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Climate-related bilateral official development assistance (ODA) and vulnerability: A comparative study of allocation and effectiveness

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Abstract

Official Development Assistance (ODA) has emerged as a crucial tool for supporting nations worldwide in mitigating and adapting to the impacts of climate change. This study investigates bilateral ODA allocated to climate change mitigation and adaptation from 2002 to 2021. Data from OECD iLibrary and World Risk Reports were analyzed to explore temporal patterns and sectoral distribution of climate-related ODA. Polynomial regression calculated the estimated average annual percentage change (EAAPC) in adaptation-focused ODA and vulnerability. We also evaluated the relationship between adaptation-focused ODA, vulnerability, and GDP per capita between 2011 and 2021. In 2021, Japan, Germany, and France provided 75% of total bilateral ODA dedicated to climate change. From 2002 to 2021, major donors directed substantial portions of climate-related ODA towards infrastructure, energy, water & sanitation, agriculture, and environmental protection. From 2011 to 2021, the highest EAAPC in vulnerability was observed in the Central African Republic (0.62; 95% CI: 0.60 to 0.64), followed by Papua New Guinea (0.57; 0.55 to 0.59), Yemen (0.50; 0.49 to 0.52), and Guinea-Bissau (0.33; 0.32 to 0.34). Despite their high vulnerability, some of these countries received disproportionately less adaptation-focused ODA. The correlation between vulnerability and adaptation-focused ODA revealed a complex regional relationship. Variations in adaptation-focused ODA and vulnerabilities underscore the dynamic relationship between international aid and a nation's intrinsic capacity to address challenges. This investigation highlights the importance of understanding these dynamics and calls for a re-evaluation of aid allocation. Strengthening climate change initiatives within the ODA framework and tailoring aid distribution to the specific needs of recipient nations in

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mitigation and adaptation can enhance its effectiveness, resulting in sustainable and impactful outcomes.

Introduction

In the current global geopolitical landscape, there is heightened attention towards addressing climate change, as evidenced by significant political commitments [1]. The Paris Agreement, which aims to limit global warming to below 2 degrees Celsius (˚C) with efforts to confine it to 1.5˚C, stands as an evidence of global collaboration [1]. Likewise, recent resolutions from the UN Climate Conference of the Parties (COP) meetings, notably the determinations made during COP27 in 2022, have emphasized the enhancement of nationally determined contributions (NDCs). They also dedicated considerable attention to the issues of loss & damage, and financial mobilization for countries most vulnerable to climate change [2, 3]. Additionally, the G7 Hiroshima Summit in 2023 emphasized the integration of climate initiatives with economic benefits and the acceleration of transitions to renewable energy infrastructures [4].

The message from these pivotal political gatherings is clear: the period for effective mitigation and adaptation is constricting, and the need for urgent action is paramount. This urgency is most acute for developing nations that face the immediate repercussions of climate change [5, 6]. Climate finance, primarily comprising bilateral and multilateral public finance along with private finance, plays a critical role in supporting the implementation of mitigation and adaptation measures. Specifically, ODA both bilateral and multilateral, has risen as a key instrument in this global effort [7]. In 2021, bilateral ODA from developed countries constituted 39% of their total climate finance contributions. Of this bilateral ODA, USD 40 billion was specifically allocated to climate-related projects, encompassing both principal and significant objectives [8, 9]. The importance of ODA lies in its potential to not only furnish substantial financial support but also bolster the adaptive and mitigation capacities of these climate-vulnerable nations against the challenges of shifting climatic patterns [10, 11].

Despite these advancements, a critical research gap persists in our understanding of how climate-focused ODA is being allocated in alignment with the specific vulnerabilities and needs of recipient countries. Previous studies have explored the flow of such aid but often lack the analysis of detailed temporal dynamics and the direct correlation between aid distribution and changes in climate vulnerability metrics over time [12]. This oversight is concerning, as a misalignment between the assistance provided and the actual requirements can result in less than optimal resilience for the nations, those are at most risk [13]. Thus, our research seeks to address these deficiencies by providing a detailed analysis of bilateral ODA allocations over time, assessing the alignment of adaptation focused ODA with recipient countries' climate vulnerabilities, and evaluating the impact of these allocations on improving resilience. By offering new insights into the effectiveness of climate-related ODA, which refers to how well adaptation focused ODA is allocated to vulnerable countries, as measured by EAAPC, this study aims to contribute valuable guidance for policymakers to refine global climate and development strategies, enhancing support for the world's most vulnerable communities.

Literature review

ODA is vital for addressing the disproportionate impacts of climate change on vulnerable nations [14–16]. Serving as a primary channel for climate finance, ODA supports mitigation and adaptation efforts in developing countries, enhancing resilience and promoting sustainable development [17]. Despite its significance, challenges persist in aligning ODA with the specific needs of these nations. A substantial gap between pledged climate finance and actual disbursements undermines trust and hampers global collaboration [14–16, 18, 19].

Studies reveal that ODA allocation often does not correspond to recipient countries' vulnerabilities, with donor interests and strategic priorities frequently influencing aid distribution [20–23]. This misalignment reduces the effectiveness of ODA in enhancing resilience [12, 17, 24]. Inadequate institutional capacity and governance challenges in recipient countries further hinder the effective utilization of funds to reduce climate vulnerability [6, 25, 26]. Weak institutions and political instability exacerbate these issues, compromising ODA effectiveness [26, 27].

Integrating climate finance with broader development goals, such as the Sustainable Development Goals (SDGs), can enhance ODA effectiveness by promoting holistic and context-specific approaches [17, 28–30]. Scholars emphasize the importance of policy integration and consideration of local needs to ensure sustainable outcomes [17, 31]. However, donor motivations often prioritize domestic political interests over recipient needs, leading to disparities in aid allocation [22, 32]. This underscores the necessity for donors to prioritize recipient vulnerability to improve ODA efficacy [33, 34].

A lack of detailed temporal analysis exists on how ODA allocations have evolved concerning recipient countries' climate vulnerabilities. Understanding these dynamics is crucial for ensuring aid effectively targets those most in need [6, 35–37]. Assessing the impact of ODA on resilience remains challenging due to governance issues and knowledge gaps, highlighting the need to refine allocation mechanisms to better align with recipient vulnerabilities and capacities [25, 27, 37, 38].

Our study addresses these gaps by analyzing bilateral ODA allocations over time, assessing their alignment with recipient countries' climate vulnerabilities, and evaluating their impact on resilience. By examining temporal and sectoral trends, we aim to identify pathways for more effective ODA alignment with the climate resilience needs of developing nations.

Research questions

1. What patterns can be observed in the sectoral allocation of climate-focused bilateral ODA over time, and how have these allocation trends potentially evolved during the study period?
2. What is the potential relationship between adaptation focused bilateral ODA distribution and recipient countries' climate vulnerability, and what insights might be gained from examining resource allocation patterns to climate-vulnerable nations?

