Exploring the nexus between natural resource depletion, renewable energy use, and environmental degradation in sub-Saharan Africa

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Abstract
This study explores the nexus between natural resource depletion, renewable energy use, and environmental degradation in 48 sub-Saharan African (SSA) countries from the period 2000 to 2020 using generalized panel quantile regression. The findings show that, at 90th quantiles the magnitude of natural resource depletion is positive and stronger associated with environmental degradation in SSA. This is probably attributed by countries with higher natural resource depletion such as Congo Republic (37.10%), Equatorial Guinea (27.60%), Angola (21.14%), Gabon (12.84%), Chad (12.19%), Burundi (8.92%), Uganda (6.16%), and Congo Democratic (5.24%). Furthermore, at lower quantiles (30th and 10th), natural resource depletion negatively affects environmental degradation in SSA. This might be attributed by countries with negligible natural resource depletion like Carbo Verde (0.16%), Central African Republic (0.04%), Comoros (1.17%), Eswatini (0.01%), Gambia (0.92%), Guinea-Bissau (0.33%), and Madagascar (0.07%). Moreover, the findings show that renewable energy use reduces environmental degradation and is statistically significant at almost all quantiles. Finally, the findings reveal that industrialization, trade, and economic growth all contribute to environmental degradation (i.e. carbon emissions) in SSA. The policy implication is to adopt measures that reduce poverty, which is linked to natural resource depletion, and scale up renewable energy use technologies for SSA. Policymakers should develop strategies to reduce carbon dioxide emissions and enable better use of natural resources by enforcing environmental laws. Concurrently, we propose natural resource management to be multi-sectoral and integrated into institutional structures by allocating funds to the natural resources sector for intervention programs in SSA countries.

Keywords Panel quantile regression · Renewable energy · Natural resource depletion

Introduction
Natural resources are the building blocks of life on Earth (we live, produce, survive, and earn from it). Sub-Saharan Africa is endowed with abundant natural resources such as forests, oil and gas reserves, mineral deposits, and water resources. Many people in sub-Saharan Africa depend on natural resources for their livelihood. However, most natural resources (land, air, minerals, wildlife, forests, and water) are degrading at an alarming rate, raising global concerns about their long term and management (Herbst 2020; Gogoi 2013). Natural resources in Africa have been depleted due to abuse and poor management, which has resulted in environmental problems (Aluu 2019). Furthermore, Africa power generation resources have been depleted over the last two decades as a result of deforestation, desertification, land degradation, water scarcity, and climate change (Ochola et al. 2010). This has resulted in increased natural resource scarcity and climate change in some African regions. For example, soil erosion and deforestation decrease the amount of fertile soil available for agricultural production and endanger biological diversity, which could affect climate change. In turn, extreme droughts can hinder people’s ability to raise livestock and grow food crops. That means farmers and pastoralists must adapt to new water regimes in order to maintain...
their livelihoods and well-being (Kabede et al., 2011). Similarly, natural resources are currently under threat from ever-increasing population and economic needs, as well as urbanization, trade, and industrialization, all of which pollute the environment (Byaro et al., 2022; Opuala et al., 2022).

Even though sub-Saharan Africa has suffered greatly as a result of environmental degradation, some environmental sustainability reforms that have been implemented are ineffective and irrelevant due to outbreak of corona virus, energy poverty, economic policy uncertainty, and pastoral land tenure conflicts (See Anser et al., 2021; Adedoyin et al., 2021; Basupiet et al. 2017). In the modern world, human activities (such as urbanization, industrialization, population growth, deforestation) and natural causes (such as floods, typhoons, droughts, rising temperatures, fires) are the most important factors that contribute to environmental degradation (Maurya et al. 2020). For instance, as the world becomes more urbanized, rural people are migrating to cities, resulting in the unplanned and rapid expansion of small cities, putting enormous strain on natural resources (Arsisso et al., 2018). Wassie (2020) argued that urbanization has resulted in uncontrolled degradation of land, forest, water, air, and minerals. Similarly, Fenta et al. (2020) claimed that countries in sub-Saharan Africa (SSA) have experienced changes in land cover and land degradation, altering natural ecosystems as a result of human activities. In developing world, increased carbon dioxide emissions, oil spills and flaring, massive deforestation, and land degradation are all major environmental issues (Adedoyin et al., 2021). Furthermore, increased exploration of natural resources, such as agriculture and mining, could result in higher carbon dioxide emissions and environmental damage due to deforestation (Nathaniel et al. 2021). Meanwhile, the use of renewable energy has been more adopted in developed countries compared to sub-Saharan Africa as an attempt to improve environmental quality (Obiakor et al. 2022).

In the light of this background, our study investigates the relationship between natural resource depletion, renewable energy use, and environmental degradation in SSA. The study is useful in providing information to policy makers to formulate and implement pertinent rules and regulations regarding the exploration of natural resources. Similarly, it will act as a guide for African governments in determining how changes in natural resources can affect environmental degradation. It is also significant in the African context because population growth, trade, economic growth, industrialization, deforestation, and depletion of natural resources (i.e. mineral depletion, forest depletion) continue to make a toll as a means of escaping poverty and improving well-being. For example, population growth and human activities such as tree cutting for agriculture and fuel have resulted in the loss of woody vegetation in the Miombo woodlands (Mitchard and Flintrop 2013). Similarly, extraction of minerals and oil in the region has contributed to the faster depletion of natural resources. For instance, mineral depletion (i.e. percentage of gross national income) in sub-Saharan Africa increased from 0.2% in 2000 to 1.9% in 2020 (World Bank Development Indicators, 2021). Furthermore, net forest depletion (i.e. percentage of gross national income) increased from 2% in 2000 to 2.3% in 2016, before falling to 1.6% in 2020 (World Bank Development Indicators, 2021). Therefore, the overall natural resource depletion in SSA increased from 6.3% in 2000 to 11.6% in 2008, before falling to 5.3% in 2020 (World Bank Development Indicators, 2021).

