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Sustainable urbanization and vulnerability to climate change in Africa: Accounting for digitalization and institutional quality

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Abstract

This study empirically examines the effect of sustainable urbanization on vulnerability to climate change over a sample of 52 African countries from 1996 to 2019. We use the two-stage system generalized method of moments (GMM) empirical strategy and mediation analysis to assess direct and indirect impacts, respectively. The results of the direct analysis reveal that sustainable urbanization reduces vulnerability to climate change. The results of the indirect analysis also show that sustainable urbanization significantly reduces vulnerability to climate change through the channels of digitalization and institutional quality. The results also highlight that considering the direct effect of sustainable urbanization alone underestimates the impact of reducing vulnerability to climate change. The results are robust to an alternative indicator of vulnerability to climate and other estimation techniques. These results have important policy implications and provide evidence for the improvement of sustainable urbanization in terms of access to basic services or reduction of vulnerability to climate change.

Keywords: Sustainable urbanization, Vulnerability to climate change, Digitalization, Institutional quality, Africa.

1. Introduction

Urbanization is the engine of global economic development in that when more people are concentrated in urban areas, resulting opportunities of communication and interaction induces the development of innovative ideas and technologies (Chan and Chan, 2022). Hence, it is not surprising that according to Di Clemente et al. (2021), more than 80% of global gross domestic product (GDP) is generated in urban locations. Moreover, in 2018, urban areas were host to about 55% of the world's population and with growth primarily concentrated in Asia and Africa, this figure is expected to reach 68% by 2050 according to the United Nations Department of Economic and Social Affairs Population Division (2018).

Only, urban areas face increasing climate change challenges (Chapman et al., 2017). As an illustration, 75% of all carbon dioxide from energy use is released by urban areas, and it is projected that by 2050, infrastructure building within the remit fast-growing cities could emit 226 gigatons of carbon dioxide in the developing world (Bai et al., 2018). This justifies the value of a sustainable urbanization[1] process; which requires the consideration of various environmental, social, economic, and governance factors (Mori & Yamashita, 2015; Yigitcanlar et al., 2015).

Although consensus is apparent on the perspective that urbanization is one of the major 21st century trends in developing countries, there remains a debate as to whether it will reduce or worsen climate vulnerability (Srinivasan et al., 2013). It is in this sense that Mitchell et al. (2015) state that urban development needs to be more resilient to climate change to achieve the post-millennium development goals (MDGs) agenda. This is more so because the United Nations' 11th and 13th Sustainable Development Goals (SDGs) which focus on cultivating sustainable urbanization and climate change resilience respectively, could be linked (Chen et al., 2022). This translates into a focus on creating safe, inclusive, resilient, and sustainable cities through the implementation of integrated plans and policies for resource efficiency and climate change adaptation (Reid, 2016). Achieving these goals is then crucial for Africa, which is the most vulnerable region to climate change (Watson et al., 1998; Nkomo et al., 2006; Collier et al., 2008).

It is to this end that Sarkodie and Strezov (2019) point out that Africa is the most exposed, vulnerable and sensitive area to climate change with an adaptive capacity that is lowest. However, in Africa urban areas are in the midst of construction or not yet built which

[1] Shen et al. (2012) define sustainable urbanization as a process of dynamic process nature enables urban sustainability to maintain or enhance a certain threshold of practice during urbanization.

this leaves a window of opportunity to choose pathways of economic development that are consistent with basic needs and internalize resilience to the growing climate change risks (Khosla & Bhardwaj, 2019). In the 21st century, rapid urban development and settlement is becoming commonplace (Chan & Chan, 2022). To this end, achieving sustainable and resilient urbanization is essential to protect the natural environment, society and human well-being (Kaur & Garg, 2019). Moreover, that the health and well-being of current and future generations is central to sustainable urban development and that the effects of climate change will lead to direct health consequences (Elmqvist et al., 2019; Tonne et al., 2021).

In this regard, although Africa is characterized by a rich and diverse environment, with persistence in environmental degradation, climate change is an increasingly troublesome issue. With the environment at the heart of its growth and transformation, however, there seems to be no apparent end to the cycle of environmental mismanagement and resulting poverty leading to unsustainable development (Omisore, 2018). It is in this vein that Nwankwo et al. (2021) emphasize the need to open a debate on the link between urbanization and climate change in order to deepen knowledge on vulnerability to climate change, particularly in Africa. This proven persistence of Africa's vulnerability to climate change arguably justifies the renewed interest in the economic and environmental literature about the association between urbanization and vulnerability to climate with a view to reducing this vulnerability (Garschagen & Romero-Lankao, 2015; Mabon & Shih, 2018; Raihan & Tuspekova, 2022). Moreover, Africa is the most rapidly urbanizing continent and its population is growing at an exponential rate. By 2050, it is projectd that the continent will be home to approximately 2.5 billion people, constituting about 55% of the population living in urban centers (Güneralp et al., 2017).

In this context, two major trends are emerging. The first, which we call the pessimistic approach, maintains that urbanization, by being associated with industrialization, deforestation, and pollution, promotes vulnerability to climate change (Nitivattananon & Srinonil, 2019; Srivastava, 2020; Vargas & Magaña, 2020; Arshad et al., 2020). It is in this sense that the study by Seto and Shepherd (2009) shows that urban areas promote vulnerability to climate by affecting precipitation patterns and changing land use patterns at the scale of thousands of square kilometers. The direct loss of plant biomass leads to imbalances in atmospheric carbon and nitrogen circulation cycles; thus leading to a series of global climate variations (Sokolov et al., 2008; Zaehle & Dalmonech, 2011). For their part, Adams and Klobodu (2017) examine the nexus between urbanization and environmental degradation in 38 African countries over the period 1970-2011 while accounting for the policy environment. Using cointegration and panel causality analyses, they establish that urbanization and environmental degradation are cointegrated. This will increase the vulnerability of populations to climate change. Similarly, Sanderson et al (2018) find that urbanization induces the destruction of natural habitats as well asbiodiversity reduction. Mignamissi and Djeufack (2022) examine the connection between urbanization and CO2 emission intensity in a panel of 48 African countries. Using an augmented STIRPAT model, they find that while urbanization is a highly significant driver of pollution in Africa, it also increases vulnerability to climate change.

Focusing on irrational urbanization, Li et al. (2017) also find that it accelerates the loss of black land which hinders resilience to climate change. In the same vein, Zerbo et al. (2020) find in analyzing sub-Saharan Africa that rapid urbanization leads to informal urban settlements that represent daily health risks with considerable cumulative impacts on the well-being and health of the vulnerable urban group. This is no less true for Wei et al. (2023) who analyze the direct and indirect effects of multidimensional urbanization on carbon emission within the countries of the Belt and Road Initiative (BRI) over the period from 2000 to 2018. Using a battery of spatial econometric approaches, they find a positive, significant, and widespread effect of urbanization on carbon emissions, which promotes vulnerability to climate change in this region.

Asongu el al. (2020), also focusing on the case of African countries, rely on the cointegration tests of Kao and Pedroni and the autoregressive distributional lag methodology of Pesaran (2006) for the long-term regression. To this end, they find a positive statistical relationship between urbanization and pollutant emissions, electricity consumption and non-renewable energy consumption. Despite this large body of work agreeing on the negative effect of urbanization on vulnerability to climate change, there are also some works that do not see this relationship in the same light insofar as they defend the idea of the participation of urbanization in reducing vulnerability to climate change.

The second, so-called optimistic, approach actually supports the fact that urbanization could help reduce vulnerability to climate change. This is the case of Henderson et al. (2017) who, in questioning whether climate change has driven urbanization in Africa, found by analyzing a panel of African neighborhoods that it provides an escape from negative agricultural moisture shocks by promoting urban migration. This will help mitigate the vulnerability of populations to climate change. Other studies by taking into account various aspects find that for urbanization to mitigate vulnerability to climate change, it must be sustainable (Castells-Quintana et al., 2018). It is then that Leichenko (2011) finds that efforts to foster resilience to climate change must be combined with efforts to promote sustainable urbanization. To do so, it must advocate for social and environmental aspects through consideration of access to basic sanitation, electricity, and basic drinking water services (Collier & Venables, 2017; Verma & Raghubanshi, 2018).

It is in this context that sustainable urbanization planning and practice has the potential to minimize climate change threats by protecting human health and mitigating social and health inequalities (Roy, 2009; Tonne et al., 2021). Also through urban greening, it plays a fundamental role in mitigating vulnerability to climate change by reducing urban temperature and promoting adaptation to climate change by urban residents (Bowler et al., 2010; Nassary et al., 2022). While climate change dampens the predictability of available water, boosts the likelihood of damage, disruption of water that is drinkable as well as the sanitation of drinking water infrastructure, urbanization creates wastewater centers that may become an important water resource for peri-urban farmers, access to water and sanitation services in urban areas would promote resilience to climate change (World Health Organization, 2009, 2016). The same is true for Satterthwaite et al. (2020) who find that water supply, sanitation, and access to electricity promote resilience to climate change.

This view is reinforced by the work of Sun et al. (2023) who find in analyzing the case of Chinese firms that the development of the electric power sector enhances firms' adaptability to climate change. The same is true for Alam et al. (2018) who in analyzing the determinants of climate change resilience in Bangladesh find that access to water reduces vulnerability to climate change by promoting household adaptation to climate change impacts. Kahn et al (2022), analyzing a global sample of 219 nations for the period 1990-2020, simultaneously use the generalized method of moments (GMM) approach and estimation via quantile regressions. They find that the higher the countries' electricity generation and renewable energy consumption, the better the countries' ability to mitigate environmental degradation by mitigating the amount of total carbon emissions over time.

Focusing on Africa, Ojo and Baiyegunhi (2020) analyze the drivers of credit constraints and corresponding effects on the adoption among rice farmers in southwest Nigeria of climate change adaptation strategies. They use an instrumental variable approach adopted to GMM in two stages and find that reduced soil and water conservation technique is one of the effective climate change adaptation strategies. The work of Grasham et al. (2019) supports this in that they find that the poor within urban environments have the same opportunities to cope with shocks as well as being deprived of water access services compared to wealthier households in sub-Saharan Africa. This greatly increases their vulnerability to climate change.

For their part, Zakari et al. (2022) use pooled regression and GMM in a panel of 33 African countries for the period 2000-2014. The author establish that environmental degradation is positively linked to infant mortality and longevity or life expectancy, thus, reflecting the populations’ vulnerability to climate change. To this end, they also find that clean water sources and sanitation facilities are worthwhile in mitigating the underlying vulnerability by reducing infant mortality rates and improving life expectancy. The work by Smith and Haddad (2015) reveals that food supply is arguably the underlying determinant most likely to be disrupted by climate change. For example, using data from 1970 to 2012 for a sample of 116 countries, they find that access to safe water and sanitation are among the most important drivers of reductions in child undernutrition.

Finally, Kabisch et al. (2016) find that nature-based solutions promoting the development of green and blue urban areas are associated with a considerable potential to reduce vulnerability and build resilience to climate change. They can thus contribute to mitigating climate change-induced impacts by facilitating proactive adaptation within economies. However, the diagnosis of this literature and related work shows that existing studies have largely focused on the exposure resulting from urbanization, or the inverse relationship while a dimension of urbanization such as sustainable urbanization has been very little represented or analyzed. This is especially important because vulnerability is not only due to climate change (Nkomo et al., 2006). It is also due to the transformations of cities that do not always take into account the future impacts of climate change. In addition, most attention has been paid to the negative effects of urbanization, while opportunities for reducing vulnerability have been underestimated.

This paper therefore fills the underlying gap by contributing to the extant literature on the determinants of climate vulnerability. Specifically, the present study extends the existing literature on climate vulnerability, which is prominent in current scientific contributions, by examining how sustainable urbanization affects vulnerability to climate change. To this end, we construct an index of sustainable urbanization in African economies that takes into account its different dimensions (economic, social and environmental).

While the literature analyzing the effect of sustainable urbanization on vulnerability to climate change is not widespread, the prediction that the analysis of the nexus between the two underlying concepts can be established via channels also leads us to conduct an indirect analysis through two channels. First, the institutional quality channel, having as its anchor the existing literature that supports the perspective that sustainable urbanization plays an important role in government policies and institutional quality by improving rules and laws, but also governmental efficiency and stability for sustainable development (Kagan et al., 2018). Based on this, the attendant literature also shows that political and economic institutions are relevant in effective adaptation to climate change through effective government interventions (He et al., 2022).

The second channel is digitalization. Indeed, urbanization and sustainable development promote the adoption of digitalization by increasing the adoption and use of information and telecommunication technologies (Goel & Vishnoi, 2022). In turn, this digitalization will promote resilience to the adverse impacts of climate change via the application of artificial intelligence (AI); which boosts the ability of the human to control climate change in view of achieving sustainability when using environmental resources (Argyroudis et al., 2022; Habila et al., 2023). The empirical approach following the consideration of endogeneity is based mainly on the GMM in a two-stage system for a sample of 52 African countries over the period from 1996 to 2019. The results confirm not only the positive effect of sustainable urbanization in reducing climate vulnerability, but also the existence of an indirect effect through the quality of institutions and digitalization that improve the overall effect of sustainable urbanization in fighting climate vulnerability. Our results are robust to alternative econometric approaches and to the consideration of pollution as an alternative variable of vulnerability to climate change. Section 2 presents some stylized facts on the evolution of this relationship. Section 3 reviews the methodology used and describes the variables. The results obtained are presented and interpreted in Section 4. Section 5 concludes the paper and proposes some recommendations.

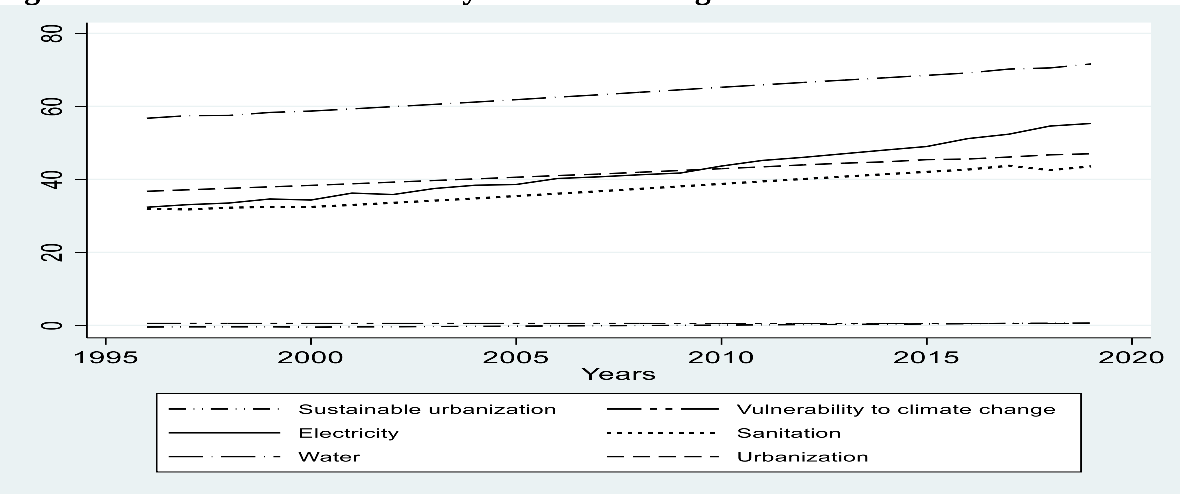
2. General facts on vulnerability to climate change and sustainable urbanization in Africa

This section discusses the intuition using theory and numerical trends to make the case that sustainable urbanization would help reduce vulnerability to climate change within African economies.

