle income) of sampled economies based on average annual frequency.

due to stringent environmental regulations after achieving high-income status (Dasgupta et al., 2002), our empirical assessment contradicts the theory to some extent, even in the era of the SDGs. Using average data spanning 2016–2017 to examine GHG-

income relationship, it is evident that agrarian economies in Sub-Saharan Africa namely inter alia, Comoros, Rwanda, Burundi, Niger, and Benin emit less anthropogenic emissions whereas service sector countries like the US, Australia, Russia, Japan, and

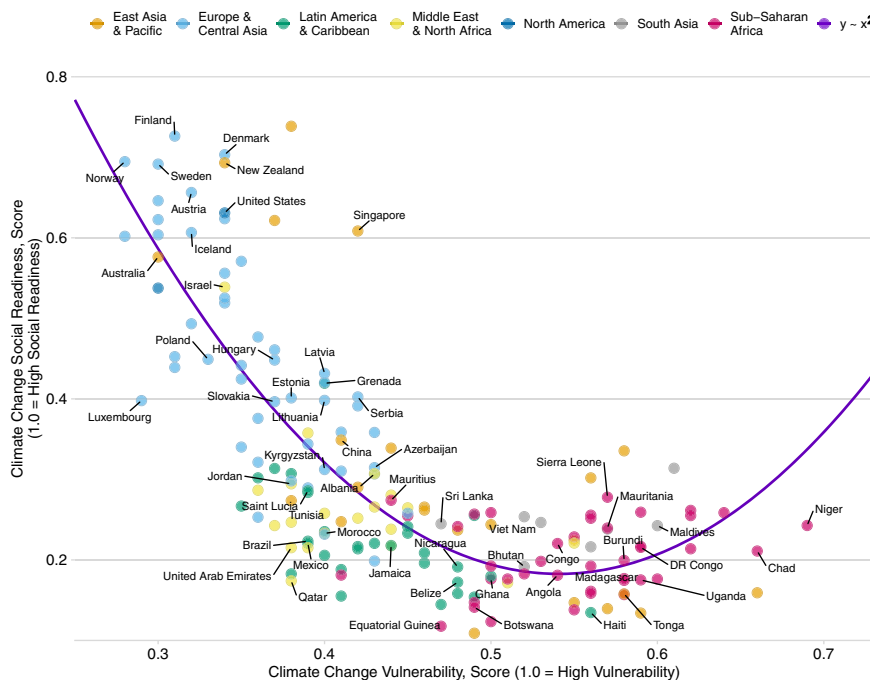


Fig. 9 Relationship between climate change social readiness and climate change vulnerability. This plot captures regional convergence (i.e., East Asia & Pacific, Europe & Central Asia, Latin America & Caribbean, Middle East & North Africa, North America, South Asia, and Sub-Saharan Africa) of sampled economies based on average annual frequency.

presented in Fig. 8. Similarly, the nexus between climate vulnerability and disaggregate climate readiness namely social, governance, and economic readiness are depicted in Figs. 9–11. We observe a negative relationship between climate change readiness and climate change vulnerability. Countries with high readiness, primarily high-income economies including Norway, Finland, Switzerland, Iceland, Australia, Austria, and the US have low vulnerability. While this hypothesis is largely true, recent occurrences show high-income does not protect against extreme weather events such as hurricanes, storms, wildfires, and droughts (Geiger et al., 2016). In contrast, low-income countries from Sub-Saharan Africa namely Niger, Somalia, Chad, Guinea-Bissau, Mali, Sudan, Liberia, Eritrea, Burkina Faso, Benin, Uganda, Ethiopia, DR Congo, Burundi, and Central African Republic with low climate readiness exhibit high climate change vulnerability (Fig. 8). Besides, economies in East Asia & Pacific, North America, and Europe & Central Asia with high social, governance, and economic readiness have low climate change vulnerability compared to developing economies (Figs. 9–11). In contrast, the high climate vulnerability across sectors in developing countries can be attributed to low social readiness (Fig. 9), poor governance readiness (Fig. 10), reduced income level, and low economic readiness (Fig. 11). Second, developing countries typically have high climate exposure and sensitivity but often fail to take precautionary measures due to limited social, governance, and economic resources, hence, becoming highly vulnerable to climate change and its impacts. The income convergence depicted in Fig. 11 reveals the importance of income in reducing climate change vulnerability in climate-exposed and sensitive regions with high poverty rates. While high-income countries have the financial muscle to take economic precautions against future climatic events, low-income countries with low or no financial capabilities are often caught unaware of future climate consequences.

Discussion

Although the impact of climate change cannot be over-emphasized, significant evidence shows the magnitude of the response differs across the globe as a function of relative vulnerability due to disparities in terms of exposure, sensitivity, and adaptability (Foden and Young, 2016; Kovach et al., 2019; Sarkodie and Strezov, 2019). We find that high governance readiness coupled with high social and economic climate readiness decline climate change vulnerability in developed countries. This implies high governance readiness with reduced corruption, political instability, and violence while upholding rule of law and institutional quality enables effective investments into climate change adaptation options that have long-term effects on environmental sustainability (Hope Sr, 2020). Second, the ease of doing business trigger both domestic and foreign investments that could facilitate climate financing and assist sustainable development, especially in developing economies. Third, reduced social inequality, improved education, innovation, and modern ICT infrastructures promote high social readiness—that has the potential of accelerating the agenda towards achieving clean and sustainable environment.