Materials and methods

OECD statistics

In this study, we utilized data on ODA projects administered by the governments of 30 Development Assistance Committee (DAC) countries from 2002 to 2021 with the exception of Lithuania and Estonia that joined the DAC post 2021. Data were sourced from the Organization for Economic Co-operation and Development (OECD) Creditor Reporting System (CRS) database for aid activities targeting global environmental issues [1]. This database provides information on ODA commitment, aid type, and target aid sector for each project and year.

Our research focused exclusively on bilateral ODA commitments that represent aid flow from official (government) sources i.e., donor country directly to the recipient country. Due to the complexity in determining the specific donor countries and their respective sector-wise ODA contributions, we excluded multilateral ODA commitments that are usually pooled from multiple countries and distributed through ODA-eligible multilateral organizations to the recipient countries. The bilateral ODA included in the analysis refers to both committed and disbursed amount between 2002 to 2021. In the OECD's CRS database, financial contributions to projects with the Rio markers for climate change mitigation and/or adaptation were defined as climate-related ODA and were extracted. An ODA project can be assigned one or both of these Rio markers [39]. Unless explicitly mentioned, ODA in this paper refers to climate-related bilateral ODA and is expressed in constant values using 2021 as the base year [40]. This study comprises two main analytical components: the first part analyzes the sectoral and temporal distribution of bilateral climate-related ODA from donor to recipient countries between 2002 and 2021, categorized by project types (adaptation, mitigation, and cross-cutting). The second part focuses specifically on adaptation focused ODA and its relationship with vulnerability in recipient countries. We calculated the Estimated Average EAAPC for both adaptation focused ODA amount and vulnerability scores for all countries from 2011 to 2021. This allowed us to observe how adaptation focused ODA and vulnerability changed over time. Additionally, a correlation analysis was conducted on a regional basis to assess the relationship between adaptation focused ODA and vulnerability, providing insights into the alignment and effectiveness of adaptation aid in different regions.

To evaluate the sector-wise allocation of climate-related ODA, we categorized aid sectors using purpose codes, commonly known as CRS codes, which the OECD employs for aid activity classification. These codes compartmentalize aid activities into broad three-digit sector categories, each further delineated by specific five-digit purpose codes [2]. For this study, we based our sector categorization on the following purpose codes for 20 distinct sectors, drawing from previous research [3]. S4 Table provides the detail related to the 20 distinct sectors and their respective purpose code.

The analysis of climate-related ODA was categorized according to project types defined by the OECD: 1. adaptation projects, 2. cross-cutting projects, and 3. mitigation projects [2, 39]. The ODA projects that are principally assigned to the adaptation measures by the donor nations following the OECD classification are termed as adaptation focused ODA [39]. Adaptation projects directly address immediate climate risks and improve resilience, making them more suitable for assessing short-term correlations with vulnerability indicators [41]. Whereas, mitigation projects are primarily focused on long-term emission reductions, which have an indirect effect on current vulnerability. Starting in 2010, the Rio Marker system was refined to distinctly classify projects into adaptation, mitigation, and cross-cutting categories, allowing for more precise tracking and reporting of climate-related development assistance. This classification improvement highlights the evolution of climate finance frameworks and facilitates a clearer understanding of historical and ongoing adaptation and mitigation efforts.

Detailed categorization of ODA and the definitions are provided elsewhere [39]. ODA allocation stratified by project type, was undertaken following the definitions provided by the OECD [2, 39]. A comprehensive explanation is available in the S1 Text.

We used vulnerability data for each country from the World Risk Reports published between 2011 and 2021 by Bündnis Entwicklung Hilft and the United Nations University–Institute for Environment and Human Security (UNU-EHS) [4]. The World Risk Report is published annually, with the inaugural report released in 2011. These reports offer a thorough analysis of the various risks and vulnerabilities countries globally encounter, especially concerning climate change and natural disasters. The term vulnerability in the World Risk Report comprises the components of susceptibility, lack of coping capacity, and lack of adaptive capacities and relates to social, physical, economic, and environmental factors which make people or systems vulnerable to the impacts of natural hazards and the adverse effects of climate change or other transformation processes. Moreover, the term vulnerability also covers the abilities and capacities of people or systems to cope with and adapt to the negative impacts of natural hazards. In the calculation of vulnerability score each of these three components are given, equal weight [4]. The scores range from 0 (lowest vulnerability) to 100 (highest vulnerability). Details on the vulnerability score calculation can be found in S5 Fig. Based on available data, 116 countries were included in this study. The categorization of countries by region is furnished in S1 Table.

For descriptive statistics, we generated figures illustrating the distribution and temporal shifts in ODA across different countries and regions from 2002 to 2021. Additionally, we employed a comparative analysis using bubble plots and Pearson correlation coefficient analysis to assess the association between climate-related adaptation focused ODA and vulnerability scores from 2011 to 2021. Details of the correlation analysis are provided in the S1 Text.

Statistical analyses

We calculated EAAPC in both vulnerability score and adaptation focused ODA amount using polynomial regression analysis. Polynomial regression is a form of regression analysis wherein the relationship between the independent variable x and the dependent variable y is modelled as an nth-degree polynomial [5, 42]. This type of regression accommodates a nonlinear relationship between the value of the independent variable x and the corresponding conditional mean of the dependent variable y, denoted as E(y|x) [42]. Second degree polynomial regression model was validated by examining the residual curve and standard errors of the coefficients. We fitted two separate polynomial regression models, one with the year as the independent variable and vulnerability score as the dependent variable, and the other with adaptation focused ODA as the dependent variable. We then used the coefficients from these regression equations to estimate changes for each year.

The regression equation is as follows:

$$vulberablity = \beta_0 + \beta_1 \times t + \beta_2 \times t^2 + \epsilon_v$$

$$ODA = \beta_0 + \beta_1 \times t + \beta_2 \times t^2 + \epsilon_o$$

Where time (represented as t) is the independent variable, corresponding to the year. β_1 and β_2 are the regression coefficients, signifying the influence of t and t^2 on the dependent variable vulnerability and adaptation focused ODA. ϵ_v and ϵ_o are the error terms, representing the differences between the observed and predicted values of the dependent variable for each year.

For any given year, the percentage change in predicted adaptation focused ODA or vulnerability form the previous year is calculated using the following formula:

$$Percentage\ change = \frac{Precicted\ value_t - predicted\ value_{t-1}}{predicted\ value_{t-1}} \times 100$$

Finally, the EAAPC over the time period is calculated by the averaging the annual percentage changes:

$$EAAPC = \frac{1}{n-1} \sum_{t=2}^{n} Percentage\ change_t$$

Where n is the total number of years in the period.