Work by Hoegh-Guldberg et al. (2018) highlights that average global temperatures are anticipated to be higher than 1.5-2°C by the end of the 21st century and thus, could exceed 3.3-5.7°C within the remit of very high greenhouse gas emission scenarios. Moreover, the world's most vulnerable people will be disproportionately affected by these climate changes. To this end, Africa is among the most vulnerable regions to climate change in the world (Birkmann, 2022); and represents the region that has experienced the most losses from global climate change (Nangombe et al., 2018). However, the African continent has been experiencing a rapid wave of urbanization since the previous decade (Sulemana et al., 2019). For example, from 2000 to 2017, the urbanization rate in Africa increased by 8% (Nathaniel & Adeleye, 2021). Only, rapid urbanization is very often accompanied by environmental degradation that leads to vulnerability following climate change (Wang et al., 2020). This is especially true in Africa, where poverty is rampant and the quality of institutions is less than desirable (Adams & Klobodu, 2017).

Furthermore, within urban centers, access to basic services such as water, electricity and sanitation reduces the vulnerability of populations to climate change (Birkmann, 2022). Thus, these variables in the context of urbanization would contribute to reducing vulnerability to climate change as shown in Figure 1.

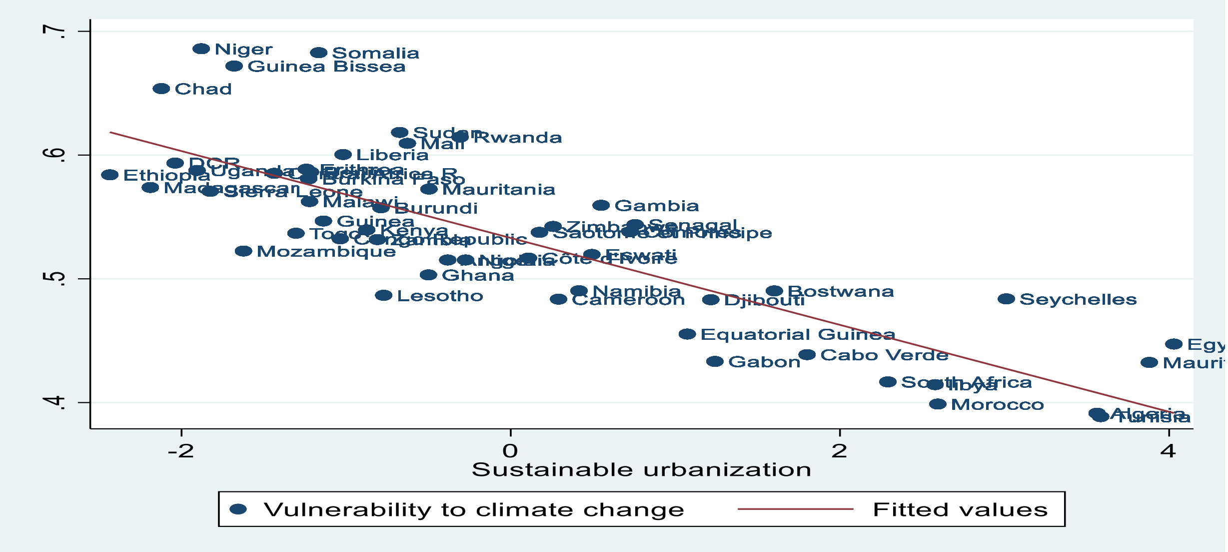
Figure 1. Evolution of vulnerability to climate change and sustainable urbanization



Source: authors

Indeed, we note initially that these variables evolve in the same direction as urbanization, which allows us to consider sustainable urbanization, which includes the association between access to these basic services and urbanization. We therefore posit that this sustainable urbanization, although showing very little variability, evolves in opposition to vulnerability to climate change, in the same way as the latter. This reflects the fact that the improvement of sustainable urbanization would be linked to the reduction of vulnerability to climate change in Africa. Figure 2 further illustrates the evolution of this relationship.

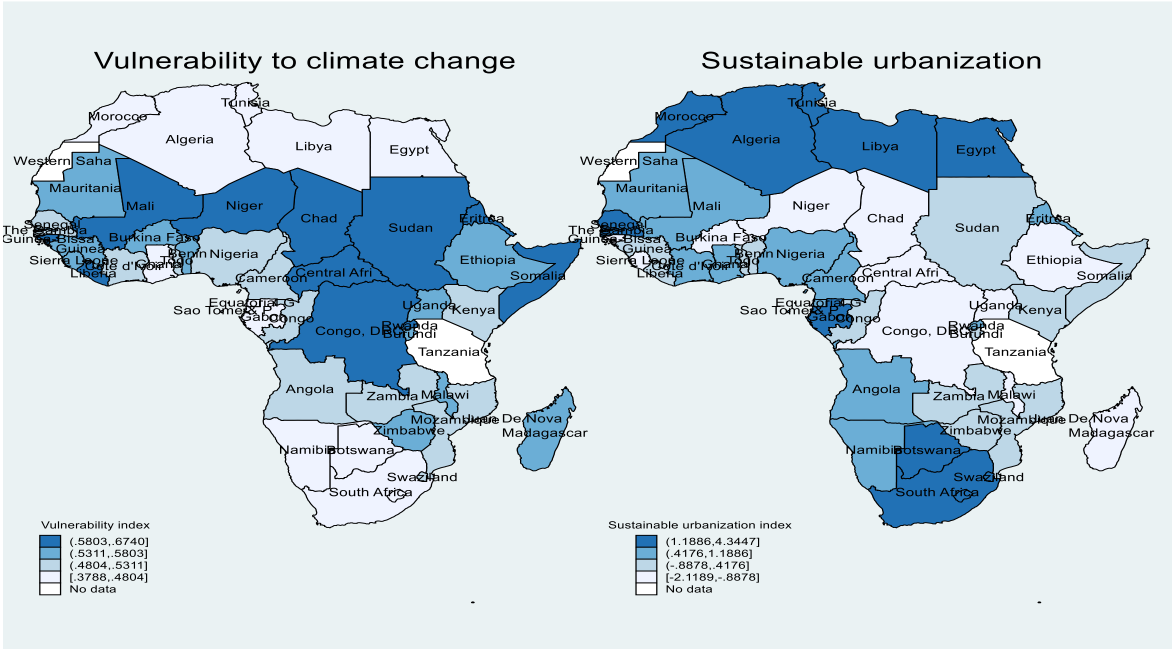
Figure 2. Analysis of the correlation between sustainable urbanization and vulnerability to climate change.



Source: authors

We consistently find that there is a negative relationship between sustainable urbanization and vulnerability to climate change. This trend can be clearly observed through this downward slope that reflects the fact that a better sustainable urbanization index would be linked to a reduction in vulnerability to climate change and vice versa. Furthermore, Figure 3, which analyzes the mapping of this relationship for the specific case of the year 2019, further supports our intuition that sustainable urbanization reduces vulnerability to climate change.

Figure 3. Mapping analysis of the relationship between vulnerability to climate change and sustainable urbanization in 2019 in Africa



Source: authors

We note that countries with a high sustainable urbanization index are mostly those with the lowest level of vulnerability to climate change. To this effect, we have countries such as South Africa, Botswana, Algeria, Morocco, Tunisia, Libya or Egypt that are in the upper bracket with a better sustainable urbanization index. However, these are also the same countries that are in the lower range in terms of vulnerability index to climate change. The reverse is also true insofar as countries such as Chad, Niger, the Central African Republic and the Democratic Republic of Congo have the lowest sustainable urbanization indices, but not surprisingly also the highest vulnerability to climate change indices.

Ultimately, the presentation of these stylized facts leads us to opt for the validation of this perception with empirical evidence.

3. Methodology

3.1 Principal component analysis (PCA)

In accordance with the literature, sustainable urbanization takes into account several dimensions including economic, social and environmental dimensions (Verma & Raghubanshi, 2018). To this end, it refers to a vast and polysemous phenomenon whose approximation is far from a consensus (Hiremath et al., 2013; Huang et al., 2015). Therefore, this study uses PCA on specific indicators in order to take into account these various dimensions that are crucial in approximating and formalizing sustainable urbanization. These variables include electricity, access to water and sanitation, all extracted from the WDI database. Electricity, which is seen as the essential component of sustainable urban development in that the economy, basic service delivery and the physical environment, grow with per capita electricity consumption (Stewart et al., 2018). It is measured by the percentage of people with access to electricity in proportion to the total population. Access to water is measured by the percentage of people using at least basic, safely managed drinking water services as a proportion of the total population. Lastly, sanitation is captured by the percentage of people using at least basic sanitation services and managed in complete safety in relation to the total population. These variables are also leading indicators of sustainable urbanization in that access to these basic services within developing economies is critical to achieving sustainable urbanization (Collier & Venables, 2017). Finally, urbanization is the most important indicator as the development of urban areas is the prerequisite for any sustainable urbanization (Mehta & Yadav, 2016). In parallel, we also calculate a digitalization index through variables such as individuals using the internet, fixed phone, and cell phone subscriptions. This index refers to the transformation of the techno-economic and social environment through digital communications and applications (Katz and

Koutroumpis, 2013). Thus, the variables used for this index are justified by their contribution to the digitalization process (Katz and Koutroumpis, 2013; Müller, 2021).

The use of PCA is justified by the high correlation and degree of substitution between these variables as illustrated in Table A1. This statistical tool is used to thus reduce a set of highly correlated variables into a smaller set of uncorrelated variables known as principal components (PC). The criterion used to retain these factors is that of Kaiser (1974) and Jolliffe (2002) who recommend retaining only those PCs whose eigenvalues are greater than the mean value. Before PCA, we perform the Bartlett sphericity test and the Kaiser-Meyer-Olkin (KMO) global sampling adequacy measure. Table A2 shows the test results. The null hypothesis of the Bartlett test is that the correlation matrices of the sustainable urbanization and digitization variables are identity matrices (or covariance matrices nately diagonal matrices). The results indicate that there is less evidence for the null hypothesis at the 1% level. The same table also gives the overall value of the KMO measure, which varies between 0 and 1. A low value corresponds to the case where it is not possible to extract synthetic factors (or general factors) or the sample is "unsuitable" for factor analysis. The overall KMO is 0.750 for the sustainable urbanization variable and 0.594 for the digitalization variable. This confirms the usefulness of PCA in our analysis.

The logic behind using PCA is to obtain broader policy implications as a result of representing variables by a common factor. Concerning sustainable urbanization, the first principal component (PC), urbanization, accounts for more than 70% of the variation in the four components, while it accounts for about 13% in the case of sanitation, 10% in the case of access to water, and 4% in the case of electricity. For digitalization, the first principal component (PC), internet, accounts for more than 69% of the variation in the three components, while it accounts for about 23% in the case of fixed phone, and 6% in the case of mobile phone. Kaiser (1974) recommends deleting factors with an eigenvalue of less than one.

3.2 Analysis model

This paper aims to examine the effects of sustainable urbanization on vulnerability to climate change in Africa. To analyze this relationship, we will consider an econometric specification that best operationalizes a device for elucidating reality. Thus, our econometric model is motivated by the work of Sarkodie and Strekov (2019). We thus adopt a model from which the relationship between vulnerability to climate change, its main determinants and sustainable urbanization is expressed in a functional form as follows:

$$Vul_{i,t} = \gamma + \lambda Vul_{i,t-1} + \alpha Surb_{i,t} + \beta X_{i,t}{}' + \tau M_{i,t}{}' + \nu_i + \mu_t + \varepsilon_{i,t} \quad \textbf{(1)}$$

With Vul represents the dependent variable that is vulnerability to climate change, and Surb is our main variable of interest that captures sustainable urbanization. X' which represents the vector of the control variables which are precipitation (Pre), temperature (Tem), foreign direct investment (Fdi), transfer of funds from migrants (Rem), economic development (Gdp), population growth (Pop), natural resource earnings (NR), trade openness (Trade), unemployment rate (Unem), financial development (FD), manufacturing industry (Man), and agricultural production (Agri) are the control variables. M' represents the vector of other control variables that integrates digitalization and the institutional quality in the model. ν_i is the country fixed effects that accounts for time-invariant country-specific unobservable features; μ_t is the temporal fixed effect, which measures the effect on the temporal variations of the climate vulnerability of each country, of the evolution of unobservable variables assumed to be common to all the countries (in particular macroeconomic, political and technological shocks). ε_{it} is the error term and λ, α, β, τ are coefficients to be estimated and δ the constant. All of these identified control variables are in line with the theoretical and empirical literature on the determinants of climate vulnerability (Sarkodie & Strekov, 2019; Abdelzaher et al., 2020).

Variations in rainfall and temperature hamper crop yields within economies, making them vulnerable to climate change (Wing et al., 2021). Foreign direct investment exacerbates climate change as it draws in developing countries, developed economies that have lax environmental policies causing a snowball effect of environmental pollution (Siebert, 1977; Sarkodie & Strezov, 2019). Moreover, the diversification of outward FDI improves resilience, mitigating inequalities induced by climate change (Paglialunga et al., 2022). Migrants' remittances sent back to communities of origin can favour adaptation to climate change by supporting water supply and irrigation projects in places of origin that can help people cope with the effects of climate change. climate change (Scheffran et al., 2012)

For its part, economic development approximating the economic situation of countries based on GDP per capita is justified by the fact that it is associated with low vulnerability to climate change (You et al., 2022). Taking into account population growth is not insignificant insofar as controlling it is imperative to mitigate vulnerability to climate change in Africa by improving socio-economic vulnerability and reducing potential exposure to climate change. drought (Ahmadalipour et al., 2019). The benefit of natural resources used as a proxy for the exploitation of natural resources insofar as an overexploitation of natural resources is associated with an increase in vulnerability to climate change (Baker, 2016; Maja & Ayano, 2021). The consideration of trade openness is justified by the fact that trade liberalization can lead to a reduction in the domestic price of foodstuffs as a result of inflation caused by climate change (Acosta-Michlik & Espaldon, 2008).