The empirical results show increasing level of anthropogenic GHG emissions exacerbate the vulnerability of ecosystem services, typically in sub-Saharan Africa, Eastern and Southern Asia. Human-induced climate change is likely to exacerbate habitat loss, which is the greatest threat to biodiversity and ecosystems. Existing studies indicate climate effects on the Arctic marine environment increase temperature, ocean acidification, and changes in sea ice cover, thereby hampering the survival and existence of marine habitat (EPA, 2016; Weiskopf et al., 2020). The direct impact of habitat loss and fragmentation is predicted to continue and exacerbate the pressure on ecosystems and species in decades (Segan et al., 2016). Increasing occurrence and intensity of extreme events triggered by climate change variabilities may diminish the already threatened population by habitat loss and fragmentation (McKechnie and Wolf, 2010).

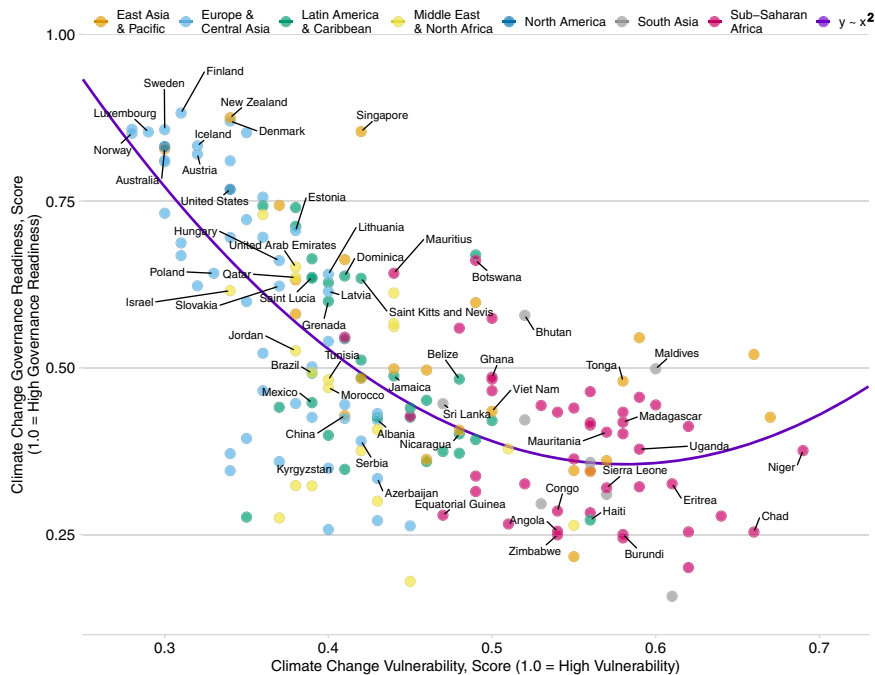


Fig. 10 Relationship between climate change governance readiness and climate change vulnerability. This plot captures regional convergence (i.e., East Asia & Pacific, Europe & Central Asia, Latin America & Caribbean, Middle East & North Africa, North America, South Asia, and Sub-Saharan Africa) of sampled economies based on average annual frequency.

The lingering effect of anthropogenic GHG emissions if not curtailed with sustained economic development, exacerbate the vulnerability of human habitat to climate change and its impacts. Yet, we observe the limiting effect of economic, governance, and social readiness on the vulnerability of human habitats to climate change. Likewise, upsurge in income level lessens the exposure and sensitivity of human habitat to climate change effects. The degree and occurrence of drought are estimated to increase due to future climate vulnerability, predominantly due to regional decline in precipitation and rising levels in evapotranspiration (IPCC, 2013).

Long-term food sector vulnerability declines with increasing level of economic, governance, and social readiness. The mitigation effect of economic readiness is reinforced by the impact of income growth on the exposure and sensitivity of the food sector to climate change vulnerability. However, the escalation of GHG emissions amidst weak income level strengthens the food sector’s vulnerability to climate change and its impacts. Climate change vulnerability will likely contribute to food price fluctuation due to its sensitivity that may stall access to the global market, especially among the poorest countries with low purchasing power (Schilling et al., 2012). High market price of food is usually associated with inadequate supply whereas persistent increase in food prices can force low-income people to reduce consumption levels required to meet the standard for healthy and good life—which may result in social uprising and food riot (FAO, 2008; Schmidhuber and Tubiello, 2007). The rise in global population in the past decades coupled with urban sprawl, dietary changes, and the rising effect of climate change has enormous pressure on food production (Sahay, 2000). The global population is estimated to increase by 2.5 billion in 2050 (i.e., 9.1 billion), thus, increasing food demand (Carvalho, 2006). Therefore, producing higher yields per unit of input such as land, plant, nutrient, and water—is essential to meet future food demands (FAO, 2008).

The continual increase in anthropogenic GHG emissions bolsters the vulnerability of health sector to climatic shocks.