Conversely, Hao (2016) argued that the ongoing development of advanced technologies and methods has enabled the huge extraction of wanted natural resources such as gas, minerals, forests, and land, resulting in environmental degradation to critical levels. In the same argument, Wassie (2020) cautioned that not all natural resource discoveries are harmful to the environment; other technologies, such as the use of renewable energy (i.e. solar and wind), provide a constant flow of energy and appear to be inexhaustible. This suggests that renewable energy technologies support lowering global emissions from the energy sector to achieve low carbon development goal (Fotio et al. 2022). While African countries are increasing their use of renewable energy, it is still hampered by high start-up costs, expertise, and supporting infrastructures, resulting in continued non-renewable energy consumption and further environmental degradation (Adedoyin et al. 2021). This suggests that sub-Saharan Africa relies on carbon-emitting non-renewable energy as their primary source of energy, leading to energy poverty (Adedoyin et al. 2021; Acheampong 2018). Likewise, an increase of economic growth and energy use in the region has lead to greater carbon emissions (Adedoyin et al. 2021). Thus, it is also worth noting that natural resources have the potential to improve environmental quality and accelerate global sustainable development reforms when backed up by proactive economic production (Feleke et al. 2021; Anser et al. 2020).

Our study is also motivated by a number of factors. First, the choice of sub-Saharan Africa (SSA) is due to its vulnerability to climate change and the depletion of its natural resources (Asongu and Odhiambo 2020). For instance, Konya (2016) reported that about 28% of the 924.7 million people who reside in SSA live in areas that have degraded since 1980. Second, the majority of people in SSA are trapped in poverty, reliant on carbon-emitting non-renewable energy (Obiakor et al. 2022; Adedoyin et al. 2021). Third, rising population growth and fast-growing African economies in terms of industrialization, trade, and high-technology in natural resource extraction can cause environmental problems that need further research. Fourth, with over 1.39 billion people living in Africa (Worldometer...
and many of them engaging in poor farming practices and deforestation, natural resource depletion can lead to environmental degradation. Fifth, as more people in sub-Saharan African (SSA) countries try to alleviate poverty and improve living standards, they may find it more difficult to protect the environment, resulting in environmental degradation. Sixth, governments, decision-makers, researchers, and international organizations have all raised awareness of the urgency of improving environmental quality in order to achieve sustainable development goals (See Obiakor et al. 2022; Adedoyin et al. 2021; Imasiku et al. 2020). Finally, the statistics show that fossil fuels still account for over 80% of total energy consumption (see Goldemberg 2018).

This study seeks to determine whether there is heterogeneity in natural resource depletion and renewable energy use on environmental degradation across 48 sub-Saharan African countries. It aims to contribute to the existing literature in SSA in four ways: First, by exploring the nexus between natural resource depletion, renewable energy use, and environmental degradation using recently updated data from the period 2000 to 2020. Second, our study departs from previous literature (as shown in Table 1) by filling a gap in the African context by employing Powell’s (2020) novel panel quantile regression methods, which control endogeneity of variables and fixed effects in the modeling approach. Unlike previous literature that deployed the ordinary Least Squares (OLS) based on mean estimation (see Table 1), the quantile regression predicts for conditional quantiles based on median and is robust to outliers explaining the heterogeneous effects of independent variables on dependent variable (see Bilgili et al. 2022; Khan et al. 2020; Chen and Lei 2018). Few studies have looked at natural resource depletion as a factor in explaining environmental degradation in developing countries (see Yang et al. 2022; Ali et al. 2021). Therefore, this is the first study to examine the nexus between natural resource depletion, renewable energy use, and environmental degradation in 48 countries in SSA using the panel quantile regression technique for the period from 2000 to 2020. Third, shocks from the corona virus (COVID-19) could have pushed back the environmental sustainability agenda, because many countries have been unable to absorb the virus, which could have serious consequences for the environment and natural resource management.

To achieve our objective, the generalized quantile regression method is used to solve endogeneity (i.e. omitted variable bias, simultaneity bias) of variables using an instrumental variables approach (see Opoku and Aluko 2021; Powell 2020). Furthermore, we apply the generalized panel quantile regression since the 48 countries selected in SSA differ substantially in terms of natural resource depletion, renewable energy use, and environmental degradation.

This study aims to address the following question: Does natural resource depletion and the use of renewable energy have heterogeneous effect on environmental degradation (i.e. carbon dioxide emission) in sub-Saharan African countries?

The rest of the paper is laid out as follows: the “Literature review” section presents the review of the literature. The methodology is presented in the “Data sources and methodology” section. The results and discussion are presented in the “Results and discussion” section, while the “Conclusion” section concludes the study.

Literature review

Theoretical literature

This study examines the theoretical literature based on the interaction of human activities and the environment. It mainly focuses on theories used to analyze environmental degradation. For instance, neoclassical economists view environmental problems as one of the consequences of the production process (Fardian et al. 2021). From this scenario, environmental economics emerges as a response to externalities that arise as a result of economic activity (Hussen 2004). On the other hand, Kuznets (1955) developed the Environmental Kuznet Curve (EKC), which states that economic growth first moves parabolically upward until it reaches its highest point before decreasing, described by an inverted U-shaped curve which connects economic growth and environmental problems. This implies that environmental problems are linked to the stages of human economic development. After that, pollutants like carbon dioxide emissions and others were formulated to be the cause of environmental damage that linked emissions and income (Grossman and Krueger 2002). In this view, several factors that contribute to environmental damage were considered. For example, economic activity, depletion of natural resources used in the production process, industrialization, trade, urbanization, and financial development were linked to GDP (see Byaro et al. 2022; Opuala et al. 2022; Ozturk and Ullah 2022; Uche and Effiom 2021). Overall, all human activities interact with the environment to cause environmental degradation, which in turn causes climate change and global warming (Fardian et al. 2021).

Empirical literature review

As shown in Table 1, previous literatures have been identified on the nexus between natural resource depletion, renewable energy use, and environmental degradation in both developing and developed countries.