Unemployment is associated with climate vulnerability insofar as it reflects the difficulty of adapting to climate change undermined by rural unemployment (Tschakert, 2007). Financial development approximated by private sector credit is associated with minimal vulnerability to climate change by improving environmental sustainability (Umar et al., 2020). Agricultural production as a proxy for agriculture is used to explain vulnerability to climate change among agricultural and rural populations (Adger, 2006; Candau et al., 2022). The manufacturing industries is justified by the fact that the manufacturing sector can be relatively less affected by climate change and therefore decrease the vulnerability of a country (Abdelzaher et al., 2020)

Due on the one hand to the poor quality of institutions and on the other hand to the development and adoption of information and communication technologies (ICT) in most African economies, this study takes into account the quality of institutions and digitization. These variables can reduce vulnerability to climate change within African economies through good governance and land management; or through the transfer of knowledge and technologies in mechanisms for reducing climate vulnerability in Africa (Mitchell et al., 2015; Balogun et al., 2020). Indeed, digitalization offers opportunities to facilitate sustainable adaptation planning in existing and future urban centers (Balogun et al., 2022). The work of Filho et al., (2022) shows that digitalization through digital technologies and artificial intelligence increases adaptation to climate change by building and proposing innovative solutions in the response to climate change. Likewise, technological innovation contributes to the reduction of CO2 emissions; while institutional quality is associated with increased CO2 emissions in Africa (Obobisa et al., 2022). For this purpose, the extended version of equation (1) can take the following form in equation (2):

$$Vul_{i,t} = \delta + \lambda Vul_{i,t-1} + \alpha Surb_{i,t} + \beta X_{i,t}^{'} + \tau_1 Dig_{i,t} + \tau_2 Insq_{i,t} + \nu_i + \mu_t + \varepsilon_{i,t} \quad \textbf{(2)}$$

Where Dig and Insq represent digitization and institutional quality respectively. The other variables and symbols remained unchanged. However, this model could have some shortcomings due to endogeneity problems from various sources. For example, in urban planning and governance, cities are directly impacted by the effects of climate change, which makes the synergies between climate policy and sustainable development become more evident (Kern & Alber 2009; Bulkeley 2010). This suggests that climate vulnerability could also influence sustainable urbanization especially since the study of Wamsler et al. (2013) demonstrates that climate change represents a serious threat to sustainable urban development. This therefore raises a problem of endogeneity caused by the inverse causality between our dependent variable and the main variable of interest. This endogeneity could also be revealed by the use of control variables that are not exogenous, by omitting variables or by multicollinearity between control variables. Thus, let us estimate equation (2) by applying the system generalized method of moments (System-GMM) proposed by Arellano and Bover (1995) and Blundell and Bond (1998). The System-GMM estimator is preferred because it is consistent and unbiased in parameter estimation while accounting for the endogeneity issues.

To take account of endogeneity bias in our estimates, we have opted for the use of internal instruments based on the variables of sustainable urbanization, natural resource income, temperature, and rainfall, which we specify as endogenous; and certain variables lagged by at least two periods to cope with any endogeneity problem by avoiding any correlation between the error term and the potential lagged endogenous variable. This specifically concerns the use of economic growth, population growth, agricultural productivity and institutional quality as lagged variables for estimates based on System-GMM.

3.3 Analysis data

Due to the availability of data[2], our sample extends to 52 African countries and covers the period 1996-2019. Estimates following the GMM approach are carried out on data covering the period 1996-2019, which we have subdivided into 6 sub-periods (1996-1999, 2000-2003, 2004-2007, 2008-2011, 2012-2015, 2016-2019). This is to ensure that the temporal dimension of the panel is much smaller than the individual dimension (Roodman, 2009). Given the multitude of variables considered, several data sources were used. Thus, the data come mainly from five sources, notably: (i) World Development Indicators (WDI) of the World Bank; (ii) Global Adaptation Index (GAI); (iii) Worldwide Governance Indicators (WGI) of the World Bank; (iv) the Intergovernmental Panel on Climate Change (IPCC) and (v) the Food and Agriculture Organization (FAO). More details on these variables is apparent in Table A3 of the appendix. The corresponding summary statistics is disclosed in Table A4 of the appendix while

[2] To deal with the problem of missing data, we used the average and moving average approaches to complete our database.

the correlation matrix is apparent in Table A7. The list of sampled countries is also disclosed in Appendix Table A8 of the appendix. The evolution of the relationship between climate vulnerability and sustainable urbanization in Africa from 1996 to 2019 is also disclosed in Table A4.

4. Empirical Analysis

This section reports and discusses the results of the analysis of the relationship between sustainable urbanization and vulnerability to climate change with particular attention to variables such as digitalization and institutional quality.

4.1 Baseline results

Table 1 presents the results of the estimation by GMM. They are globally significant on both statistical and theoretical levels. Statistically, the results of the diagnostic tests show that the models are well specified. First, the Hansen test does not reject the validity hypothesis of the instruments. Second, the rule of thumb that the number of instruments should be smaller than the number of countries is respected (Roodman, 2009). Indeed, the results of the system-based GMM estimations generated a maximum of 32 instruments, which is lower than the number of countries. Finally, the lack of second-order serial correlation is not rejected. In all our estimations, we note overall a strong significance of the autoregressive vulnerability to climate change term, which supports the choice of estimating a dynamic panel model (Fankem & Yeyouomo, 2023).

Table 1. Effect of sustainable urbanization on vulnerability to climate change

	Dependent variable : vulnerability to climate change				
	System GMM				
	(1)	(2)	(3)	(4)	(5)
Vul $_{i,t-1}$	0.974***	0.972***	0.967***	0.928***	0.923***
	(0.0587)	(0.1071)	(0.0521)	(0.0661)	(0.0294)
Surb $_{i,t}$	**-0.0037*** **				
	(0.0011)				
Urbanization $_{i,t}$		**-0.0027*** **			
		(0.0007)			
Sanitation $_{i,t}$			**-0.0004*** **		
			(0.0006)		
Water $_{i,t}$				**-0.0005*** **	
				(0.0001)	
Electricity $_{i,t}$					**-0.0003*** **
					(0.0008)
Tem $_{i,t}$	0.0011*	0.0016*	0.0023***	0.0007	0.0035***
	(0.0006)	(0.0093)	(0.0007)	(0.0006)	(0.0004)
Pre $_{i,t}$	-0.0072**	-0.0014*	-0.0078***	-0.0155***	-0.0073***
	(0.0039)	(0.0006)	(0.0028)	(0.0027)	(0.0022)
Gdp $_{i,t}$	-0.0024**	-0.0033**	-0.0031*	-0.0041***	-0.0009**
	(0.0011)	(0.0016)	(0.0016)	(0.0014)	(0.0004)
Fdi $_{i,t}$	0.0062*	0.0025***	0.0073***	0.0041*	0.0036**
	(0.0032)	(0.0009)	(0.0023)	(0.0025)	(0.0015)
Pop $_{i,t}$	0.0008*	0.0032*	0.0005**	0.0019***	0.0006*
	(0.0004)	(0.0017)	(0.0002)	(0.0003)	(0.0004)
Nr $_{i,t}$	0.0004***	0.0005***	0.0003***	0.0018**	0.0051**
	(0.0001)	(0.0002)	(0.0001)	(0.0007)	(0.0021)
Trade $_{i,t}$	-0.0014***	-0.0008**	-0.0012***	-0.0005*	-0.0008***
	(0.0003)	(0.0003)	(0.0002)	(0.0002)	(0.0002)
Unem $_{i,t}$	0.0017***	0.0017**	0.0023***	0.0022***	0.0003
	(0.0004)	(0.0007)	(0.0003)	(0.0005)	(0.0002)
Fd $_{i,t}$	-0.0004**	-0.0002	-0.0002	-0.0014	-0.0009
	(0.0001)	(0.0001)	(0.0002)	(0.0001)	(0.0001)
Man $_{i,t}$	0.0002	-0.0005	-0.0001	-0.0012***	0.0002
	(0.0002)	(0.0003)	(0.0002)	(0.0003)	(0.0002)
Agri $_{i,t}$	-0.0084***	-0.0041*	-0.0074*	-0.0018****	-0.0091***
	(0.0032)	(0.0019)	(0.0038)	(0.0005)	(0.0033)
Insq $_{i,t}$	-0.175***	-0.0794*	-0.618***	-0.801***	-0.709***
	(0.0446)	(0.0420)	(0.133)	(0.161)	(0.180)
Dig $_{i,t}$	-0.0226*	-0.0475***	-0.180***	-0.412***	-0.0334**
	(0.0121)	(0.0069)	(0.0341)	(0.0495)	(0.0162)
Instruments	32	32	31	32	31
Observations	312	312	312	312	312
Countries	52	52	52	52	52
Fisher	467.80***	188.24***	409.06***	339.74***	775.41***
Hansen (p-value)	0.211	0.189	0.221	0.158	0.166
AR(1) (p-value)	0.044	0.027	0.033	0.019	0.044
AR(2) (p-value)	0.714	0.644	0.409	0.322	0.562

Source: Authors

Note : ***, ** and * significant respectively at the 1%, 5% and 10% thresholds. Standard deviations corrected for heteroscedasticity are in parentheses. The estimates are made on the average data of four years calculated over the period 1996-2019 subdivided into 6 sub-periods to ensure that the temporal dimension of the panel is much smaller than the individual dimension (Roodman, 2009). **Vul**, Vulnerability to climate change; **Surb**, Sustainable urbanization; **Tem**, Temperature; **Pre**, precipitation; **Gdp**, Gross domestic product, **Fdi**, Foreign direct investment, **Pop**, Population, **Nr**, Natural resource, **Unem**, Unemployment, **Fd**, Financial development, **Man**, manufacturing, **Agri**, Agriculture, **Insq**, Institutional quality, **Dig**, Digitalization.

At the theoretical level, our results are economically significant. Regarding the control variables, overall as expected, rainfall, economic growth, trade openness, financial development and agricultural productivity reduce vulnerability to climate change. These results are similar to the work of Wing et al. (2021) and You et al. (2022) who find that rainfall and economic growth contribute to the reduction of vulnerability to climate change, respectively. On the other hand, the studies of Acosta-Michlik and Espaldon, (2008), Umar et al. (2020) and Candau et al. (2022) respectively corroborate that trade openness, financial development and agricultural productivity significantly promote adaptation to climate change by reducing the vulnerability of populations. Instead, temperature change and natural resource exploitation through unsurprising natural resource benefits worsen vulnerability to climate change by increasing people's sensitivity and environmental degradation (Wing et al., 2021; Maja & Ayano, 2021)

As for the variables of interest, the results are also consistent with our expectations. Overall, regardless of the sustainable urbanization indicator, the results show that it reduces vulnerability to climate change. This positive and significant effect is more significant when considering the sustainable urbanization index. Indeed, a 1% increase in sustainable urbanization leads to a 0.37% reduction in vulnerability to climate change (column 1, Table 1). In other words, an improvement in sustainable urbanization favors a reduction in climate vulnerability. This reduction is lower when only urbanization, sanitation, access to water or electricity are considered, with reductions of 0.27%, 0.04%, 0.05% and 0.03, respectively.

Overall, this result is consistent with the empirical literature that globally shows that sustainable urbanization by promoting sanitation, access to water, and electricity actively contributes to reducing vulnerability to climate change (Goebel, 2007; Roy, 2009; Sanchez Rodriguez et al., 2018). This contribution of sustainable urbanization is further justified by the fact that it promotes adaptation and resilience to climate change by facilitating access to health services, limiting environmental degradation by the development of green spaces, the development and maintenance of basic sanitation services, and the development and improvement of access to electricity and drinking water (Chen et al., 2021; Tonne et al., 2021; Buzási et al., 2022).

4.2 Robustness checks

To test the robustness of our results, we perform three robustness tests. Firstly, we replace the measure of vulnerability to climate change with CO2 emission in kiloton (kt) from the annual burning of fossil fuels and the manufacture of cement. Indeed, several studies associate pollution through CO2 emission with environmental degradation inducing climate vulnerability (Obobisa et al., 2022; Kim & Park, 2023; Izah et al., 2023). The objective is therefore to see if the previous results are not in fact driven or influenced by the type of vulnerability to climate change indicator.

Secondly, given the use of a multitude of interlinked explanatory variables, notably climate variables as witnessed in the literature, we take into account the endogeneity problem of the control variables in order to ensure the robustness of our results. To this end, we run panel regressions with lagged explanatory variables with reference to the existing literature (Asongu et al. 2018; Fankem & Yeyouomo, 2023). This allows us to thus take into account the simultaneity, multicollinearity and overparameterization problems induced by the association of these different variables. To this end, given that we are using the average of four years' data, we lag all the explanatory variables by one period (i.e. four years). Our results, as shown in Table A5, remain broadly unchanged, thus confirming their robustness despite the use of a multitude of more or less interrelated explanatory variables.

Thirdly, since Windmeijer (2005) has shown, from Monte Carlo simulations, that the estimated asymptotic standard deviations of the two-stage GMM estimator can be significantly biased downwards at finite distance, we take this possibility into account in our analysis; this is to ensure the robustness and consistency of our results. Thus, to guard against the possibility of such a bias, we use the second-stage finite-sample covariance matrix correction method proposed by Windmeijer (2005). In this respect, the results of this analysis presented in Table A6 also support the robustness of our results.

Fourth, we apply substitution econometric techniques such as dynamic common correlated effects mean group estimator (DCCEE) and quantile regressions. Indeed, the most relevant concerns worth addressing when dealing with panel data are, inter alia, cross-sectional dependence and heterogeneity, not least because ignoring these issues can engender to inconsistent estimation results (Obobisa et al., 2022). It is therefore with a view to taking these problems into account but also to analyze the relationship studied over the long term that we opt for the dynamic common correlated effects mean group estimator (DCCEE) proposed by Chudik and Pesaran (2015) as a first substitution technique in robustness.

Finally, the work of Xu and Lin (2020) shows that environmental variables and their main influencing variables are not always normally distributed. Hence the relevance of verifying our results through the quantile regression model which makes it possible to obtain findings that are more robust, compared to the traditional mean regression method in this case (Koenker & Xiao, 2002; Xu & Lin, 2020).

Table 2. Effect of sustainable urbanization on vulnerability to climate change, a robustness analysis to pollution

	Dependent variable : CO2 emissions				
	System GMM				
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
$CO2_{i,t-1}$	0.812***	0.818***	0.981***	0.919***	0.958***
	(0.0198)	(0.0263)	(0.0476)	(0.0356)	(0.0371)
$Surb_{i,t}$	-0.195***				
	(0.0240)				
$Urbanization_{i,t}$		0.00794***			
		(0.00272)			
$Sanitation_{i,t}$			-0.0266***		
			(0.00489)		
$Water_{i,t}$				-0.00744***	
				(0.00118)	
$Electricity_{i,t}$					-0.0288***
					(0.00327)
$Tem_{i,t}$	0.0089***	0.0071***	0.0216***	0.0351***	0.0357***
	(0.0009)	(0.0013)	(0.0041)	(0.0028)	(0.0019)
$Pre_{i,t}$	-0.240***	-0.140***	-1.290***	-0.585***	-0.711***
	(0.0179)	(0.0302)	(0.0966)	(0.128)	(0.0801)
$Gdp_{i,t}$	0.0481***	0.0579***	0.136***	0.210***	0.200***
	(0.0097)	(0.0109)	(0.0364)	(0.0412)	(0.0353)
$Fdi_{i,t}$	0.0003	0.0002	0.0057***	0.0074***	0.0046***
	(0.0002)	(0.0002)	(0.0007)	(0.0011)	(0.0008)
$Pop_{i,t}$	0.0687**	0.0336***	0.0997***	0.0771**	0.0917***
	(0.0081)	(0.0066)	(0.0247)	(0.0309)	(0.0291)
$Nr_{i,t}$	0.0015***	0.0047***	0.0155***	0.0253***	0.0201***
	(0.0004)	(0.0004)	(0.0015)	(0.0036)	(0.0014)
$Trade_{i,t}$	-0.0003***	-0.0166***	-0.0276***	-0.0358***	-0.0697***
	(0.0009)	(0.0019)	(0.0074)	(0.0069)	(0.0075)
$Unem_{i,t}$	-0.0052	-0.0381***	-0.0363***	-0.0793***	-0.117***
	(0.0061)	(0.0086)	(0.0129)	(0.0174)	(0.0175)
$Fd_{i,t}$	-0.0078***	-0.0018	-0.0306***	-0.0204***	0.0048***
	(0.0017)	(0.0014)	(0.0068)	(0.0053)	(0.0052)
$Man_{i,t}$	0.0042**	0.0204***	0.0283***	-0.0174***	0.0211***
	(0.0016)	(0.0018)	(0.0053)	(0.0034)	(0.0028)
$Agri_{i,t}$	-0.0181***	-0.0294***	-0.0166	-0.0273	-0.0818***
	(0.0066)	(0.008)	(0.0021)	(0.0028)	(0.0017)
$Insq_{i,t}$	-0.0475***	-0.0367***	-0.0448***	-0.0171**	-0.0283***
	(0.0062)	(0.0085)	(0.0044)	(0.0083)	(0.0032)
$Dig_{i,t}$	-0.0017*	-0.0022**	-0.0015*	-0.0025**	-0.0023***
	(0.0009)	(0.0011)	(0.0008)	(0.0009)	(0.0004)
Instruments	30	31	32	32	31
Observations	312	312	312	312	312
Countries	52	52	52	52	52
Fisher	291.09***	351.01***	546.45***	438.53***	479.75***
Hansen (p-value)	0.151	0.194	0.149	0.188	0.199
AR(1) (p-value)	0.015	0.069	0.012	0.022	0.018
AR(2) (p-value)	0.465	0.561	0.461	0.414	0.613

Source: Authors

Note : ***, ** and * significant respectively at the 1%, 5% and 10% thresholds. Standard deviations corrected for heteroscedasticity are in parentheses. The estimates are made on the average data of four years calculated over the period 1996-2019 subdivided into 6 sub-periods to ensure that the temporal dimension of the panel is much smaller than the individual dimension (Roodman, 2009). **Vul**, Vulnerability to climate change; **Surb**, Sustainable urbanization; **Tem**, Temperature; **Pre**, precipitation; **Gdp**, Gross domestic product, **Fdi**, Foreign direct investment, **Pop**, Population, **Nr**, Natural resource, **Unem**, Unemployment, **Fd**, Financial development, **Man**, manufacturing, **Agri**, Agriculture, **Insq**, Institutional quality, **Dig**, Digitalization.