To compute the 95% CI for the EAAPC

$$Standard\ error\ (SE) = \frac{\sigma}{n-1}$$

Where σ is the standard deviation of the annual percentage changes.

$$95\%\ CI = EAAPC\ \pm 1.96\ \times SE$$

Where 1.95 is the Z score for a 95% CI.

The use of EAAPC in our study is designed to capture the nuanced dynamics of vulnerability and adaptation focused ODA allocations over time, addressing both immediate and gradual shifts. It helps in identifying the effectiveness of adaptation focused ODA in enhancing a country's adaptive capacity and reducing susceptibility to future climate impacts over an extended period, rather than focusing solely on year-to-year fluctuations. Although a formal hypothesis was not established, the exploratory approach and analytical methods employed enable a comprehensive examination of the multifaceted interactions between ODA and vulnerability. This methodology provides the necessary flexibility to investigate complex, non-linear relationships while upholding a high standard of analytical rigor and robustness [43, 44].

The Pearson correlation coefficient was calculated for each region to assess both immediate and lagged linear associations (using 1-, 2-, and 3-year lags) between adaptation focused bilateral ODA and vulnerability. This approach helped identify whether past ODA allocations have a delayed impact on current vulnerability levels. The detail of statistical analysis is provided in the S1 Text.

Results

Descriptive findings

From 2002 to 2021, there was a significant upward trend in the allocation of bilateral ODA for climate change initiatives (Fig 1). The amount of climate-related ODA allocated in 2002 stood at United States dollar (USD) 1.72 billion, rising to USD 11.53 billion by 2011 and doubling to USD 25.85 billion by 2021. Among the G7 countries, Japan, France, and Germany were the primary donors, together contributing 77.6% of the total ODA for climate change in 2021. Specifically, Japan contributed 35.2%, France 24.0%, and Germany 18.4%. In contrast, the other G7 nations—the US, Canada, the UK, and Italy—had more modest allocations, with contributions of 2.2%, 1.1%, 0.8%, and 0.6% respectively. Outside the G7, South Korea was a significant donor, providing 5.5% of the total climate-related ODA, followed by Australia with 3.7% and Norway with 1.7% (Fig 1).

Examining the recipients of climate-related ODA, South Asia, Southeast Asia, North Africa & the Middle East, and East Africa were primary beneficiaries. Specifically, India, Bangladesh, and Indonesia received significant climate-related ODA between 2002 and 2021. ODA inflow to India surged from USD 830 million in 2010 to USD 6.42 billion in 2018 before decreasing to USD 2.13 billion in 2019. By 2021, India received 16.7% of the total ODA. Bangladesh and Indonesia also witnessed substantial ODA inflows, accounting for 9.2% and 4.2% of the total in 2021, respectively. However, many other nations received smaller ODA amounts, as detailed in S1 Fig.

Fig 2 provides a sectoral allocation breakdown of ODA from each of the 30 DAC member countries between 2002 and 2021. The data reveals varying ODA strategies among the donor countries. The primary sectors receiving significant climate-related ODA from 2002 to 2021 included infrastructure, energy, water & sanitation, agriculture, and environmental protection. ODA from Japan was primarily directed towards infrastructure, energy, and water &

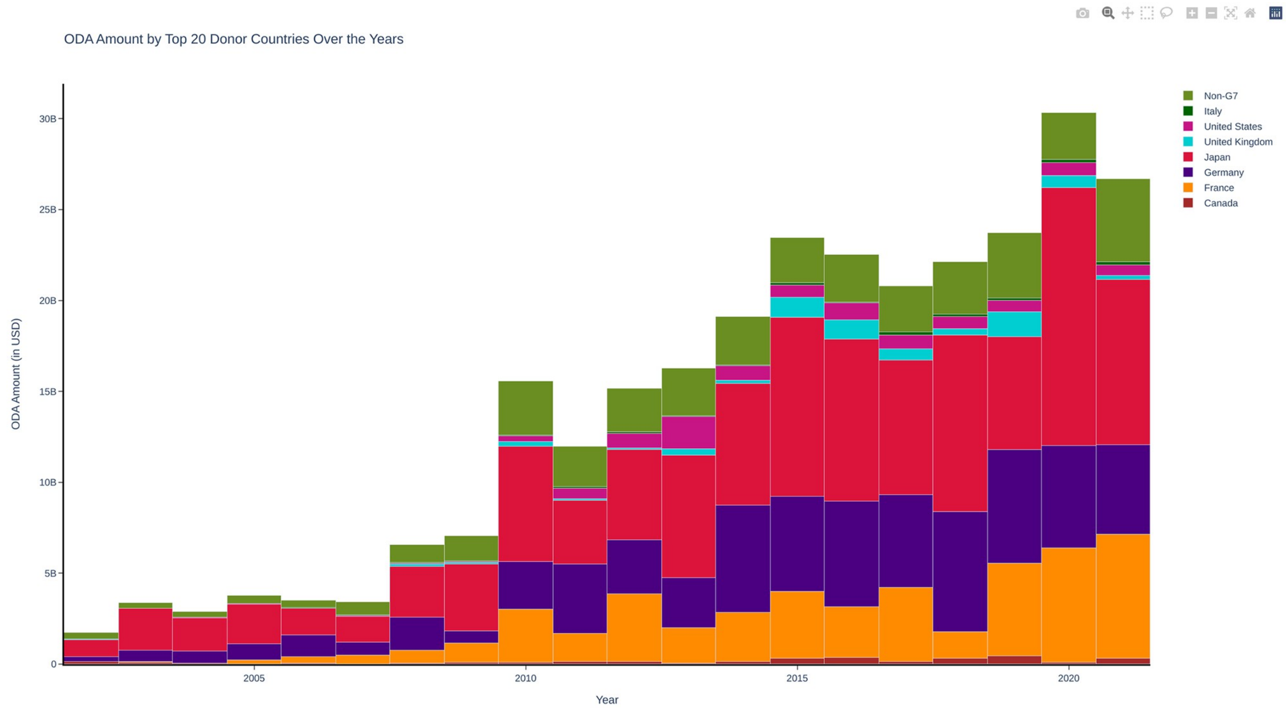

Fig 1. Trend in the allocation of bilateral ODA by G7 and non-G7 countries between 2002 and 2021. The amount shown represents the total sum of bilateral ODA between 2002 and 2021 in USD (billions). Non-G7 nations include: Australia, Austria, Belgium, Czech Republic, Denmark, Finland, Greece, Hungary, Iceland, Ireland, Lithuania, Luxembourg, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, and Switzerland.

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sanitation. In contrast, Germany and France had a more diversified allocation, covering areas like environmental protection and agriculture.

Fig 3 illustrates the flow of bilateral ODA from donor countries to recipient countries in different sectors between 2002 and 2021. ODA from Japan was channeled predominantly to the South Asian and Southeast Asian regions particularly in infrastructure and energy sector. However, other major donor countries had more diverse ODA allocation strategies in terms of sector-wise distribution and the recipients.