Environmental degradation has been a hot topic in terms of sustainable development goals. Many studies, such as Dagar et al. (2022), Usman et al. (2022), Ali et al. (2021), Tenaw and Beyene (2021), and Yahaya et al. (2020), have well captured the essence of environmental degradation in
| Author(s)          | Period        | Country                              | Variables                                                                 | Method                                      | Findings                                                                 |
|-------------------|---------------|--------------------------------------|---------------------------------------------------------------------------|---------------------------------------------|--------------------------------------------------------------------------|
| Ali et al. (2021) | 1990–2014     | Developing and developed              | Environmental degradation(co2), natural resource depletion, urbanization,   | Panel least square method                   | Natural resource depletion has insignificant results on environmental     |
|                   |               |                                      | economic growth, renewable energy consumption, trade                       |                                             | degradation. Renewable energy consumption has a negative and significant  |
| Dagar et al. (2022)| 1995–2019     | 38 OECD countries                    | Financial development, natural resources, industrial production, total      | System dynamic panel data model             | Energy consumption and natural                                          |
|                   |               |                                      | reserve, renewable energy consumption, environmental degradation           |                                             | resources reduces environmental degradation                                |
| Usman et al. (2022)| 1990–2018     | Financial resource rich-countries    | Financial development, natural resources, globalization, non-renewable,    | Second generation panel data               | Renewable energy uses with natural                                      |
|                   |               |                                      | ecological footprint, urbanization, income, natural resource rent           |                                             | resources reduce environmental deterioration                               |
| Opuala et al. (2022)| 1980–2017     | West Africa                          | Ecological footprint, energy consumption, trade openness, urbanization,     | Panel PMG estimator,                       | Natural resource rent does not contribute to environmental quality        |
|                   |               |                                      | income, natural resource rent                                             |                                             |                                                                          |
| Abbasi et al. (2022)| 1990–2019     | Pakistan                             | Globalization, technological innovation, financial development, energy use,| Dynamic autoregressive (ARDL) model        | The increase of renewable energy reduces consumption-based territory      |
|                   |               |                                      | consumption, territories based emissions                                  |                                             | emissions                                                                 |
| Awan et al. (2022) | 1996–2015     | 10 emerging countries               | Renewable energy, foreign direct investment, urbanization, internet use    | Method of Moment Quantile regression       | Internet use and renewable energy mitigates carbon dioxide emissions      |
| Gyamfi et al. (2022) | 2000–2018     | G-7 economies                        | Total natural resources, renewable energy consumption, carbon dioxide      | Quantile regression, full modified         | Total natural resources rent increases pollution at all quantiles.        |
|                   |               |                                      | emission, clean energy consumption, income levels,                         | ordinary least square (FMOLS), Mean        | Revenues gained from natural resources should be invested into clean       |
|                   |               |                                      |                                                                         | Group, Dynamic ordinary Least square (DOLS)| energy use                                                                  |
| Nathaniel et al. (2021) | 1990–2017     | Latin America and Caribbean Countries | Natural resources, carbon dioxide emissions, globalization, urbanization,   | Augmented Mean Group (AMG), Common        | Natural resources lead to the increase of carbon dioxide emission. Human   |
|                   |               |                                      | human capital, economic growth                                             | correlated effects mean group (CCEMG)      | capital mitigates its effects                                             |
| Aziz et al. (2021) | 1995–2018     | MINT countries                       | Carbon dioxide emissions, globalization, foreign direct investment,        | Method of Moment Quantile Regression       | Natural resources increase carbon dioxide emissions at lower quantile,     |
|                   |               |                                      | energy consumption,                                                          |                                             | renewable energy reduces carbon dioxide at the low half quantiles         |
| Tenaw and Beyene (2021) | 1990–2015     | Sub-Saharan Africa                   | Environmental sustainability                                              | Panel ARDL Modified EKC U-test             | Economic development can be seen as a solution to environmental degradation|
### Table 1 (continued)