Table 2 below presents the results of the estimates following the GMM approach in a two-stage system analyzing the effect of sustainable urbanization on CO2 emission. Unsurprisingly, sustainable urbanization significantly reduces CO2 emissions. Indeed, *ceteris paribus*, for a 1% increase in sustainable urbanization, the impact on CO2 emission is a reduction of 19.5% (column 1). This result is not trivial insofar as it corroborates the work of Liu and Bae (2018) who support the fact that green and sustainable urbanization does not degrade the environment; or those who defend the fact that the practice of sustainable urbanization is also associated with low CO2 emission towards the achievement of sustainable and climate change resilient cities (De jong et al., 2015).

Moreover, we note that contrary to Table 1, urbanization in itself rather promotes CO2 emission which is consistent with the results of Asongu et al. (2020) or more recently those of Wei et al. (2023) who find that urbanization by promoting excessive energy consumption and reduction of agricultural activities promotes CO2 emission. However, we note that once it is associated with sanitation, access to electricity and basic water, it rather hinders the degradation of the environment through the emission of CO2. This result is not necessarily counter-productive in that, urbanization on its own promotes CO2 emissions through the destruction of vegetation and forests, but also through the construction of infrastructure, which leads to CO2 emissions using machinery and the burning of fossil fuels. However, when combined with environmental sanitation, access to electricity and the maintenance and development of access to drinking water, it makes an unsurprising contribution to reducing vulnerability to climate change, by improving both access to infrastructure and the social living conditions of local populations.

Table 3. Effect of sustainable urbanization on vulnerability to climate change, a robustness analysis to dynamic common correlated effects estimator (DCCEE)

	Dependent variable : vulnerability to climate change				
	Dynamic common correlated effects				
	(1)	(2)	(3)	(4)	(5)
Vul $_{i,t-1}$	-0.973***	-0.919***	-0.961***	-0.949***	-0.908***
	(0.0506)	(0.0651)	(0.0508)	(0.0479)	(0.0553)
Surb $_{i,t}$	-0.0073**				
	(0.0032)				
Urbanization $_{i,t}$		-0.0009			
		(0.0002)			
Sanitation $_{i,t}$			-0.0004**		
			(0.0001)		
Water $_{i,t}$				-0.0009***	
				(0.0003)	
Electricity $_{i,t}$					-0.0031***
					(0.0008)
Tem $_{i,t}$	0.0004	0.0004	0.0003	0.0003	0.0004
	(0.0002)	(0.0003)	(0.0002)	(0.0002)	(0.0002)
Pre $_{i,t}$	-0.0081**	-0.0076**	-0.0057*	-0.0085***	-0.0052**
	(0.0031)	(0.0032)	(0.0029)	(0.0031)	(0.0024)
Gdp $_{i,t}$	-0.0025	-0.0015	-0.0017	-0.0025	-0.0022
	(0.0017)	(0.0019)	(0.0019)	(0.0019)	(0.0014)
Fdi $_{i,t}$	0.0002	0.0001	0.0003*	0.0002*	0.0003**
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Pop $_{i,t}$	0.0006	0.0004	0.0007	0.0025	0.0004
	(0.0014)	(0.0015)	(0.0014)	(0.0016)	(0.0012)
Nr $_{i,t}$	0.0004***	0.0004***	0.0004***	0.0005***	0.0003***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Trade $_{i,t}$	-0.0115***	-0.0109***	-0.0112***	-0.0098***	-0.0148***
	(0.0024)	(0.0031)	(0.0031)	(0.0032)	(0.0033)
Unem $_{i,t}$	0.0003	0.0005**	0.0002	0.0004*	0.0005**
	(0.0002)	(0.0002)	(0.0003)	(0.0002)	(0.0002)
Fd $_{i,t}$	-0.0001	-0.0002	-0.0006	-0.0005	-0.0001
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Man $_{i,t}$	0.0001	0.0004**	0.0002	0.0009	0.0003*
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Agri $_{i,t}$	-0.0008	-0.0002	-0.0005	-0.0005	-0.0002
	(0.0005)	(0.0003)	(0.0006)	(0.0007)	(0.0004)
Insq $_{i,t}$	-0.0055***	-0.0033*	-0.0071**	-0.0042*	-0.0053***
	(0.0021)	(0.0026)	(0.0029)	(0.0022)	(0.0019)
Dig $_{i,t}$	-0.0075***	-0.0081***	-0.0063***	-0.0069***	-0.0076***
	(0.0021)	(0.0021)	(0.0016)	(0.0015)	(0.0017)
Observations	1103	1103	1103	1103	1103
R-squared	0.160	0.171	0.167	0.149	0.151
CD test by Pesaran (2015) (p)	1.28(0.199)	2.21(0.271)	0.86(0.392)	-0.09(0.929)	0.68(0.493)
F-Stat (p)	1.64(0.000)	1.51(0.000)	1.56(0.000)	1.78(0.000)	1.76(0.000)

Source: Authors

Note : ***, ** and * significant respectively at the 1%, 5% and 10% thresholds. **Vul**, Vulnerability to climate change; **Surb**, Sustainable urbanization; **Tem**, Temperature; **Pre**, precipitation; **Gdp**, Gross domestic product, **Fdi**, Foreign direct investment, **Pop**, Population, **Nr**, Natural resource, **Unem**, Unemployment, **Fd**, Financial development, **Man**, manufacturing, **Agri**, Agriculture, **Insq**, Institutional quality, **Dig**, Digitalization.

Table 3 presents the results of the long-term analysis of the effect of sustainable urbanization on vulnerability to climate change. It shows that, as expected, in the long term, sustainable urbanization will always act significantly in reducing vulnerability to climate change. This result is consistent with the work of Cheshmehzangi et al. (2019) who indeed find that sustainable urbanization by promoting reduced vulnerability to climate change will facilitate the achievement of the Sustainable Development Goals (SDGs) in Africa.

Table 4. Effect of sustainable urbanization on vulnerability to climate change, a robustness analysis to quantile regression (QR)

	Dependent variable : vulnerability to climate change				
	Quantile regression				
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
	Q 0.10	**Q 0.25**	**Q 0.50**	**Q 0.75**	**Q 0.90**
$Surb_{i,t}$	-0.0250***	-0.0259***	-0.0238***	-0.0288***	-0.0326***
	(0.0016)	(0.0014)	(0.0015)	(0.0022)	(0.0019)
$Tem_{i,t}$	0.0006***	0.0007***	0.0003***	0.0003***	0.0002**
	(0.0002)	(0.0002)	(0.0001)	(0.0001)	(0.0001)
$Pre_{i,t}$	-0.0135***	-0.0158***	-0.0140***	-0.0140***	-0.0091***
	(0.0023)	(0.0014)	(0.0031)	(0.0029)	(0.0021)
$Gdp_{i,t}$	-0.0082***	-0.0081***	-0.0107***	-0.0031	-0.0004
	(0.0023)	(0.0022)	(0.0021)	(0.0022)	(0.0031)
$Fdi_{i,t}$	0.0001	0.0004***	0.0001	0.0001	0.0001
	(0.0001)	(0.0001)	(0.0002)	(0.0001)	(0.0001)
$Pop_{i,t}$	0.0044**	0.0049***	0.0048**	0.0022	-0.0009
	(0.0017)	(0.0013)	(0.0022)	(0.0016)	(0.0011)
$Nr_{i,t}$	0.0005***	0.0004***	0.0009***	0.0015***	0.0017***
	(0.0001)	(0.0001)	(0.0002)	(0.0002)	(0.0001)
$Trade_{i,t}$	-0.0018	-0.0027**	-0.0023*	-0.0019	0.0029***
	(0.0015)	(0.0011)	(0.0012)	(0.0012)	(0.0011)
$Unem_{i,t}$	0.0004**	0.0008***	0.0012***	0.0013**	0.0026***
	(0.0001)	(0.0002)	(0.0003)	(0.0005)	(0.0003)
$Fd_{i,t}$	-0.0005***	-0.0006***	-0.0009***	-0.0002	-0.0011***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0004)
$Man_{i,t}$	-0.0015***	-0.0018***	-0.0004	-0.0003	-0.0001
	(0.0002)	(0.0002)	(0.0003)	(0.0003)	(0.0002)
$Agri_{i,t}$	-0.0003***	-0.0003***	-0.0003***	-0.0003***	-0.0004***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
$Insq_{i,t}$	-0.0204***	-0.0126***	-0.0048	-0.0255***	-0.0316***
	(0.0024)	(0.0046)	(0.0054)	(0.0048)	(0.0035)
$Dig_{i,t}$	-0.0024*	-0.0045***	-0.0055***	-0.0057***	-0.0052***
	(0.0012)	(0.0016)	(0.0021)	(0.0019)	(0.0013)
Pseudo R^2	0.6175	0.5921	0.5112	0.6692	0.5163
Observations	1,199	1,199	1,199	1,199	1,199
Countries	52	52	52	52	52

Source: Authors
Note : ***, ** and * significant respectively at the 1%, 5% and 10% thresholds. **Vul**, Vulnerability to climate change; **Surb**, Sustainable urbanization; **Tem**, Temperature; **Pre**, precipitation; **Gdp**, Gross domestic product, **Fdi**, Foreign direct investment, **Pop**, Population, **Nr**, Natural resource, **Unem**, Unemployment, **Fd**, Financial development, **Man**, manufacturing, **Agri**, Agriculture, **Insq**, Institutional quality, **Dig**, Digitalization.

Table 4 reveals the results of the analysis of the effect of sustainable urbanization [3]on vulnerability to climate change using the quantile regressions approach. The information

[3] We also estimated the effect of individual sustainable urbanization indicators on vulnerability to climate change, using quantile regressions. The results confirm our findings and in no way call into question the effect of

criterion for the validity of the specifications in this approach is the coefficient of determination (Pseudo R-squared). It indeed reveals that the specifications are all valid in view of the R^2 all greater than 0.500; this further confirms the explanatory power of the explanatory variables used.

In this regard, these results reveal a negative, significant effect of sustainable urbanization regardless of the quantile considered. This reflects the fact that, regardless of the level of vulnerability to climate change of the economies considered, sustainable urbanization effectively reduces the latter. These results imply that in order to promote the fight against vulnerability to climate change, the practice of sustainable urbanization must be a global phenomenon within the region and this independently of the level of development of the economies. In essence, from the quantile regressions, there is an S-shape nexus between the dependent variable of interest and the outcome variable, not least, because the negative magnitude increases from the 10^{th} to the 25^{th} quanitle, then decreases at the median (or 50th quantile) before subsequently increasing consistently in the 75^{th} and 90^{th} quantiles. It follows that countries with above-median vulnerability to climate change are likely to benefit more from the relevance of sustainable unbarnization in reducing vulnerability to climate change, compared to their counterparts with below-median levels of vulnerability to climate change.

4.3 Analysis of the indirect effect of sustainable urbanization on vulnerability to climate change

For the analysis of the indirect and total effect of sustainable urbanization on vulnerability to climate change in Africa, we are inspired by the work of Papyrakis and Gerlagh (2004). We adapt the methodology described in the context of our study. The main hypothesis of this study is that sustainable urbanization can have not only a direct but also an indirect effect on vulnerability to climate change in such a way that it generates externalities that can either amplify or slow down vulnerability to climate change. In this regard, equation (1) may be underestimated (or overestimated) if sustainable urbanization indirectly affects vulnerability to climate change. Two channels are identified through the literature, in particular digitalization and institutional quality. To establish the existence of a mediating nexus, we specify a system of structural equations captured by equations (1) and (3) in which the mediating indicators are dependent. Equation (3) can be written as follows:

$$M_{i,t,s} = \delta_0 + \delta_1 Surb_{i,t} + \chi_{i,t,s} \qquad \textbf{(3)}$$

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sustainable urbanization on vulnerability to climate change. However, in the interests of readability, these tables are not presented in the work, but are available on request.

Where $M_{i,t,s}$ is the vector of s transmission channels. δ_1 denotes the elasticity of channels with respect to sustainable urbanization. δ_0 represents the constant, and $\chi_{i,t,s}$ is error term. The median effect is only possible if and only if δ_1 is significant. After replacing equation (3) in equation (1), we obtain the following equation (4) :

$$Vul_{i,t} = (\gamma + \tau\delta_0) + \lambda Vul_{i,t-1} + (\alpha + \tau\delta_1) Surb_{i,t} + \beta X_{i,t}' + \tau\chi_{i,t,s} + \nu_i + \mu_t + \varepsilon_{i,t} \quad \textbf{(4)}$$

With α which indicates the direct effect, while $\tau\delta_1$ capturing the indirect effect. For this purpose, $(\alpha + \tau\delta_1)$ refers to the total effect of sustainable urbanization on vulnerability to climate change. We estimate the direct and indirect impacts of sustainable urbanization on vulnerability to climate change using structural equation modeling. In addition, following the work of Papyrakis and Gerlagh (2004), the indirect effect is obtained by using the product of the Sobel coefficients. This effect is obtained from the following equation (5):

$$Indirect\ effect : \frac{\partial Vul_{i,t}}{\partial M_{i,t,s}} \times \frac{\partial M_{i,t,s}}{\partial Surb_{i,t}} = \tau\delta_1 \quad \textbf{(5)}$$

Hence, in this approach, the results contained in Table 5 reflect the effect of sustainable urbanization on the mediating variables of institutional quality and digitalization. As expected, sustainable urbanization indirectly affects vulnerability to climate change through its positive effects on these mediating variables. All else being equal, a 1% increase in sustainable urbanization leads to a 17% increase in digitalization and even more so to a 39.3% increase in institutional quality in Africa. These results partly corroborate the work of Zhao et al. (2023) who, in analyzing the specific impact of urbanization in technological digitization policy, find a synergy and interaction of knowledge leading to industrial structures and better resource allocation. They are also consistent with those obtained by Lee et al. (2013) who find that the outcome of sustainable urbanization is through the implementation of smart cities; which leads to the implementation of an integrated roadmap process for services, devices and technologies thus promoting technological innovations. They hardly dismiss the findings of Enserink and Koppenjan (2007) who find that sustainable urbanization induces the need for effective governance; thus the latter by ensuring compliance with the rules set up and the effective participation of all actors in the sustainable urbanization process will improve its institutional quality.