Fig 4 illustrates the vulnerability trajectories of the 20 countries most at risk (vulnerability risk measured through the vulnerability score) and the adaptation focused ODA for the top 20 recipients between 2011 and 2021. The size of each bubble represents the adaptation focused ODA amount allocated, with larger bubbles indicating higher amounts. A consistent pattern emerged: a majority of African nations consistently registered high vulnerability scores throughout this period. Notably, Chad, the Central African Republic, Niger, Guinea-Bissau, and Yemen were ranked as the five most vulnerable nations. Despite their persistent high vulnerability, these countries received a disproportionately low amount of adaptation focused ODA during this timeframe. In contrast, the top 20 adaptation focused ODA recipients from 2011 to 2021 exhibited a modest decline in vulnerability scores over the same period.

S2 Fig provides a comprehensive analysis of ODA allocation targeting three different project types: (1) adaptation, (2) cross-cutting, and (3) mitigation. The bubble size represents the ODA amount allocated to each project type, with colors indicating the regions. From 2002 to 2009, ODA was exclusively targeted at mitigation projects. However, from 2010 onward, there was a shift towards adaptation, leading to increased ODA for both adaptation and cross-

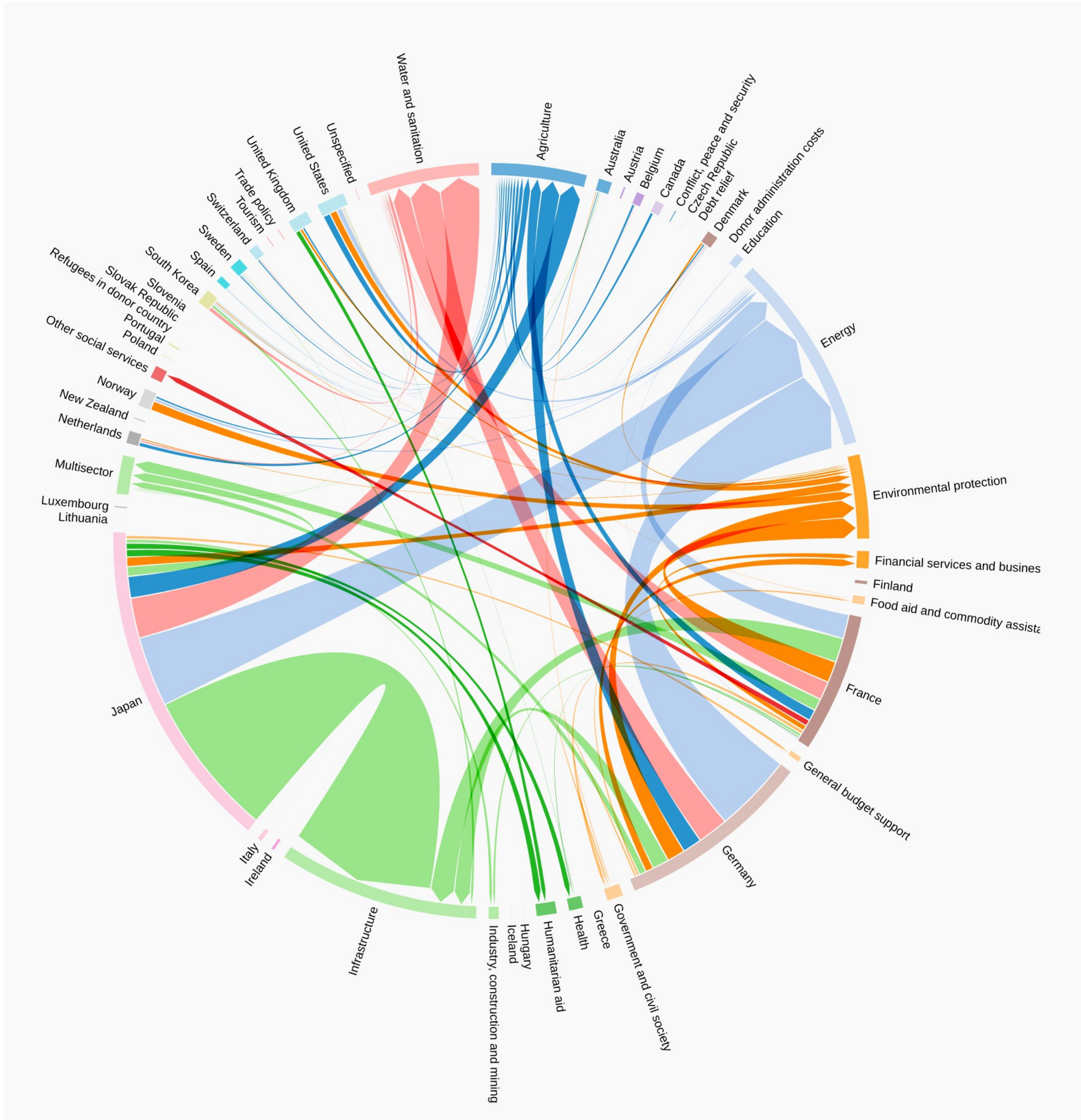

Fig 2. Sectoral allocation of bilateral ODA by donor countries between 2002 and 2021. The amount shown represents the total sum of bilateral ODA between 2002 and 2021.

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cutting projects. In 2021, countries in the Asian region were the main beneficiaries of ODA for both mitigation and adaptation projects, capturing 64.8% and 32.7% of the total allocations, respectively. Meanwhile, African countries received 18.5% of the mitigation-focused ODA and a slightly higher 34.1% for adaptation projects. Oceania received less than 1% of total adaptation focused ODA.

The heatmap in S3 Fig displays ODA amounts received by different regions targeted to various sectors from 2002 to 2021. There was a notable variance in sector-wise ODA allocation across regions. For example, between 2002 and 2021, substantial ODA was directed towards infrastructure development in South Asia (USD 34.7 billion) and Southeast Asia (USD 18.5 billion). ODA allocations to the energy sector were prominent in South Asia (USD 18 billion),