| Author(s)                        | Period       | Country                               | Variables                                                                 | Method                                             | Findings                                                                 |
|---------------------------------|--------------|---------------------------------------|---------------------------------------------------------------------------|----------------------------------------------------|--------------------------------------------------------------------------|
| AlKhars et al. (2021)           | 2010–2020    | Gulf Cooperation Council (GCC) countries | Environmental Kuznets Curve (EKC)                                        | Econometric methodology, EKC Logistic regression  | Economic growth does not increase carbon dioxide emission in developed world |
| Ahmad et al. (2021a, b)         | 1997–2016    | 31 Chinese provinces                 | urban concentration, non-renewable energy use intensity, economic development, and environmental emissions index | Augmented mean group method (AMG) Dumitrescu-Hurlin causality | Positive relationship exists between the economic development and urban emission concentration |
| Agboola et al. (2021)           | 1971–2016    | Saudi Arabia                          | Environmental sustainability Oil price Carbon reduction Total natural resources rent | Modified Wald test of Toda-Yamamoto methodology Pesaran Bounds test Regression | Significant relationship exists between energy consumption and CO₂ emission |
| Jabeen et al. (2021)            | China’s 27 provincial |                                    | Population, Affluence, and Technology economic development-carbon emissions | Cross-sectional dependence, slope heterogeneity, panel vector error-correction | Significant link between IFDI (in power and non-power sector) carbon emissions and economic development |
| Ahmad et al. (2019)             | 1997–2016    | 29 Chinese provinces                 | economic development-carbon emissions, finance, trade                     | augmented growth model                             | financial development increases energy consumption and carbon emissions, while stock market–mitigated the carbon emissions |
| Al-Mulali and Sab (2012)        | 1980–2008    | 19 different countries base on GDP   | Energy consumption CO₂ emission Economic development Financial development | Panel data analysis                               | Energy consumption enables countries to achieve high economic and financial development. However, increased the CO₂ emission |
| Santana et al. (2022)           | 2000–2015    | 32 OECD countries                    | Income growth Energy consumption Energy governance                        | Composite index Panel data analysis               | Economic growth may lead towards energy efficiency improvements in the latter |
| Abdul-Salam et al. (2022)       | 2021         | UK                                    | Carbon Emissions Net zero Petroleum Energy transition                      | Panel data analysis                               | Low competitiveness in oil decreases CO₂ emission yet affects social and economic welfare |
| Wang et al. (2022)              | 1996–2015    | 135 countries                         | Threshold model Ecological footprint Nonlinear effects Urbanization         | Panel data                                        | Urbanization influencecorrelation between the economy, carbon emissions, and ecological foot-print |
| Verbong and Loorbach, (2012)    | -            | global                                | Energy transition, carbon emission, development                            | Literature review                                  | Energy transition requires co evolve markets, networks, institutions, technologies, and policies |
| Hartley et al. (2019)           | 2018         | Global South                          | Technology, renewable energy, innovation                                  | Retrospective analysis                            | Low and high technology innovators are likely to face struggles on renewable energy engagement |
| Author(s)            | Period       | Country                          | Variables                                                                 | Method                                                                 | Findings                                                                 |
|----------------------|--------------|----------------------------------|---------------------------------------------------------------------------|-------------------------------------------------------------------------|--------------------------------------------------------------------------|
| Park (2016)          | -            | Sub-Saharan Africa               | Development, clean energy entrepreneurship                                | Empirical review                                                       | Clean energy entrepreneurship can address energy poverty and sustainable business model |
| Correljé et al. (2015)| 2014         | Global                           | Value sensitive designs, energy projects, stakeholders’ engagement, institutional designs | Literature review                                                      | Energy consumption can be extended beyond the technology, when values are integrated in institutional context to prevent conflicting values |
| Kunze & Becker (2015)| 2013         | Global                           | Renewable energy, growth, community                                       | Empirical review                                                       | CPE can potentially become blueprints for a turn towards growth practice to enhance the renewable energy production |
| Yahaya et al. (2020)  | 2000–2014    | Eight Sub-Saharan African countries | Environmental degradation, financial development, trade, corruption       | Pedroni cointegration and fully modified ordinary least squares (FMOLS) techniques for the estimation of the models | Financial development with corruption are significant determinants of level of environmental degradation |
| Weiskel and Gray (1990)| -            | Africa                           | Economic underdevelopment, ecological decline, colonialism                 | Empirical review                                                       | Economic underdevelopment and ecological decline are mutually linked |
| Asiedu et al. (2022)  | 2005–2020    | 41 Africa countries              | Finance, energy consumption, income inequality, carbon emissions, poverty headcount | Two steps systems GMM estimator, Atkinson coefficient, Gini index, and the Palma ratio | Access to finance (financial development) lead to capita energy consumption, which has a negative impact on CO2 emissions |
| Van Cam Thi and Le (2022)| 1990–2019   | Vietnam                          | Growth, renewable energy, non-renewable energy, carbon dioxide emissions    | Autoregressive Distributed Lag (ARDL)                                  | Non-renewable energy consumption increases per capita income, but CO2 emissions reduce per capita income |
| Danmaraya et al. (2021)| 1970–2019   | OPEC member countries            | Carbon emission, oil production                                           | Nonlinear panel ARDL–PMG                                               | Economic growth has a positive relationship with CO2 emissions          |
| Kwakwa (2021)        | 2020         | Ghana                            | Carbon emissions, electricity, environment                                | Autoregressive distributed lag (ARDL) and (FMOLS)                      | Industrialization and financial development increases CO2 emissions     |
| Rahman (2020)        | 1971–2011    | India                            | Environment, carbon dioxide emissions, international trade                 | Granger causality test                                                 | Economic growth and population density have positive effects on energy consumption |
| Xing and Zhang (2021) | 2011–2017    | China                            | Environmental pollution, financial investment,                                | Mediator model                                                        | Over-investment of companies increases environmental pollution           |
| Alshubiri and Elheddad (2019) | 1990 to 2015 | OECD countries                    | Economic growth, carbon dioxide emissions, foreign finance                 | Generalized method of moments (GMM) with fixed effects-instrumental variables (FE-IV) and diagnostic tests | Foreign finance and environmental quality contribute significantly to CO2 emissions |
| Author(s)                          | Period       | Country         | Variables                                                                 | Method                                                                 | Findings                                                                 |
|----------------------------------|--------------|-----------------|---------------------------------------------------------------------------|-------------------------------------------------------------------------|--------------------------------------------------------------------------|
| Ibrahiem and Hanafy (2020)       | 1971 to 2014 | Egypt           | Ecological footprints, economic growth, globalization, and energy consumption | ordinary least squares (FMOLS) and dynamic ordinary least squares (DOLS) | Income and fossil fuel consumption cause environmental deterioration, while globalization and population mitigate it |
| Imasiku et al. (2020)            | -            | Sub-Saharan Africa | Economic activity; sustainability; energy efficiency; green growth; economic growth; ecology; environmental degradation; | Case studies, empirical review                                           | Utilization of renewable energies is key to a stable energy supply, economic development, and environmental protection |
| Basupi et al. (2017)             | 1990–2017    | Botswana        | communal rangelands; property rights; environmental impacts; policy implementation; dry lands | Empirical review                                                        | Land productivity declines, implementation challenges, inequality, social conflicts, and a lack of adaptive capacity all pose challenges to environmental sustainability goals |
| Feleke et al. (2021)             | -            | Sub-Saharan Africa | circular bio economy; sustainability                                      | Outcome tracking; Gap analysis;                                          | Circular bioeconomy reduce land degradation and carbon emission          |
| Mitchard and Flintrop, (2013)    | 1982–2006    | Sub-Saharan Africa | deforestation, savanna, woody encroachment                                | Time series from the Global Inventory Modeling and Mapping Studies (GIMMS) dataset | Population growth has resulted in significant woody encroachment         |
| This study                       | 2000–2020    | 48 sub-Saharan Africa | Natural resource depletion, renewable energy use, economic growth, carbon dioxide emissions | Quantile regression developed by Powell (2020)                           | Natural resource depletion increases environmental degradation, renewable resources reduce environmental degradation in sub-Saharan Africa |
various parts of the world, including developing countries. These studies, on the other hand, did not pay much attention to natural resources, which are the foundation of the environment.

Despite the fact that environmental degradation and natural resource depletion are often used interchangeably and have a similar definition, degradation of a resource signifies a loss of value, whereas depletion signifies exhaustion and extinction. Natural resource depletion receives less attention because it is a long process with compounding effects that are more difficult to grasp intuitively. Usman et al. (2022), Opuala et al. (2022), Gyanfie et al. (2022), Ali et al. (2021), Nathaniel et al. (2021), Aziz et al. (2021), Fenta et al. (2020) are among the studies that have touched on natural resource depletion. The lack of studies linking natural resource depletion and environmental degradation is revealed by the literature review summarized in Table 1. Meanwhile, we take into account renewable energy use and other factors to see if depletion of natural resources is likely to result in further environmental degradation. The literature gap also reveals that no study in SSA has used quantile regression with fixed effects to investigate the relationship between natural resource depletion, renewable energy use, and environmental degradation.