Nevertheless, the effect of income outgrowth, economic, governance, and social readiness in reducing exposure and sensitivity of health sector dynamics is evident in its mitigation of climate change vulnerability across countries. Evidence from literature is becoming increasingly clear that climate change variabilities have severe impact on human health (WorldBank, 2018). Climate change variability such as heatwaves, floods, cold spells, and ultraviolet radiation directly affects human health, leading to morbidities including stroke, cancer, stress-related disorder, respiratory diseases, neurological diseases, and water-borne, food-borne, and vector-borne diseases (Cissé, 2019; Mateeva, 2020). Extreme climate change events including heat waves spur annual death toll than other extreme weather events combined (Luber and McGeheh, 2008). Studies show strong relationship between extreme temperature, ambient air pollution, and all-cause mortality rate (Owusu and Sarkodie, 2020; Scovronick et al., 2018; Wu et al., 2014).

The rising level in income and improvements in economic, governance, and social readiness hamper the vulnerability of infrastructure sector to climate change effects—by reducing exposure and sensitivity to climatic events. However, increasing level of GHG emissions strengthen infrastructure sector vulnerability to climate exposure and its consequences. With the many impacts of climate change, the rising sea level is considered more threatening to sustainable infrastructure, economic development, and longevity (Nicholls and Cazenave, 2010). Sea level rise may significantly contribute to estimated hundreds of million people displaced settlement globally—resulting from extreme climate change event over the next century (Nicholls et al., 2011). For instance, prior studies indicate climate change-induced overland flooding could threaten more than 600,000 people and infrastructure expansion of \$15 billion across urbanized coastal cities in California (Befus et al., 2020).

The persistent effect of GHG emissions spurs the vulnerability of water sector to climate change—by increasing climatic exposures and sensitivities. Conversely, increasing levels of income and advancement in economic, governance, and social readiness

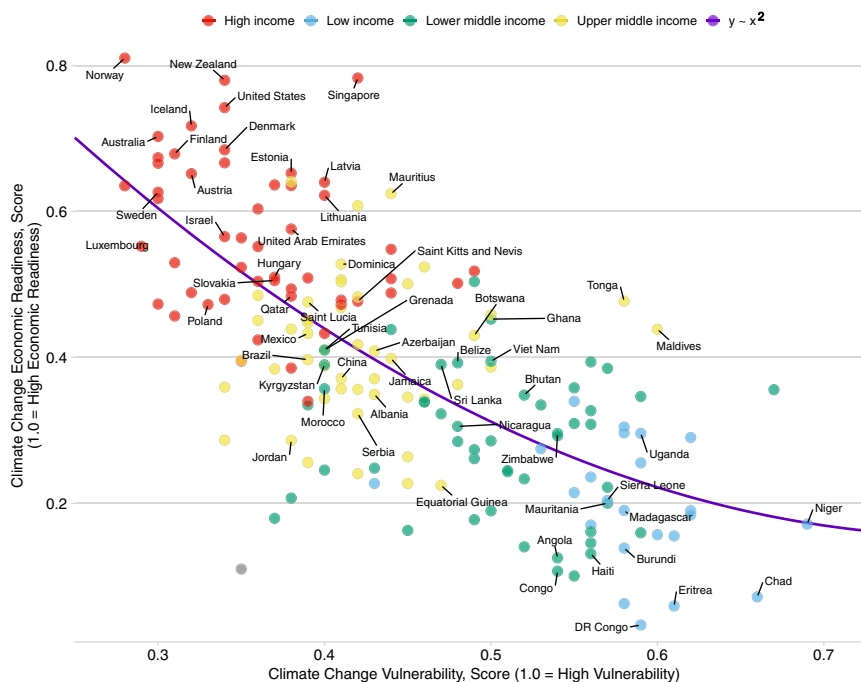


Fig. 11 Relationship between climate change economic readiness and climate change vulnerability. This plot captures income convergence (i.e., high income, low income, lower middle income, and upper middle income) of sampled economies based on average annual frequency.

decline water sector vulnerability to climate change effects. Currently, 2.2 billion people around the globe do not have access to clean drinking water (UN, 2020). Hence, climate change effects could hinder the achievement of sustainable development goal 7 of ensuring access to safe drinking water for all by 2030 (UN, 2020). Besides, several studies have established a relationship between the future decline in groundwater recharge and decline in surface runoff over the past decades (Benabdallah et al., 2018; Schilling et al., 2020). About 8% of the global population is reported to experience severe decline in water resources resulting from ~20% reduction in annual runoff—with 1% increase in global mean temperature (Schewe et al., 2014). Climate change effects alter rainfall patterns, hence, affect water availability for food and livestock production. However, water harvesting adaptation policies undertaken in vulnerable regions can improve and sustain agricultural production across seasons (Bunclark et al., 2018).

Because the effect of climate change is not country-specific but transboundary, climate change adaptation could be undertaken on cross-border cooperation to enhance collaboration across countries. The adaptation to climate change vulnerability requires strong cooperation at regional and international levels to facilitate the exchange of research findings, vulnerability risk assessment, adaptation options, and transboundary pest and disease control and prevention (FAO, 2015). Besides, investment in climate-smart agriculture, provision of timely weather warning forecasts, and appropriate adaptation measures can limit long-term climatic effects at the farm level (Kogo et al., 2021). Adaptation measures involve improving policy and governance, moderating demand, reducing food waste, and increasing food production where needed (Godfray et al., 2010). This implies adaptation technologies improve the food system to be resistant to climate change, and improve crop yield to feed the growing world population (Mbow et al., 2014). Thus, drastic measures are required at both local and national levels through climate change adaptation policies that strengthen the global agriculture sector and food production to meet the growing population.