Table 5. Effect of sustainable urbanization on the mediators

	Dependent variables									
	System GMM									
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Digitalization$_{i,t}$					**Institutional quality**$_{i,t}$				
$\mathbf{Dig}_{i,t-1}$	0.882***	0.989***	0.986***	0.952***	0.959***					
	(0.0024)	(0.0014)	(0.0074)	(0.0017)	(0.0015)					
$\mathbf{Insq}_{i,t-1}$						0.937***	0.989***	0.917***	0.964***	0.948***
						(0.0014)	(0.0069)	(0.0035)	(0.0013)	(0.0025)
$Surb_{i,t}$	0.170***					0.393***				
	(0.0026)					(0.0111)				
$Urbanization_{i,t}$		0.0853***					0.0811***			
		(0.0089)					(0.0079)			
$Sanitation_{i,t}$			0.0426***					0.0475***		
			(0.0042)					(0.0029)		
$Water_{i,t}$				0.0961***					0.0142***	
				(0.0015)					(0.0011)	
$Electricity_{i,t}$					0.0538***					0.0219***
					(0.0011)					(0.0093)
Instruments	29	29	29	29	29	29	29	29	29	29
Observations	312	312	312	312	312	312	312	312	312	312
Countries	52	52	52	52	52	52	52	52	52	52
Fisher	1863.63***	1838.68***	1975.75***	1539.96***	1744.85***	1548.71***	1891.23***	1944.31***	1729.14***	1642.54***
Hansen	0.188	0.162	0.223	0.174	0.225	0.191	0.205	0.165	0.198	0.217
AR(1)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AR(2)	0.347	0.814	0.557	0.464	0.582	0.621	0.514	0.463	0.611	0.657

Source: Authors

Note : ***, ** and * significant respectively at the 1%, 5% and 10% thresholds. Standard deviations corrected for heteroscedasticity are in parentheses. **Surb**, Sustainable urbanization**; Insq**, Institutional quality; **Dig**, Digitalization.

Table 6. Total effect of sustainable urbanization on vulnerability to climate change

	Dependent variable : vulnerability to climate change				
	System GMM				
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
Vul $_{i.t-1}$	0.974***	0.972***	0.967***	0.928***	0.923***
	(0.0587)	(0.1071)	(0.0521)	(0.0661)	(0.0294)
Surb $_{i.t}$	**-0.0762*** **				
	(0.0251)				
Urbanization $_{i.t}$		**-0.0131*** **			
		(0.0043)			
Sanitation $_{i.t}$			**-0.0373*** **		
			(0.0051)		
Water $_{i.t}$				**-0.0513*** **	
				(0.0039)	
Electricity $_{i.t}$					**-0.0175*** **
					(0.0066)
Tem $_{i.t}$	0.0011*	0.0016*	0.0023***	0.0007	0.0035***
	(0.0006)	(0.0093)	(0.0007)	(0.0006)	(0.0004)
Pre $_{i.t}$	-0.0072**	-0.0014*	-0.0078***	-0.0155***	-0.0073***
	(0.0039)	(0.0006)	(0.0028)	(0.0027)	(0.0022)
Gdp $_{i.t}$	-0.0024**	-0.0033**	-0.0031*	-0.0041***	-0.0009**
	(0.0011)	(0.0016)	(0.0016)	(0.0014)	(0.0004)
Fdi $_{i.t}$	0.0062*	0.0025***	0.0073***	0.0041*	0.0036**
	(0.0032)	(0.0009)	(0.0023)	(0.0025)	(0.0015)
Pop $_{i.t}$	0.0008*	0.0032*	0.0005**	0.0019***	0.0006*
	(0.0004)	(0.0017)	(0.0002)	(0.0003)	(0.0004)
Nr $_{i.t}$	0.0004***	0.0005***	0.0003***	0.0018**	0.0051**
	(0.0001)	(0.0002)	(0.0001)	(0.0007)	(0.0021)
Trade $_{i.t}$	-0.0014***	-0.0008**	-0.0012***	-0.0005*	-0.0008***
	(0.0003)	(0.0003)	(0.0002)	(0.0002)	(0.0002)
Unem $_{i.t}$	0.0017***	0.0017**	0.0023***	0.0022***	0.0003
	(0.0004)	(0.0007)	(0.0003)	(0.0005)	(0.0002)
Fd $_{i.t}$	-0.0004**	-0.0002	-0.0002	-0.0014	-0.0009
	(0.0001)	(0.0001)	(0.0002)	(0.0001)	(0.0001)
Man $_{i.t}$	0.0002	-0.0005	-0.0001	-0.0012***	0.0002
	(0.0002)	(0.0003)	(0.0002)	(0.0003)	(0.0002)
Agri $_{i.t}$	-0.0084***	-0.0041*	-0.0074*	-0.0018****	-0.0091***
	(0.0032)	(0.0019)	(0.0038)	(0.0005)	(0.0033)
χ_{i1} **Insq** $_{i.t}$	-0.175***	-0.0794*	-0.618***	-0.801***	-0.709***
	(0.0446)	(0.0420)	(0.133)	(0.161)	(0.180)
χ_{i2} **Dig** $_{i.t}$	-0.0226*	-0.0475***	-0.180***	-0.412***	-0.0334**
	(0.0121)	(0.0069)	(0.0341)	(0.0495)	(0.0162)
Instruments	32	32	31	32	31
Observations	312	312	312	312	312
Countries	52	52	52	52	52
Fisher	467.80***	188.24***	409.06***	339.74***	775.41***
Hansen (p-value)	0.211	0.189	0.221	0.158	0.166
AR(1) (p-value)	0.044	0.027	0.033	0.019	0.044
AR(2) (p-value)	0.714	0.644	0.409	0.322	0.562

Source: Authors

Note : ***, ** and * significant respectively at the 1%, 5% and 10% thresholds. Standard deviations corrected for heteroscedasticity are in parentheses. The estimates are made on the average data of four years calculated over the period 1996-2019 subdivided into 6 sub-periods to ensure that the temporal dimension of the panel is much smaller than the individual dimension (Roodman, 2009). **Vul**, Vulnerability to climate change; **Surb**, Sustainable urbanization; **Tem**, Temperature; **Pre**, precipitation; **Gdp**, Gross domestic product, **Fdi**, Foreign direct investment, **Pop**, Population, **Nr**, Natural resource, **Unem**, Unemployment, **Fd**, Financial development, **Man**, manufacturing, **Agri**, Agriculture, **Insq**, Institutional quality, **Dig**, Digitalization.

Subsequently, we assess the total effect of sustainable urbanization on vulnerability to climate change, which reveals a positive and significant impact in Africa (Table 6). This means that, all other things being equal, the positive indirect effect of sustainable urbanization in reducing vulnerability to climate change is associated with its direct effect in the same direction. This translates into a greater net total effect due to the joint consideration of direct and indirect effects, which, taken individually, underestimate the effect of sustainable urbanization on climate vulnerability. Indeed, a 1% increase in sustainable urbanization leads to a 7.62% reduction in vulnerability to climate change. In line with the results on the direct effect in Table 1, we can conclude that sustainable urbanization contributes more to reducing vulnerability to climate change. This improved contribution comes from digitalization and institutional quality as channels for transmitting the effect of sustainable urbanization on vulnerability to climate change.

The underlying finding is justified by the fact that by inducing an adoption and development of digitalization, sustainable urbanization will promote resilience to the adverse effects of climate change through this digitalization via artificial intelligence that is tailored to anticipate and cope effectively with the harms of climate change (Argyroudis et al., 2021). It can also reduce vulnerability to climate change by promoting sustainable agriculture by increasing large-scale farming and agricultural productivity through technology transfer in Africa (Balogun et al., 2022). It is further understood in the wake of the demands of the challenge of financing sustainable urban development in Africa, which requires good governance to respond to the fractured fiscal authority, fragmented infrastructure networks, and hybrid service delivery models that characterize African cities (Cirolia, 2020). The same is true for the work of Xiong et al. (2020) who find that achieving sustainable urbanization requires good governance thus leading to the choice of governance structure via public-private partnerships (PPPs) as the governmental response to the latter in order to safeguard public values and improve government efficiency.

In the light of the findings in Tables 1 and 5, we can calculate the contribution of each transmission mechanism to the total indirect effect of sustainable urbanization on vulnerability to climate change with reference to the work of Adams and Fotio (2022) or Zhao et al. (2023). For this purpose, we use the Sobel (1987) product coefficient approach and the corresponding findings are reported in Table 7. The results show that institutional quality explains 94.75% of the positive indirect effect of sustainable urbanization in reducing vulnerability to climate change, followed by digitalization at 4.25%.

Table 7. Indirect transmission channel and their relative contribution

	Dependent variable : vulnerability to climate change									
	$Surb_{i.t}$		**$Urbanization_{i.t}$**		**$Sanitation_{i.t}$**		**$Water_{i.t}$**		**$Electricity_{i.t}$**	
	Coef	Relative contribution	Coef	Relative contribution	Coef	Relative contribution	Coef	Relative contribution	Coef	Relative contribution
Insq	-0.0687	94.75%	-0.0064	61.53%	-0.0293	79.40	-0.0113	22.25%	-0.0155	90.12%
Dig	-0.0038	5.25%	-0.0040	38.47%	-0.0076	20.60%	-0.0395	77.75%	-0.0017	9.88%
Total	-0.0725	100%	-0.0104	100%	-0.0369	100%	-0.0508	100%	-0.0172	100%

Source: Authors' construction. **Surb**, Sustainable urbanization; **Insq**, Institutional quality, **Dig**, Digitalization.

5. Conclusion

This paper empirically analyzes the direct and indirect effects of sustainable urbanization on vulnerability to climate change in a sample of 52 African countries from 1996 to 2019 using the two-stage system GMM approach. The results of the direct analysis support the intuition that sustainable urbanization reduces vulnerability to climate change in Africa. Beyond this direct effect, the results of the indirect analysis also confirm that sustainable urbanization significantly mitigates vulnerability to climate change. This impact is made possible by digitalization and institutional quality. Overall, institutional quality is the main channel that explains 94.75% of the indirect effect of sustainable urbanization on vulnerability to climate change, compared to 5.25% for digitalization. These results show that taking into account the direct analysis alone underestimates the effect of sustainable urbanization on vulnerability to climate change. The coefficients obtained from the total effect analysis by integrating the indirect analysis are thus larger. Our results are robust both to pollution as an alternative measure of vulnerability to climate change as well as to the use of alternative econometric techniques.

In terms of economic policy implications, the development by existing governments of policies that promote access to basic services such as water, electricity and sanitation for the most vulnerable groups in the urbanization process would significantly reduce vulnerability to climate change. Similarly, improving the quality of institutions and digitalization within the region as channels for sustainable urbanization would intensify the contribution of sustainable urbanization to reducing vulnerability to climate change in Africa.

As for future research directions, the study obviously leaves room for further research, particularly with regard to examining complementary policy initiatives that can be used to enhance the impact of sustainable urbanization on vulnerability to climate change, such as the effectiveness of political decentralization. This suggestion is motivated by the fact that the debate on the place of decentralization within African economies that are characterized by poor institutional quality and laxity in the overall fight against the effects of climate change, is becoming more pronounced. Furthermore, reconsidering the analysis in the context of other UN SDGs is useful. In other words, it would be scientifically interesting and politically useful to assess how sustainable urbanization would contribute to the achievement of other SDGs in Africa. Finally, a comparative analysis based on the level of diversification of African economies would also be interesting not least because, African economies are already the most vulnerable, and those with little diversification will be the most at risk, as climate change is a global phenomenon that puts all nations on board the same boat.

References

Abdelzaher, D.M., Martynov, A., Zaher, A.M.A., 2020. Vulnerability to climate change: Are innovative countries in a better position? Research in International Business and Finance 51, 101098.

Acosta-Michlik, L., Espaldon, V., 2008. Assessing vulnerability of selected farming communities in the Philippines based on a behavioural model of agent's adaptation to global environmental change. Global Environmental Change, Local evidence on vulnerabilities and adaptations to global environmental change 18, 554–563. https://doi.org/10.1016/j.gloenvcha.2008.08.006

Adams, S., Kaffo Fotio, H., 2022. Economic integration and environmental quality: accounting for the roles of financial development, industrialization, urbanization and renewable energy. Journal of Environmental Planning and Management 0, 1–26. https://doi.org/10.1080/09640568.2022.2131510

Adams, S., Klobodu, E.K.M., 2017. Urbanization, democracy, bureaucratic quality, and environmental degradation. Journal of Policy Modeling 39, 1035–1051. https://doi.org/10.1016/j.jpolmod.2017.04.006

Adger, W.N., 2006. Vulnerability. Global Environmental Change, Resilience, Vulnerability, and Adaptation: A Cross-Cutting Theme of the International Human Dimensions Programme on Global Environmental Change 16, 268–281. https://doi.org/10.1016/j.gloenvcha.2006.02.006

Ahmadalipour, A., Moradkhani, H., Castelletti, A., Magliocca, N., 2019. Future drought risk in Africa: Integrating vulnerability, climate change, and population growth. Science of The Total Environment 662, 672–686. https://doi.org/10.1016/j.scitotenv.2019.01.278

Alam, G.M., Alam, K., Mushtaq, S., Leal Filho, W., 2018. How do climate change and associated hazards impact on the resilience of riparian rural communities in Bangladesh? Policy implications for livelihood development. Environmental science & policy 84, 7–18.

Arellano, M., Bover, O., 1995. Another look at the instrumental variable estimation of error-components models. Journal of Econometrics 68, 29–51. https://doi.org/10.1016/0304-4076(94)01642-D

Argyroudis, S.A., Mitoulis, S.A., Chatzi, E., Baker, J.W., Brilakis, I., Gkoumas, K., Vousdoukas, M., Hynes, W., Carluccio, S., Keou, O., 2022. Digital technologies can enhance climate resilience of critical infrastructure. Climate Risk Management 35, 100387.

Arshad, A., Ashraf, M., Sundari, R.S., Qamar, H., Wajid, M., Hasan, M., 2020. Vulnerability assessment of urban expansion and modelling green spaces to build heat waves risk resiliency in Karachi. International journal of disaster risk reduction 46, 101468.