On the other hand, natural resources are essential for the production and use of renewable energy. Studies by Usman et al. (2022), Awan et al. (2022), Ahmad et al. (2021a, b), Moustapha et al. (2021), Imasiku et al. (2020), Hartley et al. (2019), and Kunze and Becker (2015) have looked into renewable energy and its role in reducing carbon dioxide emissions and improving power supply stability. However, many studies did not link natural resources, which are the primary drivers of renewable energy. Although renewable energy is limitless, the depletion of other resources may have an impact on its accessibility, operation, and utilization. In this regard, our study employs Powell (2020) generalized quantile regression to address the limitations of the standard linear regression technique (i.e., ARDL, FMOLS, DOLS, AMG, GMM estimator, DID and PSM approaches). The quantile regression method is based on the assumption that the influence of the explanatory variables varies along the conditional distribution of the dependent variable (Amegavi 2022; Koenker and Bassett 1978).

**Data sources and methodology**

**Data sources**

We used unbalanced panel data to cover 48 sub-Saharan African countries from 2000 to 2020. It was justified because data for a few selected countries was missing in some particular periods. Thus, in the case of missing data, the unbalanced panel still permits the regression estimates without any problem. The dependent variable included environmental degradation (measured as carbon dioxide emissions expressed in tons per capita), while the independent variables were natural resource depletion measured as (adjusted savings % of gross national income) and renewable energy consumption (% of total final energy consumption). The control variables included GDP per capita (in constant 2015 US dollars), industrialization (% of manufactured value added), and trade (% of GDP). All variables were extracted from the World Bank’s Development Indicators (2021). The variables used in this study were also justified in other previous literature (see Byaro et al. 2022; Opuala et al. 2022; Van Cam Thi and Le, 2022; Moustapha et al. 2021; Rahman 2020).

**Model estimation techniques**

We apply the generalized panel quantile regression since the 48 countries selected in SSA differ substantially in terms of natural resource depletion, renewable energy use, and environmental degradation. The main advantage of using quantile regression is its ability to examine heterogeneity and asymmetry of explanatory variables on the conditional location of the dependent variable. This means, the effects of regressors on dependent can be negative or positive across the quantiles. Furthermore, regardless of data distribution (i.e. skewed), outliers and heteroskedasticity are not a serious problem because the method is very robust and computationally intensive (Bilgili et al. 2022). The method does not require the traditional OLS (Ordinary Least Square) assumptions of zero mean, constant variance, and normal distributions to be met (Lin and Xu, 2018). For this study, panel quantile regression is also relevant when some countries have higher and lower rates of natural resource depletion, renewable energy use, and environmental degradation, as it offers flexible results. Lastly, quantile regression enables to control country and time-specific confounders. In identifying different relationships at different points of the dependent variable’s distribution, quantile regression (i.e. median estimates) is more flexible than other regression methods.

We build a quantile regression model as follows:-

\[
Q_{\text{Env degradation}}(\tau|x_{it}) = \beta x_{it} + \mu_{it}
\]  

where \(x_{it}\) represents vector of explanatory variables for each fixed country \(i\) at time \(t\), including natural resource depletion (% of GNI), renewable energy consumption, and other control variables such as trade, industrialization, and economic growth.
\( Q_{\text{Envdegradation}}(\tau | x_i) \) is the \( \tau \)th conditional quantile of environmental degradation (proxied by carbon dioxide emissions) as a linear function of the explanatory variables. \( \beta \) is the coefficient of explanatory variables and \( \mu_i \) is the vector of residuals and \( \tau \) indicate a quantile.

It is clear that the use of a linear regression model tells us the average/mean relationship between the explanatory variables (i.e., natural resource depletion, renewable energy consumption) and the dependent variable (environmental degradation). Their estimation method relies on the dependent variable’s central distribution tendency without integrating for the upper and lower ranges (see Amegavi 2022). This also means that the linear regression estimation method does not take into account countries with higher/lower (natural resource depletion, renewable energy, and environmental degradation) than medium countries. This can cause overestimation or underestimation of regression coefficients (Sarkodie and Strezov 2019), as all data cannot be fitted to reflect reality and distorting some important information (see Amegavi 2022). For this reason, the panel quantile regression approach is used to address the limitations of the standard linear regression technique. The quantile regression method assumes that the independent variables’ impact varies along the dependent variable’s conditional distribution (Amegavi 2022; Koenker and Bassett, 1978). Powell (2020) argued the generalized panel quantile regression to produce consistent estimates in small T panels.

In the estimation process, the panel quantiles divide the data into nine different quantiles (10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th, and 90th) to explore the nexus between natural resource depletion, renewable energy use, and environmental degradation while controlling other covariates such as trade, industrialization, and economic growth. In other words, the panel quantiles show an observation of data into intervals values, whereas the country performance indicates the magnitude at a median for all countries at 50% quantile compared to other countries (Amegavi 2022). Therefore, countries with lower and higher quantiles than the median (50th Quantiles) can be described as having worse or better performance.

Using unbalanced panel data for 48 countries in sub-Saharan African from the period 2000 to 2020 (see appendix 1), the quantile regression with fixed effect was applied to control for unobserved heterogeneity and heterogeneous covariates effects. The role of including fixed effects is to control for unobserved covariates. Then, we adopted Powell’s (2020) generalized quantile (GQR) estimator, which uses regressor’s lags as an instrumental variable to eliminate the endogenous feedback, such as economic growth and trade. This procedure solves the omitted variable bias. According to Powell (2020), the generalized quantile regression is used within an instrumental variable framework for generality and to estimate unconditional quantile treatment effects for both endogenous and exogenous policy variables. Models with non-additive disturbances, which are functions of both unobserved and observed factors, are included in the framework. Finally, the generalized quantile regression model is estimated using adaptive Markov Chain Monte Carlo (MCMC) sampling and numerical optimization (see Opoku and Aluko 2021; Powell 2020).

### Results and discussion

Table 2 shows the summary of descriptive statistics of variables for 48 sub-Saharan African (SSA) countries from the year 2000 to 2020.