Conclusion

Motivated by the 2030 agenda, this study modeled the mitigation effect of adaptation readiness on climate change from economic, social, and governance perspectives. Besides, we assessed the spatial-temporal severity of climate vulnerability across sectors in 192 global economies. Second, we examined the geographical readiness (i.e., social, governance, and economic) to combat climate change and its impacts. Third, we investigated the long-term impact of climate change readiness and income expansion on sectoral-climate vulnerabilities.

The empirical procedure presented herein denotes first-best solution to mitigate climate change vulnerabilities across sectors including ecosystem services, food, health, human habitat, infrastructure, and water. We examined global common shocks and spillover effects using the cross-section dependence test and further assessed heterogeneity, for which heterogeneous effects across 192 countries were accounted for using the novel Romano–Wolf estimation technique. Besides, both non-cooperative business-as-usual scenarios and dynamic games were indirectly accounted for—by assuming countries emit too much periodically. Climate change readiness denotes investments in abatement technologies, and among other sustainable options—to limit climate change vulnerability. In contrast, the business-as-usual scenario examines the historical effects of anthropogenic GHG emissions on different sectors presented herein. The study found the stocks of periodic GHG emissions spur sectoral climate change vulnerability across countries—with much impact on developing countries. Outgrowth in income level and investment (i.e., economic, social, and governance adaptation readiness) decline investment cost by reducing long-term environmental damage. This implies income level and adaptation readiness play essential role in mitigating climate change and its impacts. As a limitation, our study fails to account for discount factors and punishment essential to examine the sustainable first-best solution to climate change effects. This infers future studies could consider these limitations and investigate how countries could achieve environmental sustainability through stringent or rewarding climate reduction measures.

From a policy perspective, this study provides primary inputs for policymakers and government in decision making towards a broader iterative cycle including planning, managing, designing, implementing, and monitoring resilient climate change vulnerability-based development actions. Empirical evidence from this study could be used to determine the strength and weaknesses of vulnerability reduction and prioritize limited natural resources in addressing and managing adaptive actions of extreme climate change vulnerabilities. Interested third parties may use our results to monitor and assess country-specific vulnerability exposure, sensitivity, and adaptation.

Data availability

All data analyzed are publicly available (see the “Methods” section).

Received: 10 November 2021; Accepted: 10 March 2022;