Asongu, S.A., Agboola, M.O., Alola, A.A., Bekun, F.V., 2020. The criticality of growth, urbanization, electricity and fossil fuel consumption to environment sustainability in Africa. Science of The Total Environment 712, 136376. https://doi.org/10.1016/j.scitotenv.2019.136376

Bai, X., Dawson, R.J., Ürge-Vorsatz, D., Delgado, G.C., Salisu Barau, A., Dhakal, S., Dodman, D., Leonardsen, L., Masson-Delmotte, V., Roberts, D.C., 2018. Six research priorities for cities and climate change. Nature 555, 23–25.

Baker, S.H., 2016. Mexican Energy Reform, Climate Change, and Energy Justice in Indigenous

Communities. Natural Resources Journal 56, 369–390.
Balogun, A.-L., Adebisi, N., Abubakar, I.R., Dano, U.L., Tella, A., 2022. Digitalization for transformative urbanization, climate change adaptation, and sustainable farming in Africa: trend, opportunities, and challenges. Journal of Integrative Environmental Sciences 19, 17–37. https://doi.org/10.1080/1943815X.2022.2033791
Balogun, A.-L., Marks, D., Sharma, R., Shekhar, H., Balmes, C., Maheng, D., Arshad, A., Salehi, P., 2020. Assessing the Potentials of Digitalization as a Tool for Climate Change Adaptation and Sustainable Development in Urban Centres. Sustainable Cities and Society 53, 101888. https://doi.org/10.1016/j.scs.2019.101888
Birkmann, J., Jamshed, A., McMillan, J.M., Feldmeyer, D., Totin, E., Solecki, W., Ibrahim, Z.Z., Roberts, D., Kerr, R.B., Poertner, H.-O., Pelling, M., Djalante, R., Garschagen, M., Leal Filho, W., Guha-Sapir, D., Alegría, A., 2022. Understanding human vulnerability to climate change: A global perspective on index validation for adaptation planning. Science of The Total Environment 803, 150065. https://doi.org/10.1016/j.scitotenv.2021.150065
Blundell, R., Bond, S., 1998. Initial conditions and moment restrictions in dynamic panel data models. Journal of econometrics 87, 115–143.
Bowler, D.E., Buyung-Ali, L., Knight, T.M., Pullin, A.S., 2010. Urban greening to cool towns and cities: A systematic review of the empirical evidence. Landscape and urban planning 97, 147–155.
Bulkeley, H., 2010. Cities and the governing of climate change. Annual review of environment and resources 35, 229–253.
Buzási, A., Jäger, B.S., Hortay, O., 2022. Mixed approach to assess urban sustainability and resilience – A spatio-temporal perspective. City and Environment Interactions 16, 100088. https://doi.org/10.1016/j.cacint.2022.100088
Candau, F., Regnacq, C., Schlick, J., 2022. Climate change, comparative advantage and the water capability to produce agricultural goods. World Development 158, 105963.
Castells-Quintana, D., Lopez-Uribe, M. del P., McDermott, T.K.J., 2018. Adaptation to climate change: A review through a development economics lens. World Development 104, 183–196. https://doi.org/10.1016/j.worlddev.2017.11.016
Chan, F.K.S., Chan, H.K., 2022. Recent research and challenges in sustainable urbanisation. Resources, Conservation and Recycling 184, 106346. https://doi.org/10.1016/j.resconrec.2022.106346
Chapman, D.A., Lickel, B., Markowitz, E.M., 2017. Reassessing emotion in climate change communication. Nature Climate Change 7, 850–852.
Chen, M., Chen, L., Cheng, J., Yu, J., 2022. Identifying interlinkages between urbanization and Sustainable Development Goals. Geography and Sustainability 3, 339–346. https://doi.org/10.1016/j.geosus.2022.10.001
Chen, M., Xian, Y., Wang, P., Ding, Z., 2021. Climate change and multi-dimensional sustainable urbanization. J. Geogr. Sci. 31, 1328–1348. https://doi.org/10.1007/s11442-021-1895-z
Cheshmehzangi, A., Dawodu, A., 2019. Sustainable Urban Development in the Age of Climate Change, in: Cheshmehzangi, A., Dawodu, A. (Eds.), Sustainable Urban Development in the Age of Climate Change: People: The Cure or Curse. Springer, Singapore, pp. 157–182. https://doi.org/10.1007/978-981-13-1388-2_5
Chudik, A., Pesaran, M.H., 2015. Common correlated effects estimation of heterogeneous dynamic panel data models with weakly exogenous regressors. Journal of econometrics 188, 393–420.
Cirolia, L.R., 2020. Fractured fiscal authority and fragmented infrastructures: Financing sustainable urban development in Sub-Saharan Africa. Habitat International 104,

102233.
Collier, P., Conway, G., Venables, T., 2008. Climate change and Africa. Oxford Review of Economic Policy 24, 337–353.
Collier, P., Venables, A.J., 2017. Urbanization in developing economies: The assessment. Oxford Review of Economic Policy 33, 355–372.
De Jong, M., Joss, S., Schraven, D., Zhan, C., Weijnen, M., 2015. Sustainable–smart–resilient–low carbon–eco–knowledge cities; making sense of a multitude of concepts promoting sustainable urbanization. Journal of Cleaner Production, Special Issue: Toward a Regenerative Sustainability Paradigm for the Built Environment: from vision to reality 109, 25–38. https://doi.org/10.1016/j.jclepro.2015.02.004
Di Clemente, R., Strano, E., Batty, M., 2021. Urbanization and economic complexity. Scientific Reports 11, 1–10.
Enserink, B., Koppenjan, J., 2007. Public participation in China: sustainable urbanization and governance. Management of Environmental Quality: An International Journal.
Fankem, G.G.S., Yeyouomo, K.A., 2023. Conflits et développement financier en Afrique subsaharienne. Revue d'economie politique 47–104.
Garschagen, M., Romero-Lankao, P., 2015. Exploring the relationships between urbanization trends and climate change vulnerability. Climatic Change 133, 37–52. https://doi.org/10.1007/s10584-013-0812-6
Goebel, A., 2007. Sustainable urban development? Low-cost housing challenges in South Africa. Habitat International 31, 291–302. https://doi.org/10.1016/j.habitatint.2007.03.001
Goel, R.K., Vishnoi, S., 2022. Urbanization and sustainable development for inclusiveness using ICTs. Telecommunications Policy, Information Technology and Sustainability in Developing Countries 46, 102311. https://doi.org/10.1016/j.telpol.2022.102311
Grasham, C.F., Korzenevica, M., Charles, K.J., 2019. On considering climate resilience in urban water security: A review of the vulnerability of the urban poor in sub-Saharan Africa. Wiley Interdisciplinary Reviews: Water 6, e1344.
Güneralp, B., Lwasa, S., Masundire, H., Parnell, S., Seto, K.C., 2017. Urbanization in Africa: challenges and opportunities for conservation. Environmental research letters 13, 015002.
Habila, M.A., Ouladsmane, M., Alothman, Z.A., 2023. Chapter 21 - Role of artificial intelligence in environmental sustainability, in: Srivastav, A., Dubey, A., Kumar, A., Kumar Narang, S., Ali Khan, M. (Eds.), Visualization Techniques for Climate Change with Machine Learning and Artificial Intelligence. Elsevier, pp. 449–469. https://doi.org/10.1016/B978-0-323-99714-0.00009-1
He, X., Yan, J., Yang, L.E., Zhou, H., Wu, Y., Wu, S., 2022. The role of government interventions in household climate adaptation on the Tibetan Plateau. Journal of Rural Studies 95, 544–559. https://doi.org/10.1016/j.jrurstud.2022.10.003
Henderson, J.V., Storeygard, A., Deichmann, U., 2017. Has climate change driven urbanization in Africa? Journal of Development Economics 124, 60–82. https://doi.org/10.1016/j.jdeveco.2016.09.001
Hiremath, R.B., Balachandra, P., Kumar, B., Bansode, S.S., Murali, J., 2013. Indicator-based urban sustainability—A review. Energy for sustainable development 17, 555–563.
Hoegh-Guldberg, O., Jacob, D., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A., Djalante, R., Ebi, K., Engelbrecht, F., Guiot, J., 2018. Impacts of 1.5 C global warming on natural and human systems. Global warming of 1.5° C.
Huang, L., Wu, J., Yan, L., 2015. Defining and measuring urban sustainability: a review of indicators. Landscape ecology 30, 1175–1193.
Izah, S.C., Iyiola, A.O., Yarkwan, B., Richard, G., 2023. Chapter 7 - Impact of air quality as a

component of climate change on biodiversity-based ecosystem services, in: Srivastav, A., Dubey, A., Kumar, A., Kumar Narang, S., Ali Khan, M. (Eds.), Visualization Techniques for Climate Change with Machine Learning and Artificial Intelligence. Elsevier, pp. 123–148. https://doi.org/10.1016/B978-0-323-99714-0.00005-4

Jolliffe, I.T., 2002. Principal component analysis for special types of data. Springer.

Kabisch, N., Frantzeskaki, N., Pauleit, S., Naumann, S., Davis, M., Artmann, M., Haase, D., Knapp, S., Korn, H., Stadler, J., Zaunberger, K., Bonn, A., 2016. Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. Ecology and Society 21.

Kagan, S., Hauerwaas, A., Holz, V., Wedler, P., 2018. Culture in sustainable urban development: Practices and policies for spaces of possibility and institutional innovations. City, Culture and Society 13, 32–45. https://doi.org/10.1016/j.ccs.2017.09.005

Kaiser, H.F., 1974. An index of factorial simplicity. psychometrika 39, 31–36.

Katz, R.L., Koutroumpis, P., 2013. Measuring digitization: A growth and welfare multiplier. Technovation 33, 314–319. https://doi.org/10.1016/j.technovation.2013.06.004

Kaur, H., Garg, P., 2019. Urban sustainability assessment tools: A review. Journal of Cleaner Production 210, 146–158. https://doi.org/10.1016/j.jclepro.2018.11.009

Kern, K., Alber, G., 2009. Governing climate change in cities: modes of urban climate governance in multi-level systems, in: The International Conference on Competitive Cities and Climate Change, Milan, Italy, 9-10 October, 2009. pp. 171–196.

Khan, M.K., Trinh, H.H., Khan, I.U., Ullah, S., 2022. Sustainable economic activities, climate change, and carbon risk: an international evidence. Environment, Development and Sustainability 24, 9642–9664.

Khosla, R., Bhardwaj, A., 2019. Urbanization in the time of climate change: Examining the response of Indian cities. Wiley Interdisciplinary Reviews: Climate Change 10, e560.

Kim, S.K., Park, S., 2023. Impacts of renewable energy on climate vulnerability: A global perspective for energy transition in a climate adaptation framework. Science of The Total Environment 859, 160175. https://doi.org/10.1016/j.scitotenv.2022.160175

Koenker, R., Xiao, Z., 2002. Inference on the quantile regression process. Econometrica 70, 1583–1612.

Leal Filho, W., Wall, T., Rui Mucova, S.A., Nagy, G.J., Balogun, A.-L., Luetz, J.M., Ng, A.W., Kovaleva, M., Safiul Azam, F.M., Alves, F., Guevara, Z., Matandirotya, N.R., Skouloudis, A., Tzachor, A., Malakar, K., Gandhi, O., 2022. Deploying artificial intelligence for climate change adaptation. Technological Forecasting and Social Change 180, 121662. https://doi.org/10.1016/j.techfore.2022.121662

Lee, J.H., Phaal, R., Lee, S.-H., 2013. An integrated service-device-technology roadmap for smart city development. Technological Forecasting and Social Change, World problems, Emerging technologies and Creative Enterprise 80, 286–306. https://doi.org/10.1016/j.techfore.2012.09.020

Leichenko, R., 2011. Climate change and urban resilience. Current opinion in environmental sustainability 3, 164–168.

Li, W., Wang, D., Li, H., Liu, S., 2017. Urbanization-induced site condition changes of peri-urban cultivated land in the black soil region of northeast China. Ecological indicators 80, 215–223.

Liu, X., Bae, J., 2018. Urbanization and industrialization impact of CO2 emissions in China. Journal of Cleaner Production 172, 178–186. https://doi.org/10.1016/j.jclepro.2017.10.156

Mabon, L., Shih, W.-Y., 2018. What might ‘just green enough’ urban development mean in the context of climate change adaptation? The case of urban greenspace planning in Taipei

Metropolis, Taiwan. World Development 107, 224–238. https://doi.org/10.1016/j.worlddev.2018.02.035
Maja, M.M., Ayano, S.F., 2021. The Impact of Population Growth on Natural Resources and Farmers' Capacity to Adapt to Climate Change in Low-Income Countries. Earth Syst Environ 5, 271–283. https://doi.org/10.1007/s41748-021-00209-6
Mehta, S., Yadav, K.K., 2016. Planning for a Smart City with a Human Face in Developing India. International Journal of Sustainable Land Use and Urban Planning 3.
Mignamissi, D., Djeufack, A., 2022. Urbanization and CO2 emissions intensity in Africa. Journal of Environmental Planning and Management 65, 1660–1684.
Mitchell, D., Enemark, S., van der Molen, P., 2015. Climate resilient urban development: Why responsible land governance is important. Land Use Policy 48, 190–198. https://doi.org/10.1016/j.landusepol.2015.05.026
Mori, K., Yamashita, T., 2015. Methodological framework of sustainability assessment in City Sustainability Index (CSI): A concept of constraint and maximisation indicators. Habitat International 45, 10–14.
Müller, P., 2021. Impacts of inward FDIs and ICT penetration on the industrialisation of Sub-Saharan African countries. Structural Change and Economic Dynamics 56, 265–279.
Nangombe, S., Zhou, T., Zhang, W., Wu, B., Hu, S., Zou, L., Li, D., 2018. Record-breaking climate extremes in Africa under stabilized 1.5 C and 2 C global warming scenarios. Nature Climate Change 8, 375–380.
Nassary, E.K., Msomba, B.H., Masele, W.E., Ndaki, P.M., Kahangwa, C.A., 2022. Exploring urban green packages as part of Nature-based Solutions for climate change adaptation measures in rapidly growing cities of the Global South. Journal of Environmental Management 310, 114786.
Nathaniel, S.P., Adeleye, N., 2021. Environmental preservation amidst carbon emissions, energy consumption, and urbanization in selected African countries: implication for sustainability. Journal of Cleaner Production 285, 125409.
Nations, U. World Urbanization Prospects: The 2018 Revision; United Nations: New York, NY, USA, 2019; pp. 1–126.
Nitivattananon, V., Srinonil, S., 2019. Enhancing coastal areas governance for sustainable tourism in the context of urbanization and climate change in eastern Thailand. Advances in Climate Change Research 10, 47–58. https://doi.org/10.1016/j.accre.2019.03.003
Nkomo, J.C., Nyong, A.O., Kulindwa, K., 2006. The impacts of climate change in Africa. Final draft submitted to the Stern Review on the Economics of Climate Change 51.
Nwankwo, C.F., Ossai, O.G., Ayadiuno, R.U., Ikeogu, C.C., 2021. Spatial dimension of climate change vulnerability and urbanization relationship in Nigeria. International Journal of Urban Sciences 0, 1–22. https://doi.org/10.1080/12265934.2021.1956365
Obobisa, E.S., Chen, H., Mensah, I.A., 2022. The impact of green technological innovation and institutional quality on CO2 emissions in African countries. Technological Forecasting and Social Change 180, 121670. https://doi.org/10.1016/j.techfore.2022.121670
Ojo, T.O., Baiyegunhi, L.J.S., 2020. Determinants of credit constraints and its impact on the adoption of climate change adaptation strategies among rice farmers in South-West Nigeria. Journal of Economic Structures 9, 1–15.
Omisore, A.G., 2018. Attaining Sustainable Development Goals in sub-Saharan Africa; The need to address environmental challenges. Environmental Development 25, 138–145. https://doi.org/10.1016/j.envdev.2017.09.002
Paglialunga, E., Coveri, A., Zanfei, A., 2022. Climate change and within-country inequality: New evidence from a global perspective. World Development 159, 106030. https://doi.org/10.1016/j.worlddev.2022.106030
Papyrakis, E., Gerlagh, R., 2004. The resource curse hypothesis and its transmission channels.