The median for carbon dioxide emissions (i.e. environmental degradation) and natural resource depletion in SSA were 0.26 tons per capita and 2.59%, respectively. Likewise, the mean for natural resource depletion and carbon dioxide emissions in the region were 6.11% and 0.95 tons per capita, respectively. The median and mean uses of renewable energy were 77.22% and 65.63%, respectively. Among the countries with high environmental degradation (i.e. carbon dioxide emissions) are South Africa (7.49 tons per capita), Seychelles (6.40 tons per capita), Equatorial Guinea (5.09 tons per capita), Botswana (3.64 tons per capita), Mauritius (3.34 tons per capita), and Gabon (2.17 tons per capita). Countries with high natural resource depletion (% of GNI) include Congo Republic (37.10%), Equatorial Guinea (27.60%),

| Variables                  | \( N \) | Mean  | Median | Skewness | Std Dev | Min  | Max  |
|----------------------------|--------|-------|--------|----------|---------|------|------|
| Co2 emissions (tons per capita) | 912    | 0.95  | 0.26   | 3.26     | 1.85    | 0.1  | 11.67|
| Natural resource depletion (% of GNI) | 899    | 6.11  | 2.59   | 2.86     | 9.50    | 0.1  | 71.29|
| Renewable energy (%)        | 912    | 65.63 | 77.22  | -0.97    | 26.73   | 0.1  | 98.34|
| Industrialization (%)       | 881    | 10.48 | 9.32   | 1.41     | 5.80    | 0.23 | 35.21|
| Trade (%)                   | 885    | 69.73 | 60.62  | 1.27     | 26.73   | 0.78 | 225.02|
| GDP per capita(constant US$ 2015) | 972    | 2120.45 | 1081.92 | 2.64 | 34.76 | 258.62 | 16,438.64|

Source: Authors’ computation (2022).
Angola (21.14%), Gabon (12.84%), Chad (12.19%), Burundi (8.92%), Uganda (6.16%), and Congo Democratic (5.24%). Among the 13 countries in sub-Saharan Africa with high renewable energy use over 80 includes Burundi (85.52%), Cameroon (80.63%), Central African Republic (80.94%), Democratic Republic of Congo (96.69%), Somalia (98.34%), Uganda (90.33%), Ethiopia (89.92%), Guinea Bissau (86.78%), Liberia (87.21%), Madagascar (81.56%), Rwanda (85.69%), Tanzania (83.65%), Zambia (85.10%), and Zimbabwe (81.36%). Countries with lower renewable energy use include Angola (56.78%), Benin (43.97%), Carbo Verde (23%), Equatorial Guinea (4.90%), Lesotho (38.41%), Mauritania (25.13%), Mauritius (9.20%), Namibia (30.32%), Sao Tome (37.84%), Seychelles (1.22%), and South Sudan (0.1%).

Table 3 shows the generalized quantile regression with fixed effects for 48 countries in SSA from the year 2000 to 2020.

The result shows heterogeneous effects of natural resource depletion on environmental degradation (i.e. carbon dioxide emissions) at 10th, 30th, 40th, 50th, and 90th quantiles. At the 10th quantile, resource depletion has a negative impact on environmental degradation, whereas at the 40th quantile, it has a positive impact. This implies that natural resource depletion has a nonlinear relationship with environmental degradation. The magnitude of natural resource depletion is positive and stronger associated with environmental degradation at the 40th quantile. At the 50th quantile, the magnitude of natural resource depletion is positive and stronger associated with environmental degradation compared to median countries quantiles (i.e. 50th quantiles). This is probably attributed by countries with higher natural resource depletion such as Congo Republic (37.10%), Angola (21.14%), Burundi (8.92%), Equatorial Guinea (27.60%), Chad (12.19%), Gabon (12.84%), Uganda (6.16%), and Congo Democratic (5.24%). Furthermore, at 30th and 10th quantiles, natural resource depletion negatively affects environmental degradation in SSA.

On the other hand, the findings show that using renewable energy reduces environmental degradation in the majority of quantiles and is statistically significant at the 20th to 90th quantiles. The findings also reveal that industrialization has nonlinear relationships with environmental degradation. Industrialization increases environmental degradation in SSA at the 20th, 30th, 50th, and 90th quantiles. Furthermore, it reduces environmental degradation at the 60th and 70th quantiles. On the other hand, trade and economic activities (i.e. GDP) in the region continue to increase environmental degradation. This is true across all quantiles and is statistically significant.

Discussion of findings

This study examines the nexus between natural resource depletion, renewable energy, and environmental degradation in 48 countries in sub-Saharan Africa from the period 2000 to 2020. The findings indicate that natural resource depletion increases environmental degradation (i.e. carbon dioxide emissions) at 40th, 50th, and 90th quantiles. At 90th quantiles the magnitude of natural resource depletion is positive and stronger associated with environmental degradation compared to median countries quantiles (i.e. 50th quantiles). This is probably attributed by countries with higher natural resource depletion such as Congo Republic (37.10%), Angola (21.14%), Burundi (8.92%), Equatorial Guinea (27.60%), Chad (12.19%), Gabon (12.84%), Uganda (6.16%), and Congo Democratic (5.24%). Furthermore, at 30th and 10th quantiles, natural resource depletion negatively affects environmental degradation in SSA. This might be attributed by countries with negligible natural resource depletion (% of gross national income) like Carbo Verde (0.16%), Central African Republic (0.04%), Comoros

Table 3 Generalized quantile regression. Dependent variable (CO2 emissions)

| Quantiles | Resoures depletion | Renewable | Industrial | Trade | GDP |
|-----------|--------------------|-----------|------------|-------|-----|
| τ = 0.10  | -0.01*** (0.003)   | 0.13*** (0.009) | 0.02 (0.018) | 0.18*** (0.059) | 1.46*** (0.023) |
| τ = 0.20  | 0.01 (0.006)      | -0.11*** (0.041) | 0.15** (0.011) | 0.31*** (0.091) | 1.19*** (0.071) |
| τ = 0.30  | -0.01*** (0.002)  | -0.04*** (0.004) | 0.05*** (0.006) | 0.23*** (0.021) | 1.24*** (0.011) |
| τ = 0.40  | 0.01*** (0.003)   | -0.40*** (0.059) | -0.04 (0.028) | 0.30*** (0.019) | 1.03*** (0.027) |
| τ = 0.50  | 0.004 *(0.003)    | -0.13*** (0.016) | 0.05*** (0.013) | 0.24*** (0.005) | 1.15*** (0.013) |
| τ = 0.60  | -0.001 (0.004)    | -0.23*** (0.021) | -0.08* (0.048) | 0.38*** (0.013) | 1.11*** (0.036) |
| τ = 0.70  | -0.013 (0.015)    | -0.33*** (0.040) | -0.12** (0.063) | 0.41*** (0.061) | 0.91*** (0.040) |
| τ = 0.80  | -0.056 (0.057)    | -0.72 *** (0.174) | -0.12 (0.189) | 0.42** (0.187) | 0.73*** (0.102) |
| τ = 0.90  | 0.064*** (0.000)  | -0.46*** (0.000) | 0.43*** (0.000) | 0.66*** (0.001) | 0.95*** (0.000) |