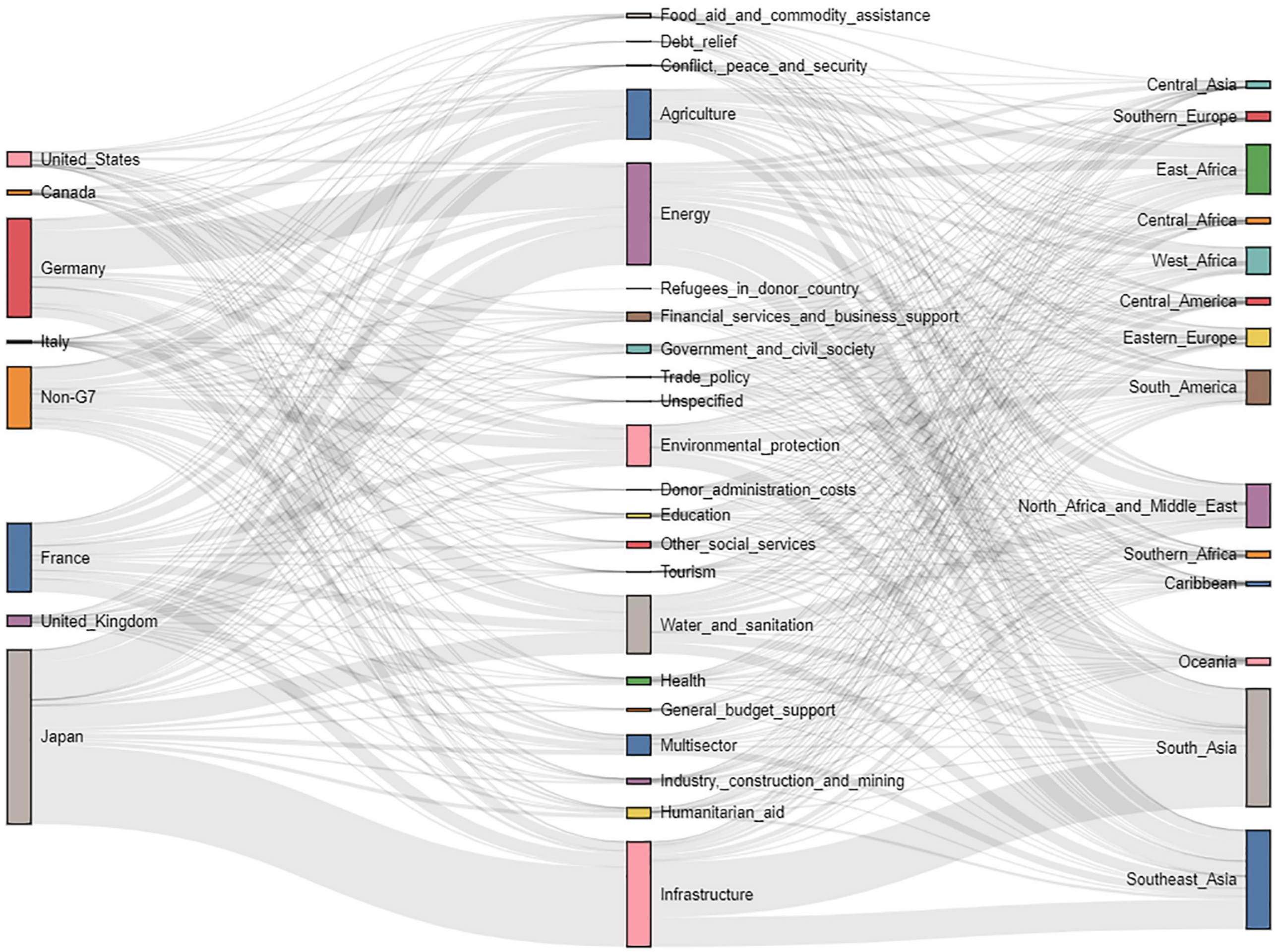

Fig 3. Flow of climate-related ODA from donor countries to different regions sector-wise from 2002 to 2021. The amount of ODA flow indicates the total sum of bilateral ODA between 2002 and 2021.

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Southeast Asia (USD 11.3 billion), North Africa & the Middle East (USD 8.8 billion), and East Africa (USD 6.5 billion).

Estimated average annual percentage change (EAAPC) in vulnerability and adaptation focused ODA: 2011 and 2021

Table 1, S2 and S3 Tables provide comprehensive analysis of the change in vulnerability scores, adaptation focused bilateral ODA amount between 2011 and 2021, alongside their respective EAAPC, expressed with a 95% CI. In 2021, Chad, the Central African Republic, and Niger had the highest vulnerability scores, registering 75.75, 73.09, and 72.15, respectively (Table 1). Between 2011 and 2021, seven out of 20 countries shown in the table experienced increase in their vulnerability scores, with the highest average percentage increase seen in the Central African Republic with an EAAPC of 0.62 (0.60 to 0.64) followed by Papua New Guinea; EAAPC of 0.57 (0.55 to 0.59) and Yemen; EAAPC of 0.50 (0.49 to 0.52). At the same time these countries experienced drastic decline in their respective GDP per capita., Niger experienced a decline with an EAAPC of -0.42 (-0.44 to -0.40). West African nations demonstrated significant vulnerability, with nine of its countries featuring in the top 20 most vulnerable nations in 2021.