Journal of Comparative Economics 32, 181–193. https://doi.org/10.1016/j.jce.2003.11.002

Pesaran, M.H., 2006. Estimation and inference in large heterogeneous panels with a multifactor error structure. Econometrica 74, 967–1012.

Pesaran, M.H., 2015. Testing weak cross-sectional dependence in large panels. Econometric reviews 34, 1089–1117.

Raihan, A., Tuspekova, A., 2022. Dynamic impacts of economic growth, energy use, urbanization, agricultural productivity, and forested area on carbon emissions: New insights from Kazakhstan. World Development Sustainability 1, 100019. https://doi.org/10.1016/j.wds.2022.100019

Reid, H., 2016. Ecosystem- and community-based adaptation: learning from community-based natural resource management. Climate and Development 8, 4–9. https://doi.org/10.1080/17565529.2015.1034233

Roodman, D., 2009. How to do xtabond2: An introduction to difference and system GMM in Stata. The stata journal 9, 86–136.

Roy, M., 2009. Planning for sustainable urbanisation in fast growing cities: Mitigation and adaptation issues addressed in Dhaka, Bangladesh. Habitat International, Climate Change and Human Settlements 33, 276–286. https://doi.org/10.1016/j.habitatint.2008.10.022

Sanchez Rodriguez, R., Ürge-Vorsatz, D., Barau, A.S., 2018. Sustainable Development Goals and climate change adaptation in cities. Nature Climate Change 8, 181–183.

Sanderson, E.W., Walston, J., Robinson, J.G., 2018. From bottleneck to breakthrough: Urbanization and the future of biodiversity conservation. Bioscience 68, 412.

Sarkodie, S.A., Strezov, V., 2019. Economic, social and governance adaptation readiness for mitigation of climate change vulnerability: Evidence from 192 countries. Science of the Total Environment 656, 150–164.

Satterthwaite, D., Archer, D., Colenbrander, S., Dodman, D., Hardoy, J., Mitlin, D., Patel, S., 2020. Building resilience to climate change in informal settlements. One Earth 2, 143–156.

Scheffran, J., Marmer, E., Sow, P., 2012. Migration as a contribution to resilience and innovation in climate adaptation: Social networks and co-development in Northwest Africa. Applied Geography, The Health Impacts of Global Climate Change: A Geographic Perspective 33, 119–127. https://doi.org/10.1016/j.apgeog.2011.10.002

Seto, K.C., Shepherd, J.M., 2009. Global urban land-use trends and climate impacts. Current Opinion in Environmental Sustainability 1, 89–95.

Shen, L., Peng, Y., Zhang, X., Wu, Y., 2012. An alternative model for evaluating sustainable urbanization. Cities 29, 32–39. https://doi.org/10.1016/j.cities.2011.06.008

Shen, L., Peng, Y., Zhang, X., Wu, Y., 2012. An alternative model for evaluating sustainable urbanization. Cities 29, 32–39. https://doi.org/10.1016/j.cities.2011.06.008

Siebert, H., 1977. Environmental quality and the gains from trade. Kyklos 30, 657–673.

Smith, L.C., Haddad, L., 2015. Reducing Child Undernutrition: Past Drivers and Priorities for the Post-MDG Era. World Development 68, 180–204. https://doi.org/10.1016/j.worlddev.2014.11.014

Sobel, M.E., 1987. Direct and indirect effects in linear structural equation models. Sociological Methods & Research 16, 155–176.

Sokolov, A.P., Kicklighter, D.W., Melillo, J.M., Felzer, B.S., Schlosser, C.A., Cronin, T.W., 2008. Consequences of considering carbon–nitrogen interactions on the feedbacks between climate and the terrestrial carbon cycle. Journal of Climate 21, 3776–3796.

Srinivasan, V., Seto, K.C., Emerson, R., Gorelick, S.M., 2013. The impact of urbanization on water vulnerability: A coupled human–environment system approach for Chennai,

India. Global Environmental Change 23, 229–239. https://doi.org/10.1016/j.gloenvcha.2012.10.002
Srivastava, R.K., 2020. Urbanization-Led Neo Risks and Vulnerabilities: A New Challenge, in: Srivastava, R.K. (Ed.), Managing Urbanization, Climate Change and Disasters in South Asia, Disaster Studies and Management. Springer, Singapore, pp. 251–296. https://doi.org/10.1007/978-981-15-2410-3_6
Stewart, I.D., Kennedy, C.A., Facchini, A., Mele, R., 2018. The electric city as a solution to sustainable urban development. Journal of Urban Technology 25, 3–20.
Sulemana, I., Nketiah-Amponsah, E., Codjoe, E.A., Andoh, J.A.N., 2019. Urbanization and income inequality in Sub-Saharan Africa. Sustainable cities and society 48, 101544.
Sun, Y., Zou, Y., Jiang, J., Yang, Y., 2023. Climate change risks and financial performance of the electric power sector: Evidence from listed companies in China. Climate Risk Management 39, 100474.
Tonne, C., Adair, L., Adlakha, D., Anguelovski, I., Belesova, K., Berger, M., Brelsford, C., Dadvand, P., Dimitrova, A., Giles-Corti, B., Heinz, A., Mehran, N., Nieuwenhuijsen, M., Pelletier, F., Ranzani, O., Rodenstein, M., Rybski, D., Samavati, S., Satterthwaite, D., Schöndorf, J., Schreckenberg, D., Stollmann, J., Taubenböck, H., Tiwari, G., van Wee, B., Adli, M., 2021. Defining pathways to healthy sustainable urban development. Environment International 146, 106236. https://doi.org/10.1016/j.envint.2020.106236
Tschakert, P., 2007. Views from the vulnerable: Understanding climatic and other stressors in the Sahel. Global Environmental Change 17, 381–396. https://doi.org/10.1016/j.gloenvcha.2006.11.008
Umar, M., Ji, X., Kirikkaleli, D., Xu, Q., 2020. COP21 Roadmap: Do innovation, financial development, and transportation infrastructure matter for environmental sustainability in China? Journal of Environmental Management 271, 111026. https://doi.org/10.1016/j.jenvman.2020.111026
Vargas, N., Magaña, V., 2020. Climatic risk in the Mexico city metropolitan area due to urbanization. Urban Climate 33, 100644.
Verma, P., Raghubanshi, A.S., 2018. Urban sustainability indicators: Challenges and opportunities. Ecological indicators 93, 282–291.
Wamsler, C., Brink, E., Rivera, C., 2013. Planning for climate change in urban areas: from theory to practice. Journal of Cleaner Production, Special Issue: Advancing sustainable urban transformation 50, 68–81. https://doi.org/10.1016/j.jclepro.2012.12.008
Wang, Y., Li, X., Zhang, F., Wang, W., Xiao, R., 2020. Effects of rapid urbanization on ecological functional vulnerability of the land system in Wuhan, China: A flow and stock perspective. Journal of Cleaner Production 248, 119284.
Watson, R.T., Zinyowera, M.C., Moss, R.H., 1998. The regional impacts of climate change: an assessment of vulnerability. Cambridge University Press.
Wei, G., Bi, M., Liu, X., Zhang, Z., He, B.-J., 2023. Investigating the impact of multi-dimensional urbanization and FDI on carbon emissions in the belt and road initiative region: Direct and spillover effects. Journal of Cleaner Production 384, 135608. https://doi.org/10.1016/j.jclepro.2022.135608
Windmeijer, F., 2005. A finite sample correction for the variance of linear efficient two-step GMM estimators. Journal of econometrics 126, 25–51.
Wing, I.S., De Cian, E., Mistry, M.N., 2021. Global vulnerability of crop yields to climate change. Journal of Environmental Economics and Management 109, 102462. https://doi.org/10.1016/j.jeem.2021.102462
World Health Organization., 2009. Summary and policy implications Vision 2030: The resilience of water supply and sanitation in the face of climate change.
World Health Organization., 2016. Health as the pulse of the new urban agenda: United Nations

conference on housing and sustainable urban development, Quito, October 2016.
Xiong, W., Chen, B., Wang, H., Zhu, D., 2020. Public–private partnerships as a governance response to sustainable urbanization: Lessons from China. Habitat International 95, 102095. https://doi.org/10.1016/j.habitatint.2019.102095
Xu, B., Lin, B., 2020. Investigating drivers of CO2 emission in China's heavy industry: A quantile regression analysis. Energy 206, 118159.
Yigitcanlar, T., Dur, F., Dizdaroglu, D., 2015. Towards prosperous sustainable cities: A multiscalar urban sustainability assessment approach. Habitat International 45, 36–46.
You, W., Zhang, Y., Lee, C.-C., 2022. The dynamic impact of economic growth and economic complexity on CO2 emissions: An advanced panel data estimation. Economic Analysis and Policy 73, 112–128. https://doi.org/10.1016/j.eap.2021.11.004
Zaehle, S., Dalmonech, D., 2011. Carbon–nitrogen interactions on land at global scales: current understanding in modelling climate biosphere feedbacks. Current Opinion in Environmental Sustainability 3, 311–320.
Zakari, A., Taghizadeh-Hesary, F., Tawiah, V., Alvarado, R., Li, G., 2022. The impact of environmental cleanliness and cultural factors on child health in Africa. Environ Sci Pollut Res 29, 59619–59632. https://doi.org/10.1007/s11356-022-20016-4
Zerbo, A., Delgado, R.C., González, P.A., 2020. Vulnerability and everyday health risks of urban informal settlements in Sub-Saharan Africa. Global Health Journal 4, 46–50.
Zhao, Y., Song, Z., Chen, J., Dai, W., 2023. The mediating effect of urbanisation on digital technology policy and economic development: Evidence from China. Journal of Innovation & Knowledge 8, 100318. https://doi.org/10.1016/j.jik.2023.100318

Appendix

Table A1 PCA result for the construction of sustainable urbanization and digitalization index

PC	Initial Eigen values			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
Sustainable urbanization						
Urbanization	2.823	70.580	70.580	2.823	70.580	70.580
Sanitation	0.558	13.964	84.545	0.558	13.964	84.545
Water	0.428	10.710	95.255			
Electricity	0.189	4.744	100.000			
Digitalization						
Internet	2.080	69.338	69.338	2.080	69.338	69.338
Fixed telephone	0.718	23.932	93.270	0.718	23.932	93.270
Mobile phone	0.202	6.30	100.000			

Source: Authors construction. PC: Principal component.

Table A2 Results of Bartlett's test and KMO sampling adequacy

Bartlett's test of sphericity		
	Sustainable urbanization	Digitalization
Chi-Square (observed value)	2580.850	1492.874
Chi-Square (critical value)	12.592	7.815
Df	6	3
P-value	< 0.0001	< 0.0001
Alpha	0.05	0.05
Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy		
KMO	0.750	0.594

Source: Authors' construction

Table A3 Description of variables

Variables	Description	Sources
Vul	Vulnerability to climate change. It is about the propensity or predisposition of human societies to suffer the negative effects in the event of climatic shocks. This variable varies between "0 and 100."	Global Adaptation Index (2021)
Surb	This variable represents sustainable urbanization measured by an index of calculated through a principal component approach based on urbanization, sanitation, water and electricity.	PCA/ WDI
Urbanization	It refers to percentage of people living in urban areas compared to percentage of total population	WDI
Electricity	It's the percentage of population with access to electricity	WDI
Water	The percentage of people using at least basic drinking water services measured as percentage of total population	WDI
Sanitation	The percentage of people using at least basic sanitation services measured as percentage of total population	WDI
CO2	It refers to pollution measured by CO2 emissions in kiloton (kt) from the annual burning of fossil fuels and the manufacture of cement taken in natural logarithm (ln).	WDI
Fdi	Net inflows of foreign direct investment. They are measured as a percentage of GDP.	WDI
Gdp	Gross domestic product expressed in current dollars taken in natural logarithm (ln).	WDI
Man	Manufacturing refers to the value added of industries.	WDI
Tem	These are the average annual temperature measurements for each country, given in centigrade taken in natural logarithm (ln).	IPCC data base
Pre	These are the average annual precipitation measurements for each country, given in millimeters taken in natural logarithm (ln).	IPCC data base
Trade	Trade openness measured by the share of the sum of merchandise exports and imports in GDP taken in natural logarithm (ln).	WDI
Unem	Unemployment rate. It is calculated as a percentage of the total labor force.	WDI
Insq	Institutional quality. Measured by an index constructed from the sum of six variables, namely: control of corruption, political stability, government effectiveness, rule of law, regulatory quality, and voice and accountability.	Authors' calculation from WGI variables
Nr	It refers to benefit from sum of oil rents, natural gas rents, coal rents (hard and soft), mineral rents, and forest rents, expressed as a percentage of GDP.	WDI
Agri	Net production agricultural index of each product is weighted by average international commodity prices for 2014-16 and summed for each year. The aggregate for a given year, measured in international dollars, is divided by the average aggregate for the base period 2014-16.	FAO
Pop	Population growth rate. It is measured as an annual percentage.	WDI
Fd	Financial development. It is measured by domestic credit granted to the private sector relative to GDP.	WDI
Dig	Digitalization is measured by an index of calculated through a principal component approach based on percentage of individuals using the internet, fixed telephone and mobile phone subscriptions.	PCA/ WDI

Source : Authors

Table A4 Descriptive statistics

Variables	Observations	Mean	Standard deviation	Minimum	Maximum
Vul	1248	0.5330016	0.0734889	0.3788139	0.7069541
CO2	1248	7.920763	1.907954	2.302585	13.01239
Surb	1248	-1.43E-08	1.780561	-3.170919	4.344777
Urbanization	1248	41.82337	17.59901	7.412	89.741
Sanitation	1248	37.3116	26.01524	2.755094	100
Water	1248	63.6949	18.38622	18.08545	99.89152
Electricity	1248	42.13113	29.52303	1.252269	100
Tem	1248	5.686498	0.1795333	4.950885	6.395262
Pre	1248	6.605773	0.9635572	3.11795	8.062716
Gdp	1248	6.925539	1.221618	2.937213	10.04075
Fdi	1248	4.31799	8.969462	-11.19898	161.8238
Pop	1248	2.567857	1.8059	-2.628656	20.88523
Nr	1248	12.56897	14.27241	-2.475175	72.68
Trade	1248	4.569937	2.427877	2.781368	21.46521
Unem	1248	8.96455	7.25532	0.1926568	37.96
Fd	1248	19.2839	16.93017	-0.1490045	106.2603
Man	1248	11.39393	6.599711	0.2326077	49.87942
Agri	1248	44.74842	22.24386	3.190979	80.88847
Insq	1248	-0.6591781	0.6286736	-2.410851	0.8757154
Dig	1248	-1.06E-09	1.439991	-1.316006	6.530483