Published online: 05 April 2022

References

- Befus K, Barnard PL, Hoover DJ, Hart JF, Voss CI (2020) Increasing threat of coastal groundwater hazards from sea-level rise in California. *Nat Clim Change* 10(10):946–952
- Benabdallah S, Mairech H, Hummel FM (2018) Assessing the impacts of climate change on groundwater recharge for the Chiba Basin in Tunisia. In: Calvache, M., Duque, C., Pulido-Velazquez, D. (eds) *Groundwater and global change in the western Mediterranean area*. Environmental Earth Sciences. Springer, Cham. pp. 27–33. https://doi.org/10.1007/978-3-319-69356-9_4
- Bergsma E, Gupta J, Jong P (2012) Does individual responsibility increase the adaptive capacity of society? The case of local water management in the Netherlands. *Resour Conserv Recycl* 64:13–22
- Beyene T, Lettenmaier DP, Kabat P (2010) Hydrologic impacts of climate change on the Nile River Basin: implications of the 2007 IPCC scenarios. *Clim Change* 100(3):433–461
- Bradshaw MJ (2010) Global energy dilemmas: a geographical perspective. *Geogr J* 176(4):275–290
- Bunclark L, Gowing J, Oughton E, Ouattara K, Ouoba S, Benao D (2018) Understanding farmers’ decisions on adaptation to climate change: exploring adoption of water harvesting technologies in Burkina Faso. *Global Environ Change* 48:243–254
- Burgiel S, Hall T, Adams N, Anderson K, Bella E, Bierwagen B, Boroja M, Brusati E, Burgett J, Carlisle L (2014) Bioinvasions in a changing world: a resource on invasive species-climate change interactions for conservation and natural resource management. The Aquatic Nuisance Species Task Force (ANSTF) and The National Invasive Species Council (NISC).
- Campbell S, Remenyi TA, White CJ, Johnston FH (2018) Heatwave and health impact research: a global review. *Health Place* 53:210–218
- Cartier KMS (2021) Climate change uproots global agriculture. *Biogeosciences*. <https://eos.org/features/climate-change-uproots-global-agriculture>
- Carvalho FP (2006) Agriculture, pesticides, food security and food safety. *Environ Sci Policy* 9(7–8):685–692
- Chen C, Noble I, Hellmann J, Coffee J, Murillo M, Chawla N (2015) University of Notre Dame global adaptation index country index technical report. ND-GAIN, South Bend, IN, USA
- Cissé G (2019) Food-borne and water-borne diseases under climate change in low- and middle-income countries: further efforts needed for reducing environmental health exposure risks. *Acta Trop* 194:181–188
- Clarke D, Romano JP, Wolf M (2020) The Romano-Wolf multiple-hypothesis correction in Stata. *Stata J* 20(4):812–843
- Cole MA, Elliott RJ, Strobl E (2014) Climate change, hydro-dependency, and the African dam boom. *World Dev* 60:84–98
- Connell-Buck CR, Medellín-Azuara J, Lund JR, Madani K (2011) Adapting California’s water system to warm vs. dry climates. *Clim Change* 109(1):133–149
- D’Odorico P, Carr JA, Laio F, Ridolfi L, Vandoni S (2014) Feeding humanity through global food trade. *Earth’s Futur* 2(9):458–469
- Dasgupta S, Laplante B, Wang H, Wheeler D (2002) Confronting the environmental Kuznets curve. *J Econ Perspect* 16(1):147–168. <https://doi.org/10.1257/0895330027157>. Win
- Denton F, Wilbanks TJ, Abeyinghe AC, Burton I, Gao Q, Lemos MC, Masui T, O’Brien KL, Warner K (2014) Climate-resilient pathways: adaptation, mitigation, and sustainable development. In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL (eds) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. Cambridge University Press, pp. 1101–1131.
- Droogers P, Immerzeel W, Terink W, Hoogeveen J, Bierkens M, Van Beek L, Debele B (2012) Water resources trends in Middle East and North Africa towards 2050. *Hydrol Earth Syst Sci* 16(9):3101–3114
- EDGAR (2020) Emission database for global atmospheric research. Retrieved 23 Feb 2020 from <https://edgar.jrc.ec.europa.eu/>
- EEA (2004). EU emissions trading—an open scheme promoting global innovation to combat climate change. European Environmental Agency.
- EEA (2005) Vulnerability and adaptation to climate change in Europe. European Environmental Agency Technical report, Issue. E. E. Agency. file:///Users/a.myakubu/Downloads/EEA_Technical_report_7_2005.pdf
- EPA (2016) Climate change indicators in the United States. USEP Agency. https://www.epa.gov/sites/production/files/2016-08/documents/climate_indicators_2016.pdf
- EPA (2016a) Climate change Indicators: Sea Level. United States Environmental Protection Agency. <https://www.epa.gov/climate-indicators/climate-change-indicators-sea-level>
- FAO (2008) Climate change and food security: a framework document. F. a. A. O. o. t. U. Nations. <http://www.fao.org/3/au035e/au035e.pdf>
- FAO (2011) The state of food and agriculture. Women in agriculture: closing the gender gap for development. Food and Agriculture Organization of the United Nations. F. A. A. O. O. T. U. NATIONS. <http://www.fao.org/3/i2050e/i2050e.pdf>
- FAO (2015) Climate change and food security: risks and response. F. a. A. O. o. t. U. Nation. <http://www.fao.org/3/i5188e/i5188e.pdf>
- Ferreira J, Aragão L, Barlow J, Barreto P, Berenguer E, Bustamante M, Gardner T, Lees A, Lima A, Louzada J (2014) Brazil’s environmental leadership at risk. *Science* 346(6210):706–707
- Foden WB, Young BE (2016) IUCN SSC guidelines for assessing species’ vulnerability to climate change. IUCN Cambridge, England and Gland, Switzerland
- Füssel H-M, Klein RJ (2006) Climate change vulnerability assessments: an evolution of conceptual thinking. *Clim change* 75(3):301–329
- Geiger T, Frieler K, Levermann A (2016) High-income does not protect against hurricane losses. *Environ Res Lett* 11(8):084012
- Gersonius B, Ashley R, Pathirana A, Zevenbergen C (2013) Climate change uncertainty: building flexibility into water and flood risk infrastructure. *Clim Change* 116(2):411–423
- GFN (2017) Global Footprint Network (GFN): national footprint accounts, ecological footprint. Retrieved 21 June 2017 from <http://data.footprintnetwork.org>
- Gitz V, Meybeck A, Lipper L, Young CD, Braatz S (2016) Climate change and food security: risks and responses. Food and Agriculture Organization of the United Nations (FAO) Report, p. 110.
- Glick P, Stein BA, Edelson NA (2011) Scanning the conservation horizon: a guide to climate change vulnerability assessment. National Wildlife Federation, Washington, DC, p. 168
- Godfray HJG, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, ... & Toulmin C (2010) Foodsecurity: the challenge of feeding 9 billion people. *science*, 327(5967), 812–818
- Gosling SN, Arnell NW (2016) A global assessment of the impact of climate change on water scarcity. *Climat Change* 134(3):371–385
- Guerra OJ, Tejada DA, Reklaitis GV (2019) Climate change impacts and adaptation strategies for a hydro-dominated power system via stochastic optimization. *Appl Energy* 233:584–598
- Halofsky JE, Peterson DL, Harvey BJ (2020) Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecol* 16(1):4
- Hayashi A, Akimoto K, Sano F, Mori S, Tomoda T (2010) Evaluation of global warming impacts for different levels of stabilization as a step toward determination of the long-term stabilization target. *Clim change* 98(1):87–112
- Hoffmann M, Hilton-Taylor C, Angulo A, Böhm M, Brooks TM, Butchart SH, Carpenter KE, Chanson J, Collen B, Cox NA (2010) The impact of conservation on the status of the world’s vertebrates. *Science* 330(6010):1503–1509
- Holsman KK, Hazen EL, Haynie A, Gourguet S, Hollowed A, Bograd SJ, Samhoury JF, Aydin K (2019) Towards climate resiliency in fisheries management. *ICES J Mar Sci* 76(5):1368–1378
- Hope KR, Sr (2020) Peace, justice and inclusive institutions: overcoming challenges to the implementation of Sustainable Development Goal 16 *Glob Change Peace Secur* 32(1):57–77. <https://doi.org/10.1080/14781158.2019.1667320>
- IEA (2016) World energy outlook. International Energy Agency.