Standard errors in parentheses (). The notation *, **, *** show significant at 10%, 5%, and 1% level respectively. Acceptance rate is set at 0.5 for the algorithm. The algorithm performs 1000 draws and burn in of 100 through MCMC diagnostic. Year dummies (time -fixed effects) are included in the regression. All independent variables are lagged by one as instrumental variables.
It is important to note that, as the human population grows and economies develop, more natural resources are being used in different ways. For instance, the struggle of communities to survive and earn enough income to meet their daily needs is a major cause of resource depletion. Weisckel and Gray (1990) support this claim by stating that the more poor and vulnerable people there are, the greater the likelihood of environmental degradation and resource depletion. In sub-Saharan Africa for example, minerals, forests, water, and fertile soils, among other natural resources, are depleted faster than nature can replenish it. During the dry season, most communities degrade more resources such as water and forest than they do during the rainy season, when these resources are plentiful. This suggests that resource utilization varies depending on the season, which could explain the nonlinear relationship between natural resource depletion and environmental degradation in SSA. Ibrahiem and Hanafy (2020) supported this claim that income and fossil fuel consumption deplete resources, and this is especially true in Africa, where most communities rely on natural resource extraction to support their daily lives. Meanwhile, the faster depletion of natural resources will likely have an impact on sub-Saharan Africa’s GDP growth. For instance, as more people rely on natural resources to support their daily lives, natural resource depletion lowers national income and creates a vicious cycle of poverty in the region. Similarly, depletion of natural resources increases carbon dioxide emissions and contributes to global warming.

In Africa, wood still remains the most common fuel. Over 90% of the population in sub-Saharan Africa relies on firewood and charcoal for energy, especially for cooking, and wood fuels account for over 80% of the primary energy supply (https://nextbillion.net 2021). In the USA, for example, wood fuels accounts for only 2% of total energy consumption (https://nextbillion.net 2021). According to these statistics, the use of firewood and charcoal in SSA is heavily influenced by limited technology and poverty (Hartely et al., 2019). Therefore, as Africa’s population is expected to double by 2050, the region will face greater pressure on resource extraction and depletion (Mitchard and Flintrop 2013).

On the other hand, the findings suggest that SSA should adopt renewable energy technologies as a clean source of energy in order to reduce the use of charcoal and firewood. Renewable energy reduces environmental degradation in the majority of quantiles and is statistically significant from 20th to 90th quantiles. Renewable energy has transformed the reduction of carbon dioxide emissions from human activities, which is essential for sustainable development (Abbasi et al. 2022; Imasiku et al. 2020). Our descriptive statistics show that renewable energy is used at an average rate of 65% in sub-Saharan Africa. By increasing the use of renewable energy to at least an average of 85%, the continent will be able to move away from its reliance on wood fuel and charcoal, preserve natural resources while maintaining sustainable development. For instance, countries with high natural resource depletion (% of gross national income, GNI) such as Angola (21.14%), Burundi (8.92%), Chad (12.19%), Congo Republic (37.10%), Equatorial Guinea (27.60%), Gabon (12.84%), Uganda (6.16%), and Congo Democratic (5.24%) should immediately adopt more renewable energy technologies to avoid the prolonged natural resource depletion and environmental degradation. Among the studies claiming that renewable energy can help to reduce environmental degradation include (Usman et al. 2022; Dagar et al. 2022; Abbasi et al. 2022; Awan et al. 2022; Aziz et al. 2021; Imasiku et al. 2020). In addition, some studies show that natural resource depletion is linked to environmental degradation (see Nathaniel et al. 2021; Ali et al. 2021).

On the other hand, industrialization is seen as a path to poverty reduction in most sub-Saharan African countries. Tanzania, Rwanda, and Kenya, for example, have undertaken numerous economic reforms aimed at promoting industrial development. However, while such reforms are good-intentioned, they are linked with the threat of environmental degradation (see Byaro et al. 2022; Kwakwa 2021; Xing and Zhang, 2021). This argument is in line with the findings of our study that industrialization increases environmental degradation (i.e. carbon dioxide emissions) at the 20th, 30th, 50th, and 90th quantiles in sub-Saharan Africa. In similar vein, industrialization reduces environmental degradation at the 60th and 70th quantiles in sub-Saharan Africa. These findings are also supported by Opoku and Aluko (2021) who found that industrialization increases environmental degradation in sub-Saharan Africa at the lower quantiles and reduces it at the upper quantiles. This implies that environmental degradation is minimized when industrialization is effectively implemented with caution and the use of renewable resources. Feleke et al. (2021), Imasiku et al. (2020), and Park (2016) all emphasized the importance of incorporating bioeconomy and renewable energy into existing institutional frameworks.

It is also worth noting that, with globalization, trade is becoming more open, influencing people to engage in productive activities in order to meet market demand and stimulate the economy. The findings show that, across all quantiles (10th to 90th), both trade and economic growth (GDP) contribute to environmental degradation (i.e. carbon dioxide emissions) in sub-Saharan Africa. The struggle to establish and expand industries and trade has resulted in increased GDP in African countries, both of which are detrimental to the environment. This claim is also supported by Byaro et al. (2022) and Yahaya et al. (2021). It is true that in terms of economic development, sub-Saharan Africa continues to lag behind compared to developed countries.
While attempting to eradicate poverty through improved economic growth, trade, and industrialization in SSA, these variables exacerbate environmental degradation. This serves as a reminder that not all that glitters is gold. To achieve long-term development in the region, both consumers and producers involved in trade activities should protect the environment.

The best way to reduce environmental degradation (i.e., carbon dioxide emissions) that cause climate change in sub-Saharan Africa is to reduce poverty, which increases the high consumption of charcoal and firewood through deforestation (i.e., depleting more natural resources). It is also advisable for sub-Saharan African countries to use sustainable agriculture practices (i.e. fewer chemicals) and scale up renewable energy use technologies from the current average of 65% to 90% by 2030. The overall practical implication of our findings is to develop strategies to reduce carbon dioxide emissions and enable better use of natural resources by enforcing environmental laws. Policymakers need to formulate and implement relevant rules and regulations governing the exploration of natural resources.