Source: Authors

Table A5 Effect of sustainable urbanization on vulnerability to climate change, a robustness analysis to endogeneity of control variables

	Dependent variable : vulnerability to climate change				
	System GMM				
	(1)	(2)	(3)	(4)	(5)
Vul $_{i,t-1}$	0.935***	0.927***	0.932***	0.993***	0.903***
	(0.0517)	(0.0417)	(0.0504)	(0.0443)	(0.0716)
Surb$_{i,t-1}$	-0.0076**				
	(0.0038)				
Urbanization$_{i,t-1}$		-0.0016***			
		(0.0006)			
Sanitation$_{i,t-1}$			-0.0008***		
			(0.0001)		
Water$_{i,t-1}$				-0.0003***	
				(0.0001)	
Electricity$_{i,t-1}$					-0.0019**
					(0.0009)
Tem$_{i,t-1}$	0.0492*	0.0092**	0.0068*	0.0037*	0.0119*
	(0.0280)	(0.0038)	(0.0039)	(0.0019)	(0.0072)
Pre$_{i,t-1}$	-0.0056**	-0.0088**	-0.0099**	-0.0107***	-0.0100***
	(0.0025)	(0.0041)	(0.0037)	(0.0041)	(0.0025)
Gdp$_{i,t-1}$	-0.0075***	-0.0055***	-0.0065***	-0.0065**	-0.0025*
	(0.0029)	(0.0018)	(0.0025)	(0.0027)	(0.0015)
Fdi$_{i,t-1}$	0.0167***	0.0129*	0.0173**	0.0144	0.0178***
	(0.0049)	(0.0077)	(0.0072)	(0.0095)	(0.0069)
Pop$_{i,t-1}$	0.0166***	0.0097**	0.0018**	0.0190**	0.0125
	(0.0025)	(0.0044)	(0.0009)	(0.0077)	(0.0003)
Nr$_{i,t-1}$	0.0036***	0.0002**	0.0005***	0.0077***	0.0032**
	(0.0014)	(0.0001)	(0.0002)	(0.0011)	(0.0012)
Trade$_{i,t-1}$	-0.0149***	-0.0086**	-0.0166***	-0.0019	-0.0046*
	(0.0033)	(0.0037)	(0.0037)	(0.0036)	(0.0027)
Unem$_{i,t-1}$	0.0008**	0.0029***	0.0048	0.0029***	0.0022***
	(0.0004)	(0.0003)	(0.0060)	(0.0006)	(0.0004)
Fd$_{i,t-1}$	-0.0103***	-0.0012	-0.0092***	-0.0020	-0.0083***
	(0.0011)	(0.0013)	(0.0025)	(0.0022)	(0.0014)
Man$_{i,t-1}$	-0.0084*	-0.0102**	-0.0201***	-0.0049	-0.0011***
	(0.0044)	(0.0040)	(0.0041)	(0.0041)	(0.0003)
Agri$_{i,t-1}$	-0.0098**	-0.0093**	-0.0059*	0.0065*	0.0092
	(0.0048)	(0.0045)	(0.0031)	(0.0035)	(0.0069)
Insq$_{i,t-1}$	-0.0276***	-0.0192**	-0.0215**	-0.0365***	-0.0082
	(0.0062)	(0.0086)	(0.0094)	(0.0082)	(0.0053)
Dig$_{i,t-1}$	-0.0027**	-0.0055***	0.0018	-0.0051***	-0.0046*
	(0.0011)	(0.0016)	(0.0012)	(0.0011)	(0.0029)
Instruments	34	34	33	33	34
Observations	312	312	312	312	312
Countries	52	52	52	52	52
Fisher	2037.26	2974.01	8201.57	3235.65	14142.04
Hansen (p-value)	0.203	0.189	0.224	0.331	0.192
AR(1) (p-value)	0.076	0.021	0.052	0.031	0.067
AR(2) (p-value)	0.676	0.502	0.614	0.439	0.453

Source: Authors

Note : ***, ** and * significant respectively at the 1%, 5% and 10% thresholds. Standard deviations corrected for heteroscedasticity are in parentheses. The estimates are made on the average data of four years calculated over the period 1996-2019 subdivided into 6 sub-periods to ensure that the temporal dimension of the panel is much smaller than the individual dimension (Roodman, 2009). **Vul**, Vulnerability to climate change; **Surb**, Sustainable urbanization; **Tem**, Temperature; **Pre**, precipitation; **Gdp**, Gross domestic product, **Fdi**, Foreign direct investment, **Pop**, Population, **Nr**, Natural resource, **Unem**, Unemployment, **Fd**, Financial development, **Man**, manufacturing, **Agri**, Agriculture, **Insq**, Institutional quality, **Dig**, Digitalization.

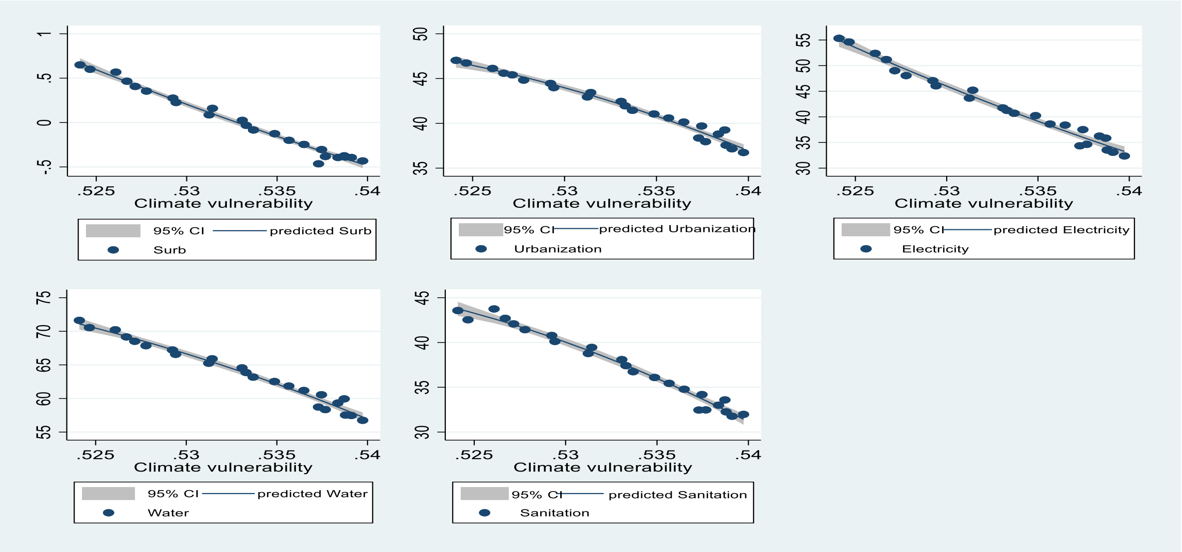
Table A6 Effect of sustainable urbanization on vulnerability to climate change, a robustness analysis to finite-sample covariance matrix Windmeijer correction.

	Dependent variable : vulnerability to climate change				
	System GMM				
	(1)	(2)	(3)	(4)	(5)
Vul $_{i.t-1}$	1.010***	1.004***	0.971***	0.923***	0.991***
	(0.135)	(0.109)	(0.105)	(0.0810)	(0.0827)
Surb$_{i.t}$	-0.0711***				
	(0.0036)				
Urbanization$_{i.t}$		-0.0945***			
		(0.0034)			
Sanitation$_{i.t}$			-0.0513**		
			(0.0242)		
Water$_{i.t}$				-0.0187***	
				(0.0027)	
Electricity$_{i.t}$					-0.0461***
					(0.0151)
Tem$_{i.t}$	0.0428***	0.0347***	0.0189***	0.0646***	0.0257***
	(0.0011)	(0.0021)	(0.0012)	(0.0017)	(0.0013)
Pre$_{i.t}$	-0.0103***	-0.0704***	-0.0365	-0.0124***	-0.0135***
	(0.0061)	(0.0063)	(0.0841)	(0.0057)	(0.0059)
Gdp$_{i.t}$	-0.0714**	-0.0469	-0.0642*	-0.0656**	-0.0720***
	(0.0311)	(0.0319)	(0.0334)	(0.0283)	(0.0226)
Fdi$_{i.t}$	0.0185***	0.0223***	0.0438***	0.0135***	0.0077**
	(0.0033)	(0.0023)	(0.0031)	(0.0032)	(0.0031)
Pop$_{i.t}$	0.0054***	0.0099***	0.0191**	0.0085*	0.0168***
	(0.0019)	(0.0017)	(0.0082)	(0.0054)	(0.0026)
Nr$_{i.t}$	0.0401*	0.0347	0.0205***	0.0162***	0.0119
	(0.0231)	(0.0221)	(0.0021)	(0.0018)	(0.0131)
Trade$_{i.t}$	-0.0553**	-0.0450**	-0.0012	-0.0031**	-0.0044**
	(0.0252)	(0.0212)	(0.0023)	(0.0014)	(0.0021)
Unem$_{i.t}$	0.0137**	0.0139**	0.0071	0.0066	0.0087*
	(0.0066)	(0.0056)	(0.0085)	(0.0082)	(0.0051)
Fd$_{i.t}$	-0.0135***	-0.0095***	-0.0266*	-0.0305*	-0.0042**
	(0.0033)	(0.0021)	(0.0146)	(0.0172)	(0.0018)
Man$_{i.t}$	-0.0196***	-0.0195**	-0.00347***	-0.0027	-0.0502***
	(0.0058)	(0.0079)	(0.0012)	(0.0051)	(0.0093)
Agri$_{i.t}$	-0.0725**	-0.0153*	-0.0047*	-0.0025**	-0.0113
	(0.0301)	(0.0091)	(0.0028)	(0.0012)	(0.0086)
Insq$_{i.t}$	-0.1313***	-0.0517	-0.0179*	-0.1681*	-0.1551***
	(0.0091)	(0.0703)	(0.0110)	(0.0968)	(0.0604)
Dig$_{i.t}$	-0.0029**	-0.0024**	-0.0027*	-0.0038**	-0.0079***
	(0.0012)	(0.0012)	(0.0015)	(0.0015)	(0.0017)
Instruments	27	28	27	27	28
Observations	312	312	312	312	312
Countries	52	52	52	52	52
Fisher	14104.23	5560.41	4333.43	4534.33	6370.51
Hansen (p-value)	0.193	0.173	0.228	0.199	0.207
AR(1) (p-value)	0.027	0.081	0.017	0.011	0.092
AR(2) (p-value)	0.719	0.420	0.641	0.351	0.421

Source: Authors

Note : ***, ** and * significant respectively at the 1%, 5% and 10% thresholds. Standard deviations corrected for heteroscedasticity are in parentheses. The estimates are made on the average data of four years calculated over the period 1996-2019 subdivided into 6 sub-periods to ensure that the temporal dimension of the panel is much smaller than the individual dimension (Roodman, 2009). Windmeijer corrected standard error are taken into account for the values reported in "()". **Vul**, Vulnerability to climate change; **Surb**, Sustainable urbanization; **Tem**, Temperature; **Pre**, precipitation; **Gdp**, Gross domestic product, **Fdi**, Foreign direct investment, **Pop**, Population, **Nr**, Natural resource, **Unem**, Unemployment, **Fd**, Financial development, **Man**, manufacturing, **Agri**, Agriculture, **Insq**, Institutional quality, **Dig**, Digitalization.

Figure A1 Evolution of the relationship between climate vulnerability and sustainable urbanization in Africa from 1996 to 2019.



Source : Authors

Table A7 Correlation matrix.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
(1)Vul	1																			
(2)CO2	0.545***	1																		
(3)Surb	-0.799***	-0.459***	1																	
(4)Urbanization	-0.653***	-0.393***	0.618***	1																
(5)Sanitation	-0.724***	-0.402***	0.935***	0.514***	1															
(6)Water	-0.729***	-0.326***	0.893***	0.619***	0.767***	1														
(7)Electricity	-0.801***	-0.524***	0.917***	0.683***	0.804***	0.831***	1													
(8)Gdp	-0.654***	0.384***	0.739***	0.680***	0.670***	0.703***	0.742***	1												
(9)Tem	0.318***	0.129***	-0.242***	0.143***	-0.315***	-0.126***	-0.114***	-0.0615*	1											
(10)Pre	-0.0935***	-0.310***	-0.299***	-0.0592*	-0.257***	-0.168***	-0.225***	-0.107***	0.0994***	1										
(11)Fdi	0.00637	0.0911**	-0.0258	0.0758**	-0.0223	-0.00981	-0.00812	0.0154	0.0971***	0.0978***	1									
(12)Pop	0.344***	0.0874**	-0.387***	-0.252***	-0.335***	-0.435***	-0.338***	-0.503***	0.139***	0.136***	0.0468	1								
(13)Nr	0.0640*	0.136***	-0.197***	0.0722*	-0.123***	-0.236***	-0.128***	-0.220***	0.197***	0.221***	0.115***	0.571***	1							
(14)Trade	-0.0276	-0.0265	-0.0870**	-0.0908**	-0.0478	-0.131***	-0.0655*	-0.335***	-0.0382	0.0952***	0.0467	0.742***	0.562***	1						
(15)Unem	0.506***	0.256***	0.443***	0.397***	0.395***	0.442***	0.393***	0.515***	-0.249***	-0.247***	-0.0477	-0.344***	-0.0894**	-0.0457	1					
(16)Fd	-0.536***	-0.328***	0.621***	0.249***	0.541***	0.526***	0.566***	0.449***	-0.300***	-0.323***	-0.0546	-0.327***	-0.350***	-0.0358	0.296***	1				
(17)Man	-0.339***	0.218***	0.347***	0.0523	0.343***	0.233***	-0.315***	0.194***	-0.260***	-0.174***	-0.113***	-0.184***	-0.109***	0.00359	0.325***	0.141***	1			
(18)Agri	-0.180***	-0.0595*	0.312***	0.178***	0.316***	0.365***	0.268***	0.319***	-0.109***	0.0758**	0.0618*	-0.0439	-0.0908**	0.152***	0.0532	0.269***	-0.000926	1		
(19)Insq	-0.468***	-0.0800**	0.433***	0.172***	0.349***	0.497***	0.368***	0.369***	-0.238***	-0.0841**	-0.000173	-0.202***	-0.389***	0.0492	0.299***	0.534***	0.0900**	0.208***	1	
(20)Dig	-0.543***	-0.328***	0.714***	0.461***	0.652***	0.680***	0.695***	0.650***	-0.129***	-0.107***	0.0180	-0.289***	-0.179***	-0.0160	0.266***	0.594***	0.0882**	0.467***	0.438***	1

Source: Authors

Table A8 List of countries

Algeria	Cote d'Ivoire	Eswatini	Lesotho	Morocco	Seychelles	Uganda
Angola	Democratic Republic of Congo	Ethiopia	Liberia	Mozambique	Sierra Leone	Zambia
Benin	Djibouti	Gabon	Libya	Namibia	Somalia	Zimbabwe
Botswana	Chad	Gambia	Madagascar	Niger	South Africa	
Burkina Faso	Comoros	Ghana	Malawi	Nigeria	Sudan	
Burundi	Congo	Guinea	Mali	Rwanda	Tanzania	
Cameroon	Egypt	Guinea-Bissau	Mauritania	Sao Tome and Principe	Togo	
Cabo Verde	Erithrea	Kenya	Mauritius	Senegal	Tunisia	

Source: Authors