- Iizumi T, Shin Y, Kim W, Kim M, Choi J (2018) Global crop yield forecasting using seasonal climate information from a multi-model ensemble. *Clim Serv* 11:13–23
- IPCC (2007) Climate change 2007: impacts, adaptation and vulnerability. Working Group II contribution to the fourth assessment report of the Intergovernmental Panel on Climate Change https://www.ipcc.ch/site/assets/uploads/2018/03/ar4_wg2_full_report.pdf
- IPCC (2013) Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. <https://www.ipcc.ch/report/ar5/wg1/>
- IPCC (2018) Global Warming of 1.5 °C an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Intergovernmental Panel on Climate Change. <https://www.ipcc.ch/sr15/download/>
- IPCC (2021) Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
- IWMI (2007) Water for food water for life: a comprehensive assessment of water management in agriculture. I. W. M. Institute.
- Kerr RA (1990) Global warming continues in 1989. *Science* 247(4942):521–521
- Kirwan ML, Gedan KB (2019) Sea-level driven land conversion and the formation of ghost forests. *Nat Clim Change* 9(6):450–457
- Knott JF, Daniel JS, Jacobs JM, Kirshen P (2018) Adaptation planning to mitigate coastal-road pavement damage from groundwater rise caused by sea-level rise. *Transp Res Rec* 2672(2):11–22
- Kogo BK, Kumar L, Koech R (2021). Climate change and variability in Kenya: a review of impacts on agriculture and food security. *Environment, Development and Sustainability*. 23(1):23–43
- Kovach RP, Dunham JB, Al-Chokhachy R, Snyder CD, Letcher BH, Young JA, Beever EA, Pederson GT, Lynch AJ, Hitt NP (2019) An integrated framework for ecological drought across riverscapes of North America. *BioScience* 69(6):418–431
- Kundzewicz ZW, Doell P (2009) Will groundwater ease freshwater stress under climate change? *Hydrol Sci J* 54(4):665–675
- Latta G, Temesgen H, Adams D, Barrett T (2010) Analysis of potential impacts of climate change on forests of the United States Pacific Northwest. *Forest Ecol Manag* 259(4):720–729
- Lindsey R (2021) Climate change: global sea level. *Climate Science and Information for a climate-smart nation*. <https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level>
- Lionello P, Scarascia L (2018) The relation between climate change in the Mediterranean region and global warming. *Reg Environ Change* 18(5):1481–1493
- Lu X, Zhang S, Xu J (2010) Climate change and sediment flux from the roof of the world. *Earth Surf Process Landf* 35(6):732–735
- Luber G, McGehehin M (2008) Climate change and extreme heat events. *Am J Prev Med* 35(5):429–435
- Mateeva Z (2020) Climate change: human health-related risks and vulnerability—some global and local (Bulgarian) pictures. In: *Smart geography. Key Challenges in Geography*. Springer, Cham. pp. 75–89. https://doi.org/10.1007/978-3-030-28191-5_7
- Mavromatis T (2015) Crop–climate relationships of cereals in Greece and the impacts of recent climate trends. *Theor Appl Climatol* 120(3):417–432
- Mbow C, Smith P, Skole D, Duguma L, Bustamante M (2014) Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. *Curr Opin Environ Sustain* 6:8–14
- McCarthy JJ, Canziani OF, Leary NA, Dokken DJ, White KS (Eds.), *Climate change (2001): Impacts, adaptation, and vulnerability*. Contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change, vol 2. Cambridge University Press.
- McGehehin MA, Mirabelli M (2001) The potential impacts of climate variability and change on temperature-related morbidity and mortality in the United States. *Environ Health Perspect* 109(Suppl 2):185–189
- McGowan PJ (2006) Coups and conflict in West Africa, 1955–2004: Part II, empirical findings. *Armed Forces Soc* 32(2):234–253
- McKechnie AE, Wolf BO (2010) Climate change increases the likelihood of catastrophic avian mortality events during extreme heat waves. *Biol Lett* 6(2):253–256
- McMichael AJ, Friel S, Nyong A, Corvalan C (2008) Global environmental change and health: impacts, inequalities, and the health sector. *BMJ* 336(7637):191–194
- Menz T, Kühling J (2011) Population aging and environmental quality in OECD countries: evidence from sulfur dioxide emissions data *Popul Environ* 33(1):55–79. <https://doi.org/10.1007/s11111-011-0132-6>
- Murray S (2006) Poverty and health. *CMAJ* 174(7):923–923
- ND-GAIN (2018) ND-GAIN Data. Retrieved 16 Jul 2018 from <https://gain.nd.edu/our-work/country-index/download-data/>
- Nellemann C, MacDevette M (2009) The environmental food crisis: the environment's role in averting future food crises: a UNEP rapid response assessment. *UNEP/Earthprint*
- Nicholls RJ, Cazenave A (2010) Sea-level rise and its impact on coastal zones. *Science* 328(5985):1517–1520