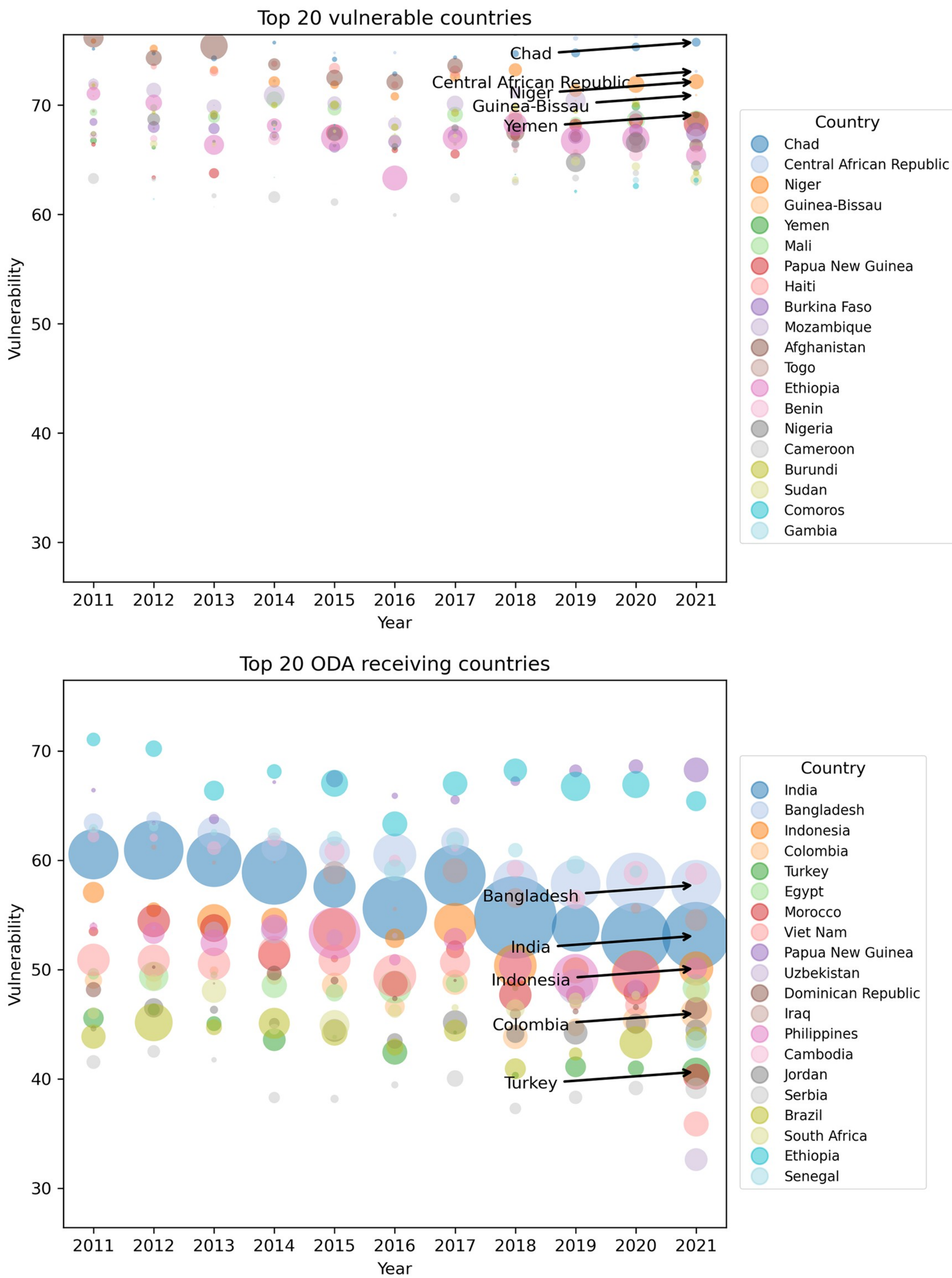

Fig 4. Comparison of top 20 vulnerable countries versus top 20 adaptation focused ODA recipient countries between 2011 and 2021. * The arrows represent names of top 5 vulnerable countries versus top 5 ODA recipient countries. The ODA amount presented is adaptation focused ODA.

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Table 1. Vulnerability score of the 20 most vulnerable countries in 2021 and their respective EAAPC.

Country	Region	Vulnerability score (out of 100)		GDP per capita		EAAPC (95% CI), 2011–2021	
		2011	2021	2011	2021	Vulnerability	Adaptation focused ODA
Chad	Central Africa	75.14	75.75	988	686	0.07 (0.06 to 0.07)	1.09 (1.07 to 1.11)
Central African Republic	Central Africa	72.42	73.09	515	461	0.62 (0.60 to 0.64)	1.77 (1.76 to 1.79)
Niger	West Africa	75.86	72.15	508	591	-0.42 (-0.44 to -0.40)	0.99 (0.96 to 1.01)
Guinea-Bissau	West Africa	70.84	70.92	684	795	0.33 (0.32 to 0.34)	0.67 (0.65 to 0.69)
Yemen	North Africa & Middle East	66.76	69.12	1,285	544	0.50 (0.49 to 0.52)	0.09 (0.09 to 0.10)
Mali	West Africa	69.35	68.64	810	882	-0.18 (-0.19 to -0.17)	0.83 (0.81 to 0.85)
Papua New Guinea	Oceania	66.41	68.27	2,304	2,625	0.57 (0.55 to 0.59)	1.55 (1.53 to 1.57)
Haiti	Caribbean	71.77	67.91	1,307	1,824	-0.86 (-0.91 to -0.81)	0.20 (0.19 to 0.21)
Burkina Faso	West Africa	68.46	67.48	728	889	-0.08 (-0.08 to -0.07)	0.69 (0.67 to 0.71)
Mozambique	East Africa	71.95	67.12	615	504	-0.41 (-0.43 to -0.39)	0.12 (0.11 to 0.12)
Afghanistan	South Asia	76.19	66.29	609	356	-1.47 (-1.57 to -1.37)	-0.41 (-0.43 to -0.39)
Togo	West Africa	69.45	66.23	804	977	-0.42 (-0.44 to -0.40)	1.21 (1.18 to 1.23)
Ethiopia	East Africa	71.05	65.41	348	925	-0.53 (-0.55 to -0.50)	0.53 (0.51 to 0.54)
Benin	West Africa	67.24	65.33	1,099	1,361	-0.26 (-0.28 to -0.25)	0.61 (0.59 to 0.63)
Nigeria	West Africa	67.37	64.46	2,505	2,066	-0.53 (-0.56 to -0.51)	0.75 (0.73 to 0.77)
Cameroon	Central Africa	63.29	64.21	1,498	1,654	0.23 (0.22 to 0.24)	-0.10 (-0.11 to -0.10)
Burundi	East Africa	71.82	63.81	237	221	-0.49 (-0.51 to -0.46)	0.41 (0.40 to 0.42)
Sudan	North Africa & Middle East	67.44	63.22	1,983	750	-0.62 (-0.65 to -0.58)	1.06 (1.04 to 1.09)
Comoros	East Africa	NA	63.13	1,527	1,578	-1.16 (-1.22 to -1.09)	3.89 (3.77 to 4.01)
Gambia	West Africa	62.63	62.78	706	772	0.17 (0.16 to 0.17)	2.78 (2.75 to 2.80)

*EAAPC–estimated average annual percentage change; ODA–adaptation focused official development assistance; CI–confidence interval; NA–not available, Comoros vulnerability score for 2011 is not available hence the vulnerability score from 2012 has been used for the calculation of EAAPC

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On the other hand, the most significant annual reduction in vulnerability from 2011 to 2021 was noted in Afghanistan (South Asia) with an EAAPC of -1.47 (-1.57 to -1.37), followed by Comoros (East Africa) at -1.16 (-1.22 to -1.09) and Haiti (Caribbean) at -0.86 (-0.91 to -0.81).

Several countries demonstrated reductions in vulnerability scores coupled with economic growth, suggesting that effective utilization of adaptation focused ODA can enhance adaptive capacity along with economic development. For instance, Bangladesh's GDP per capita grew significantly from 856 USD in 2011 to 2,458 USD in 2021, during which its vulnerability score declined from 63.41 to 57.74. This period also saw a substantial increase in climate-related adaptation focused ODA, from 353.7 million USD in 2011 to 2.37 billion USD in 2021, suggesting a potential association between increased ODA support and reduced vulnerability. Similarly, Indonesia experienced an increase in GDP per capita from 3,614 USD in 2011 to 4,334 USD in 2021, along with a reduction in vulnerability from 57.06 to 50.10. The increase in adaptation focused ODA from 421.9 million USD in 2011 to 1.1 billion USD in 2021 reflects targeted efforts in reducing climate vulnerability. Ethiopia also showed a remarkable rise in GDP per capita from 348 USD in 2011 to 925 USD in 2021, with a corresponding decline in vulnerability from 71.05 to 65.41. The substantial inflow of adaptation focused ODA, increasing from 176.6 million USD in 2011 to 379.5 million USD in 2021, supported these improvements.

