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Adaptation, Loss and Damage: A Global Climate Impact Fund for Climate Justice

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Abstract

This paper discusses climate justice in the context of increasing climate costs triggered by anthropogenic climate change. It stresses the urgent need of supporting countries most affected by climate change, including Small Island Developing States (SIDS), by helping them to cover climate impact costs such as adaptation and loss and damage (L&D). Following on the previous paper by Sachs et al. (2022), and building on the literature, this paper provides a taxonomy of climate-induced costs to identify their different types, sources and interactions. The paper also proposes a pilot integrated conceptual and methodological framework to quantify and assess responsibilities across countries for adaptation and L&D costs, using indicator frameworks and methodologies from the existing attribution and contribution studies. It then makes an initial attempt to frame a dedicated Global Climate Impact Fund (GCIF) to share fairly and globally the burden of financing for adaptation and L&D costs from anthropogenic activities, among responsible countries. We argue that increased funding for adaptation and loss and damages must come hand-in-hand with the development of long-term resilience and sustainable development pathways, including medium term investment frameworks, in highly vulnerable countries and other countries.

About the SDSN

The UN Sustainable Development Solutions Network (SDSN) mobilizes scientific and technical expertise from academia, civil society, and the private sector to support practical problem solving for sustainable development at local, national, and global scales. The SDSN has been operating since 2012 under the auspices of the UN Secretary-General. The SDSN is building national and regional networks of knowledge institutions, solution-focused thematic networks, and the SDG Academy, an online university for sustainable development.

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Table of contents

List of Figures and Tables 4

List of abbreviations 5

1. Background 6

2. A taxonomy of climate costs 9

3. A pilot conceptual and methodological framework to assess adaptation and L&D costs and countries' financial responsibility 12

4. A Global Climate Impact Fund for adaptation and L&D costs 20

5. Conclusion 22

Annexes 24

Annex 1. Proposed adaptation indicator framework 24

Annex 2. Proposed L&D cost indicator framework 26

Annex 3. Suggestions of potential useful data sources to assess L&D costs 31

References 38

List of Figures and Tables

Figure 1. Cumulative production-based CO2 emissions from fossil fuels, by income group 7

Figure 2. The three pillars of climate-induced costs 9

Figure 3. From natural and anthropogenic climate change to climate-induced costs 12

Figure 4. Pilot integrated framework to assess climate impact costs and third countries' contribution to adaptation and L&D costs in affected countries 14

Table 1. Adaptation and L&D cost indicator frameworks 17

List of abbreviations

CO_2	Carbon dioxide
COP	Conference of the parties
CVF	Climate Vulnerable Forum
EM-DAT	Emergency Events Database
FAO	Food and Agriculture Organization
GCIF	Global Climate Impact Fund
GDP	Gross Domestic Product
GFDRR	Global Facility for Disaster Reduction and Recovery
GHG	Greenhouse gases
HIC	High-income countries
IDMC	Internal Displacement Monitoring Centre
IDPs	Internally Displaced People
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
IRDR	Integrated Research on Disaster Risk
L&D	Loss and Damage
LIC	Low-income countries
LMIC	Lower-middle-income countries
MDB	Multilateral Development Bank
OECD	Organisation for Economic Co-operation and Development
SDSN	Sustainable Development Solutions Network
SIDS	Small Islands Developing States
TC	Transitional Committee
UMIC	Upper-middle-income countries
UN	United Nations
UNDP	United Nations Development Program
UNEP	United Nations Environment Program
UNESCAP	United Nations Economic and Social Commission for Asia and the Pacific
UNFCCC	United Nations Framework Convention on Climate Change
WHO	World Health Organization

1. Background

The climate system is currently undergoing changes of an unprecedented scale that will have long lasting effects on people's lives and the planet. There is an undeniable rise in the frequency and magnitude of extreme weather events such as floods, droughts and heatwaves, and a growing number of countries are affected by slow-onset processes, including increased surface temperatures and rising sea levels (IPCC, 2022; OECD, 2021). These have major human, economic and social consequences in highly vulnerable countries (Massa et al., 2023). In small island developing states (SIDS), over the last two decades the frequency of natural hazards has doubled (Akiwumi, 2022), and several small islands have experienced land-loss and coastal erosion due to increased sea levels (Martyr-Koller et al., 2021). A recent scientific study shows that global warming may exceed 1.5°C this decade (Hansen et al, 2023). Other scenarios even consider that global warming could exceed 2°C and even reach 3°C; even in the most optimistic scenario, global warming is projected to be in the range of 1.8°C to 2.5°C (UNEP, 2023). Scientists, with the validation of the Intergovernmental Panel on Climate Change (IPCC), agree that a large share of the changes in climate is directly due to human activities (IPCC, 2022)[8].