- Nicholls RJ, Marinova N, Lowe JA, Brown S, Vellinga P, De Gusmao D, Hinkel J, Tol RS (2011) Sea-level rise and its possible impacts given a 'beyond 4 C world' in the twenty-first century. *Philos Trans R Soc A* 369(1934):161–181
- Nunfam VF, Adusei-Asante K, Van Etten EJ, Oosthuizen J, Frimpong K (2018) Social impacts of occupational heat stress and adaptation strategies of workers: a narrative synthesis of the literature. *Sci Total Environ* 643:1542–1552
- Owusu P, Asumadu SS (2016) A review of renewable energy sources, sustainability issues and climate change mitigation. *Cogent Eng* 3(1):1167990. <https://doi.org/10.1080/23311916.2016.1167990>
- Owusu PA, Sarkodie SA (2020) Global estimation of mortality, disability-adjusted life years and welfare cost from exposure to ambient air pollution. *Sci Total Environ* 742:140636. <https://doi.org/10.1016/j.scitotenv.2020.140636>. 2020/11/10/
- Pasquini L, van Aardenne L, Godsmark CN, Lee J, Jack C (2020) Emerging climate change-related public health challenges in Africa: a case study of the heat-health vulnerability of informal settlement residents in Dar es Salaam, Tanzania. *Sci Total Environ* 747:141355
- PBLNEAA (2014) Towards a world of cities in 2050. PBL Netherlands Environment Assessment Agency. <https://www.pbl.nl/en/publications/towards-a-world-of-cities-in-2050-an-outlook-on-water-related-challenges>
- Sahay VS (2000) Feeding the world: a challenge for the twenty-first century. By Vaclav Smil. Cambridge, MA: The MIT Press (2000). Reviewed by Vijoy S. Sahay. *J Political Ecol* 7(1):52–54
- Sailor DJ (2001) Relating residential and commercial sector electricity loads to climate—evaluating state level sensitivities and vulnerabilities. *Energy* 26(7):645–657
- Sarkodie SA, Strezov V (2019) Economic, social and governance adaptation readiness for mitigation of climate change vulnerability: Evidence from 192 countries *Sci Total Environ* 656:150–164. <https://doi.org/10.1016/j.scitotenv.2018.11.349>
- Sarkodie SA, Owusu PA, Leirvik T (2020) Global effect of urban sprawl, industrialization, trade and economic development on carbon dioxide emissions *Environ Res Lett* 15(3):034049. <https://doi.org/10.1088/1748-9326/ab7640>
- Schewe J, Heinke J, Gerten D, Haddeland I, Arnell NW, Clark DB, Dankers R, Eisner S, Fekete BM, Colón-González FJ (2014) Multimodel assessment of water scarcity under climate change. *Proc Natl Acad Sci USA* 111(9):3245–3250
- Schilling J, Freier KP, Hertig E, Scheffran J (2012) Climate change, vulnerability and adaptation in North Africa with focus on Morocco. *Agric Ecosyst Environ* 156:12–26. <https://doi.org/10.1016/j.agee.2012.04.021>. 2012/08/01/
- Schilling J, Hertig E, Trambly Y, Scheffran J (2020) Climate change vulnerability, water resources and social implications in North Africa. *Reg Environ Change* 20(1):1–12
- Schmidhuber J, Tubiello FN (2007) Global food security under climate change. *Proc Natl Acad Sci USA* 104(50):19703. <https://doi.org/10.1073/pnas.0701976104>
- Schmitt JD, Peoples BK, Castello L, Orth DJ (2019) Feeding ecology of generalist consumers: a case study of invasive blue catfish *Ictalurus furcatus* in Chesapeake Bay, Virginia, USA. *Environ Biol Fishes* 102(3):443–465
- Schneider S, Sarukhan J, Adejuwon J, Azar C, Baethgen W, Hope C, Moss R, Leary N, Richels R, Van Ypersele J (2001) Overview of impacts, adaptation, and vulnerability to climate change. *Clim change* 75–103.
- Scovronick N, Sera F, Acquotta F, Garzena D, Fratianni S, Wright CY, Gasparrini A (2018) The association between ambient temperature and mortality in South Africa: a time-series analysis. *Environ Res* 161:229–235
- SEEFCCA (2012) Regional climate vulnerability assessment. http://awsassets.panda.org/downloads/regional_cva_synthesis_report.pdf
- Segan DB, Murray KA, Watson JE (2016) A global assessment of current and future biodiversity vulnerability to habitat loss—climate change interactions. *Global Ecol Conserv* 5:12–21
- Short MD, Peirson WL, Peters GM, Cox RJ (2012) Managing adaptation of urban water systems in a changing climate. *Water Resour Manag* 26(7):1953–1981
- Siebert S, Burke J, Faures JM, Frenken K, Hoogeveen J, Döll P, Portmann FT (2010) Groundwater use for irrigation—a global inventory. *Hydrol Earth Syst Sci* 14(10):1863–1880. <https://doi.org/10.5194/hess-14-1863-2010>
- Smit B, Wandel J (2006) Adaptation, adaptive capacity and vulnerability. *Global Environ Change* 16(3):282–292
- Spencer PD, Hollowed AB, Sigler MF, Hermann AJ, Nelson MW (2019) Trait-based climate vulnerability assessments in data-rich systems: an application to eastern Bering Sea fish and invertebrate stocks. *Global Change Biol* 25(11):3954–3971