Conversely, some countries experienced an increase in vulnerability scores despite receiving substantial adaptation focused ODA and exhibiting economic growth, indicating that factors such as political instability and conflict can undermine the effectiveness of ODA. Yemen's vulnerability score increased from 66.76 in 2011 to 69.12 in 2021, while GDP per capita significantly declined from 1,285 USD to 544 USD. The modest rise in adaptation focused ODA, from 15.7 million USD in 2011 to 458.4 million USD in 2021, was insufficient to counteract the severe impacts of ongoing conflict and political instability. Chad's vulnerability score increased from 75.14 in 2011 to 75.75 in 2021, and its GDP per capita decreased from 988 USD to 686 USD, suggesting that the adaptation focused ODA provided did not effectively address the underlying factors contributing to Chad's vulnerability. Similarly, the Central African Republic saw its vulnerability score rise from 72.42 in 2011 to 73.09 in 2021, with GDP per capita declining from 515 USD to 461 USD, highlighting challenges in the effective utilization of increased adaptation focused ODA. Additionally, countries like Papua New Guinea and Afghanistan exhibited mixed trends, where improvements in GDP per capita did not necessarily correspond to proportional reductions in vulnerability scores, underscoring the complex interplay between economic growth, vulnerability, and the effectiveness of adaptation focused ODA.

In terms of adaptation focused ODA, Comoros saw the most substantial average annual percentage increase with an EAAPC of 3.89% (95% CI: 3.77 to 4.01), succeeded by Gambia at 2.78 (2.75 to 2.80), and the Central African Republic at 1.77 (1.76 to 1.79). This shows a marked rise in bilateral aid inflow from 2011 to 2021 in these countries. However, Yemen, a North African & Middle Eastern nation, recorded a minimal increase in adaptation focused ODA with an EAAPC of 0.09% (95% CI: 0.09 to 0.10), despite its annual vulnerability score growth of 0.50% (95% CI: 0.49 to 0.52). It was important to note that the countries with increase in vulnerability between 2011 and 2021 had decrease in GDP per capita in the same period showing the inverse relationship between vulnerability and GDP per capita.

S2 Table illustrates the EAAPC in adaptation focused ODA and vulnerability across 116 countries, categorized by their regions. These results shed light on the intricate interplay between adaptation focused climate-related ODA and vulnerability, unearthing notable regional disparities. In addition, S3 Table shows the top 20 adaptation focused bilateral ODA recipient countries in 2021 with Bangladesh, Burkina Faso, and Cambodia, being the top three recipients in 2021. Furthermore, these countries also have an increase in GDP per capita between 2011 and 2021. S4 Fig further maps out the correlation between vulnerability and adaptation focused ODA from 2011 to 2021, region-wise. Regions such as Central Asia, Southern Europe, and the Middle East & North Africa posted negative correlation coefficients of -0.27 (95% CI: -0.51 to 0.01), -0.27 (-0.43 to -0.10), and -0.27 (-0.57 to -0.09), respectively, indicating a negative relationship between adaptation focused ODA inflow and vulnerability. In contrast, regions like the Caribbean, Oceania, and Central Africa demonstrated positive correlation coefficients of 0.19 (95% CI: -0.08 to 0.44), 0.16 (-0.07 to 0.37), and 0.16 (-0.08 to 0.38), respectively (S4 Fig).

Discussion

Our comprehensive analysis of bilateral climate-related ODA from 2002 to 2021, combined with comparative study of vulnerability scores and adaptation focused ODA from 2011 to 2021, offers profound insights into global efforts to counteract climate change. A notable surge in bilateral ODA allocations earmarked for climate change initiatives was observed, with Japan, Germany, and France standing out as leading donors. Together, these nations were responsible for approximately 77.6% of all bilateral ODA dedicated to climate change interventions in 2021, corroborating findings from prior studies [3, 6, 7]. Conversely, our assessment reveals that other G7 members; the US, Canada, the UK, and Italy, provided comparably reduced bilateral assistance. An in-depth exploration of biennial reports [10] confirms significant variations in bilateral assistance allocations among G7 countries. This disparity could be attributed to the heterogeneous financial commitments made by donor nations [45, 46]. However, our study also flagged concerns regarding the equitable dispersion of bilateral ODA for climate change.

The sector-specific bilateral ODA distribution by donor nations forms another pivotal facet of our analysis. For instance, the substantial bilateral ODA allocated to the energy sector by Japan and Germany mirrors a global shift toward renewable energy sources as a mitigation strategy against climate change, in line with Warren (2019) [47]. Contrarily, France's broader bilateral ODA dispersal strategy implies a more comprehensive approach, concentrating not solely on energy but also on infrastructure, water & sanitation, and agriculture targeting both mitigation and adaptation strategies. This diversified focus also resonates with the United Nations Sustainable Development Goals, which underline the interrelated nature of different sectors in achieving sustainability [48]. Identifying methods to effectively allocate ODA by each sector targeting not only mitigation but also adaptation strategies to reduce vulnerability in recipient countries could be a prospective research trajectory. The sectoral analysis directly addresses our first research question regarding temporal dynamics of climate-related ODA flows by revealing how donor priorities and focuses have evolved over time. Understanding the sectoral distribution of climate aid is crucial because it shows whether donor countries' allocation patterns align with recipient countries' needs and global climate action priorities. For instance, examining the balance between mitigation and adaptation funding across sectors helps identify potential gaps or biases in climate finance allocation.

Upon examining the recipients of climate-related bilateral ODA, we discerned that South Asia, Southeast Asia, North Africa & the Middle East, and East Africa emerged as primary beneficiaries. Understandably, these regions, characterized by their developing economies, significant population densities, and pronounced climate vulnerabilities, are in pressing need of climate finance [49]. Yet, the bilateral ODA distribution within these regions seems disproportionately focused on selected countries. For instance, while India's pronounced bilateral ODA share is consistent with its global stature and climate endeavours, a more balanced distribution across other vulnerable South Asian countries could be more efficacious [15].