Conclusion

The objective of the study is to explore the nexus between natural resource depletion, renewable energy, and environmental degradation in 48 sub-Saharan African countries from the year 2000 to 2020. Carbon dioxide emissions (CO2) expressed in metric tons per capita are used as a measure of environmental degradation; the adjusted savings percentage of gross national income is used as a measure of natural resource depletion; and renewable energy consumption is expressed as a percentage of total final energy consumption. The study also included control variables such as GDP per capita to measure economic growth; percentage of manufactured value added as a measure of industrialization; and trade measured as a percentage of GDP. The study fills the gaps in the literature and specifically in sub-Saharan African countries using generalized panel quantile regression developed by Powell (2020).

The findings show heterogeneous effects of natural resource depletion on environmental degradation (i.e. carbon dioxide emissions) at 10th, 30th, 40th, 50th, and 90th quantiles. At 90th quantiles, the magnitude of natural resource depletion is positive and stronger associated with environmental degradation in SSA. This is probably attributed by countries with higher natural resource depletion such as Congo Republic (37.10%), Angola (21.14%), Burundi (8.92%), Equatorial Guinea (27.60%), Chad (12.19%), Gabon (12.84%), Uganda (6.16%), and Congo Democratic (5.24%). Moreover, at 30th and 10th quantiles, natural resource depletion negatively affects environmental degradation in SSA.

This might be attributed by countries with negligible natural resource depletion (% of gross national income) like Cabo Verde (0.16%), Central African Republic (0.04%), Comoros (1.17%), Eswatini (0.01%), Gambia (0.92%), Guinea-Bissau (0.33%), and Madagascar (0.07%). The findings also show that renewable energy reduces environmental degradation in the majority of quantiles and is statistically significant at the 20th to 90th quantiles. This suggests scaling up renewable energy use technologies in SSA from the recent average of 65% to 90% by 2030. Furthermore, the findings reveal that, across all quantiles (10th to 90th), both trade and economic growth (GDP) contribute to environmental degradation (i.e. carbon dioxide emissions) in sub-Saharan Africa. The findings imply that economic development is sustainable and safe with the use of renewable energy in industrial sector.

Addressing environmental sustainability reforms is a practical implication for SSA in order to realize sustainable development goals. Since industrialization, economic growth, trade, and natural resource depletion increase carbon emissions (i.e., environmental degradation), African governments should reduce carbon dioxide emissions by implementing carbon-efficient technologies. This suggests investing in clean energy production and technologies is crucial in the region. SSA should increase its use of renewable energy technologies from its current average of 65% to 90% by 2030. To make these technologies available across the continent, both local and international funding are required to ensure the region’s environmental sustainability agenda. Similar to this, other taxes should be charged for pollution-producing activities like mining and industrial waste.

As population growth in SSA continues to rise, the demand for more natural resources will increase, resulting in more resource depletion. Therefore, governments should encourage their citizens to adopt clean technologies like the use of renewable energy and the recycling of plastics and other materials. Furthermore, natural resources like fossil fuels are used to generate electricity in sub-Saharan African countries. To minimize the depletion of natural resources from fossil fuels, the policy implication is to promote the production of electricity from renewable sources like wind and sunlight. It is also worth noting that forests are rich in natural resources. Therefore, the best way to minimize the depletion of natural resources is to promote sustainable forest management practices. For instance, forest harvesting plans and establishing protected areas.

The other policy implication for SSA countries is to adopt measures that reduce poverty levels, which increase high consumption of charcoal and firewood through deforestation (i.e. depleting more natural resources). Concurrently, we propose the natural resource management to be multi-sectoral and integrated into institutional structures by allocating fund to the natural resources sector for intervention programs in SSA countries.
The current study has some limitations, such as the inability to consider other econometric techniques based on the mean. Despite the fact that our findings are limited to sub-Saharan Africa, they should not be generalized. More research beyond SSA is needed to influence the generalization of the findings. However, the study findings are robust and support other researchers to conduct similar studies in the future using more variables, other environmental metrics, and econometrics techniques to provide more policy options.

Appendix 1: Countries included in the analysis

| S/N | Name of Country       | S/N | Name of Country               |
|-----|-----------------------|-----|-------------------------------|
| 1   | Angola                | 29  | Mauritania                   |
| 2   | Benin                 | 30  | Mauritius                    |
| 3   | Botswana              | 31  | Mozambique                   |
| 4   | Burundi               | 32  | Namibia                      |
| 5   | Cameroon              | 33  | Niger                        |
| 6   | Burkina Faso          | 34  | Nigeria                      |
| 7   | Cabo Verde            | 35  | Rwanda                       |
| 8   | Central African       | 36  | Sao Tome and Principe        |
|     | Republic              |     |                               |
| 9   | Chad                  | 37  | Senegal                      |
| 10  | Comoros               | 38  | Seychelles                   |
| 11  | Congo, Rep            | 39  | Sierra Leone                 |
| 12  | Congo, Dem. Rep       | 40  | Somalia                      |
| 13  | Cote d’Ivoire         | 41  | South Africa                 |
| 14  | Equatorial Guinea     | 42  | Sudan                        |
| 15  | Eritrea               | 43  | South Sudan                  |
| 16  | Eswatini              | 44  | Tanzania                     |
| 17  | Ethiopia              | 45  | Togo                         |
| 18  | Gabon                 | 46  | Zambia                       |
| 19  | Ghana                 | 47  | Uganda                       |
| 20  | Gambia                | 48  | Zimbabwe                     |
| 21  | Guinea                |     |                               |
| 22  | Guinea-Bissau         |     |                               |
| 23  | Kenya                 |     |                               |
| 24  | Lesotho               |     |                               |
| 25  | Liberia               |     |                               |
| 26  | Madagascar            |     |                               |
| 27  | Malawi                |     |                               |

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Author contribution Mwoya Byaro: conceptualization, methodology, software, writing—reviewing and editing. Mwoya Byaro: data curation, writing—original draft preparation. Juvenal Nkonoki: supervision, reviewing and editing. Gemma Mafwolo: writing—original draft preparation, literature review writing, reference checking, reviewing and editing.

Data availability The data was extracted from public available database (World Bank Development Indicators, 2021) Database.

Declarations

Ethics approval and consent to participate The manuscript does not involve human participants. Not applicable.

Consent for publication The manuscript does not contain data from any individuals reported.

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