- Stagge JH, Kohn I, Tallaksen LM, Stahl K (2015) Modeling drought impact occurrence based on meteorological drought indices in Europe. *J Hydrol* 530:37–50. <https://doi.org/10.1016/j.jhydrol.2015.09.039>. 2015/11/01/
- Stuart-Hill SI, Schulze RE (2010) Does South Africa's water law and policy allow for climate change adaptation? *Clim Dev* 2(2):128–144
- TI (2022) 2021 Corruptions Perceptions Index—explore the results. Retrieved 28 Jan 2022 from <https://www.transparency.org/en/cpi/2021>
- Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. *Proc Natl Acad Sci USA* 108(50):20260. <https://doi.org/10.1073/pnas.1116437108>
- Timperley J (2021) The broken \$100-billion promise of climate finance—and how to fix it. *Nature* 598:400–402. <https://doi.org/10.1038/d41586-021-02846-3>
- Trace S (2019) The impact of climate change on hydropower in Africa. *Oxford Policy Management*. <https://www.opml.co.uk/blog/the-impact-of-climate-change-on-hydropower-in-africa>
- UN (2020) UN World Water Development Report 2020: 'water and climate change'. United Nation. <https://www.unwater.org/publications/world-water-development-report-2020/>
- UNDESA (2019) World urbanization prospects: the 2018 revision. <https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf>
- United Nations (2015) Sustainable development goals. Retrieved 24 Oct 2015 from <https://sustainabledevelopment.un.org/?menu=1300>
- USAID (2014) Compendium of lessons learned from ARCC climate change vulnerability assessments. USAID. <https://www.climatelinks.org/resources/compendium-lessons-learned-arcc-climate-change-vulnerability-assessments-0>
- USGCRP (2018): Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller DR, Avery CW, Easterling DR, Kunkel KE, Lewis, KLM, Maycock TK, Stewart BC (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 1515. <https://doi.org/10.7930/NCA4.2018>
- Vörösmarty CJ, Green P, Salisbury J, Lammers RB (2000) Global water resources: vulnerability from climate change and population growth. *Science* 289(5477):284–288
- Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, Glidden S, Bunn SE, Sullivan CA, Liermann CR (2010) Global threats to human water security and river biodiversity. *Nature* 467(7315):555–561
- Watts RJ, Richter BD, Opperman JJ, Bowmer KH (2011) Dam reoperation in an era of climate change. *Mar Freshw Res* 62(3):321–327
- Weiskopf SR, Rubenstein MA, Crozier LG, Gaichas S, Griffis R, Halofsky JE, Hyde KJ, Morelli TL, Morissette JT, Muñoz RC (2020) Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. *Sci Total Environ* 733:137782
- West JM, Julius SH, Kareiva P, Enquist C, Lawler JJ, Petersen B, Johnson AE, Shaw MR (2009) US natural resources and climate change: concepts and approaches for management adaptation. *Environ Manag* 44(6):1001
- Wheeler TR, Craufurd PQ, Ellis RH, Porter JR, Prasad PV (2000) Temperature variability and the yield of annual crops. *Agric Ecosyst Environ* 82(1–3):159–167
- WHO (2018a) Guidelines on sanitation and health. <https://apps.who.int/iris/bitstream/handle/10665/274939/9789241514705-eng.pdf>
- WHO (2018b) *Health inequities and their causes*. World Health Organization: WHO. Retrieved 28 Jan 2022 from <https://www.who.int/news-room/facts-in-pictures/detail/health-inequities-and-their-causes>
- Wigley T, Barnett T (1990) Detection of the greenhouse effect in the observations. In: *Climate change: the IPCC scientific assessment*, Cambridge University Press, Cambridge, pp. 239–256.
- Williams AP, Abatzoglou JT, Gershunov A, Guzman-Morales J, Bishop DA, Balch JK, Lettenmaier DP (2019) Observed impacts of anthropogenic climate change on wildfire in California. *Earth's Future* 7(8):892–910
- World Bank (2020) World development indicators. Retrieved 24 Feb 2020 from <http://data.worldbank.org/country>
- WorldBank (2018) World Bank Group commits US\$200 billion over five years for climate action. World Bank Group. <https://sdg.iisd.org/news/world-bank-group-commits-us200-billion-over-five-years-for-climate-action/>
- Wu J, Zhou Y, Gao Y, Fu JS, Johnson BA, Huang C, Kim Y-M, Liu Y (2014) Estimation and uncertainty analysis of impacts of future heat waves on mortality in the eastern United States. *Environ Health Perspect* 122(1):10–16
- Yamba FD, Walimwipi H, Jain S, Zhou P, Cuamba B, Mzezewa C (2011) Climate change/variability implications on hydroelectricity generation in the Zambezi River Basin. *Mitig Adapt Strateg Global Change* 16(6):617–628
- Yeruham E, Shpigel M, Abelson A, Rilov G (2020) Ocean warming and tropical invaders erode the performance of a key herbivore. *Ecology* 101(2):e02925
- Zarfl C, Lumsdon AE, Berlekamp J, Tydecks L, Tockner K (2015) A global boom in hydropower dam construction. *Aquat Sci* 77(1):161–170

Acknowledgements

Open access funding provided by Nord University.

Author contributions

SAS designed the study, collected the data, performed the data analysis, coordinated and supervised the study. MYA and PAO drafted the manuscript. All authors reviewed the manuscript and approved it for submission.

Competing interests

The authors declare no competing interests.

Ethical approval

Not applicable.

Informed consent

This article does not contain any studies with human participants performed by any of the authors.

Additional information

Correspondence and requests for materials should be addressed to Samuel Asumadu Sarkodie.

Reprints and permission information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2022