Our comparative analysis of vulnerability scores in relation to adaptation focused ODA allocations (EAAPC analysis) along with the correlation analysis uncovers a nuanced relationship marked by significant regional disparities. Although an increase in climate-related ODA can support both mitigation and adaptation efforts, it does not always guarantee a reduction in severe climate impacts and vulnerability, thus undermining the effectiveness of climate related ODA. Outcomes of ODA are influenced by several factors, including governance, institutional readiness, and strategic planning in recipient countries [12, 50]. Additionally, the sector-wise distribution of ODA is shaped by both donor priorities and motivation, as well as the priorities of recipient countries [50, 51]. For instance, investments in infrastructure, often prioritized by donors and recipients alike, tend to have a more directed towards mitigation strategy which could indirectly reduce vulnerability whereas [52], support for other sectors such as water supply and sanitations, and disaster prevention and preparedness offer direct benefits to reduce vulnerability. Since 2010, adaptation focused ODA has indeed increased significantly, reflecting growing recognition of the need to build resilience to climate impacts. However, the allocation of these resources remains uneven in many vulnerable countries particularly in Africa, Asia, and the Pacific. This disproportionate distribution could be due to several factors, including donor priorities, governance challenges, and insufficient alignment between financial flows and the specific vulnerabilities of recipient countries [9]. Thorough evaluations and improved mechanisms for allocation are necessary to ensure that the most vulnerable countries receive sufficient adaptation focused ODA to enhance their resilience and reduce climate-induced risks. Thus, understanding how adaptation focused sector-specific ODA allocations affect vulnerability is essential for enhancing the resilience of vulnerable countries and improving the overall impact of climate-related ODA.

Previous research suggests that the mounting effects of climate change, combined with political instability [38, 53], economic challenges [54], ongoing conflicts [55], and, in some scenarios prevalent governmental corruption [56, 57], may explain the paradox of heightened vulnerability despite growing adaptation based ODA allocations. Thus, our findings emphasize the imperative of a holistic strategy for enhanced resilience and long-term sustainability to improve adaptative capacity. This approach should encapsulate not just financial assistance but also emphasize the need to enhance capacity building, technology transfer, and cogent policy reforms in those vulnerable countries. Furthermore, our findings showed that countries having increasing GDP per capita between 2011 and 2021 showed decrease in vulnerability during the same period, which depicts that improvement and growth in economy could contribute to strengthening country's coping and adaptive capacity along with improved susceptibility thereby decreasing the vulnerability.

It is also important to understand potential bidirectional relationship between adaptation aid and vulnerability. On one hand, more vulnerable countries are likely to attract greater adaptation focused ODA due to their higher risks and needs. On the other hand, over time, increased adaptation aid could lead to a reduction in vulnerability by enhancing resilience and adaptive capacity. This feedback loop suggests that the causality between aid and vulnerability is complex and may involve time lags, where the effects of adaptation interventions take time to manifest. Future research should examine these temporal effects more closely, considering how long-term aid strategies influence vulnerability reduction, while accounting for the initial vulnerability levels that may have driven higher aid allocation in the first place.

Several limitations of this study warrant consideration. First, our analysis focused only on bilateral ODA, excluding multilateral ODA and other forms of climate financing tools such as Green Climate Fund (GEF) [58] and Global Environmental Facility (GCF) [59]. This omission could prevent a full understanding of the international climate funding landscape for recipient countries. In addition, the distinction of ODA allocation as loans and grants is not done due to lack of segregated data. This inclusion could have significantly enhanced the understanding of donor generosity and the financial implications for recipient countries in our analysis. Second, this study did not evaluate the ratio of ODA in relation to Gross National Income (GNI) or the cumulative carbon emissions of donor countries. By not incorporating these ratios, we might overlook the relative economic capacities of donor countries, potentially not capturing whether these countries are adequately addressing their climate change responsibilities [60]. Third, we did not factor in external determinants that could influence sectoral ODA allocation. Such factors could encompass political, security, and economic considerations of donor nations. Aspects like historical diplomatic relations, geographic closeness, strategic reciprocity, trade dynamics, geopolitical events, global economic shifts, and the political architectures of both donor and recipient countries could play pivotal roles in ODA allocation decisions [51, 61]. Fourth, the calculation of vulnerability score involves not only climate-related risks but also other risks which are not associated with climate change such as earthquake and tsunami. The development of a dataset representing vulnerability due to climate change could further increase the viability of the analysis. Fifth, due to the limited data availability, we relied on simple correlations between adaptation focused ODA, vulnerability, and GDP per capita. This approach may not fully capture the complex interplay of factors influencing these variables, which should be addressed in future research with a more robust model. Lastly, due to data constraints, we could not probe the factors leading to the observed disparities in ODA allocation to various countries over the studied timeframe. A deeper dive here might offer valuable insights into donor country strategies when apportioning bilateral ODA.

Conclusion

In conclusion, this study offers valuable insights into the patterns, temporal trends, and disparities of global climate-related bilateral ODA allocations specifically adaptation focused ODA. The observed variations between adaptation focused bilateral ODA and vulnerability metrics illuminate the intricate relationship between international aid and a nation's inherent ability to tackle challenges. Our findings underscore the imperative for a more equitable and focused distribution of resources and emphasize the need for ongoing efforts to fortify resilience and reduce immediate impact of climate change in the most vulnerable countries. This necessitates a thorough re-evaluation of aid allocation, especially in bolstering climate change initiatives within the ODA framework. Future research should delve into understanding the tangible impacts of adaptation focused climate-centric ODA on diminishing vulnerabilities and augmenting resilience, as well as finding ways to enhance the efficacy and fairness of climate finance. For instance, considerations could include potential time lags before adaptation focused ODA initiatives tangibly lessen vulnerabilities. Our study stands out for its quantitative approach to the pivotal question of adaptation focused ODA's efficacy in vulnerability reduction and offers valuable perspectives for guiding future research.

Supporting information

S1 Table. Categorization of countries by their respective regions.
(DOCX)

S2 Table. EAAPC in vulnerability and ODA between 2011 and 2021.
(DOCX)

S3 Table. Top 20 highest recipient countries of adaptation-focused ODA in 2021. * GDP per capita–Gross domestic product per capita. Both adaptation-focused ODA and GDP per capita are based on US dollar value of 2021.
(DOCX)

S4 Table. List of purpose codes, names and descriptions to identify the sector of destination of a ODA contribution based on CRS/ purpose code. * CRS–creditor reporting system / purpose code (s).
(DOCX)

S1 Fig. Top 15 climate-related ODA recipient countries between 2002 to 2021.
(PNG)

S2 Fig. Bilateral ODA allocation by project three major project types between 2002 and 2021. * The three major project types are: 1.Adaptation project, 2. cross-cutting project, & 3. mitigation project. The Rio Marker for adaptation and cross-cutting project was introduced in 2009 hence the data is shown from 2009 and forward.
(PNG)

S3 Fig. Sectoral allocation of bilateral ODA by recipient region between 2002 and 2021. * The amount shown represents the total sum of bilateral ODA between 2002 and 2021.
(PNG)

S4 Fig. Correlation between change in adaptation-focused ODA and vulnerability between 2011 and 2021 by region.
(PNG)

S5 Fig. Calculation of vulnerability score. *Source: Bündnis Entwicklung Hilft and UNU-EHS.
(PNG)

S1 Text.
(DOCX)

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