Among all human actions affecting the climate, greenhouse gas emissions (GHG) are the largest source of anthropogenic climate change. GHG emissions are the main cause for the increase in air temperatures (they are responsible for a rise by 1°C to 2°C), the intensification of heavy precipitations across the world, the ice loss in the Arctic Sea, and the rise in observed global sea levels. The scientific community also shows that other human drivers such as aerosol emissions contributed to cooling temperatures, while the impact of natural drivers (between -0.1°C and 0.1°C) and internal variability (between -0.2°C and 0.2°C) were weaker. Therefore, the observed warming in global climate is mainly driven by GHG emissions from human activities, which are partly dissimulated by aerosol emissions (IPCC, 2021). GHG emissions, together with changes in land use, are also recognized as the principal drivers of climate-related loss and damage (L&D) (James et al., 2019).

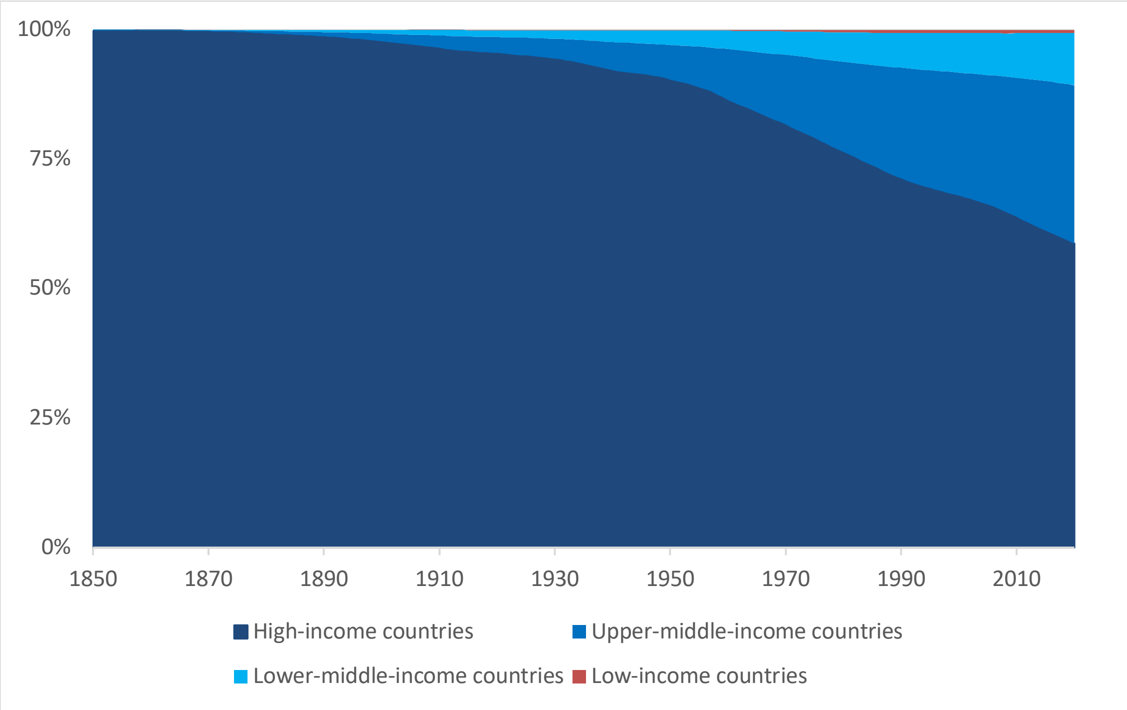
Among GHG emissions, the largest contributor to anthropogenic climate change is the increase in atmospheric concentrations of carbon dioxide (CO_2) (IPCC, 2021). CO_2 emissions are principally resulting from the combustion of fossil fuels (i.e. coal, oil, natural gas) and land use changes (e.g. deforestation). Since 1850, humans released more than 2,500 Gt of CO_2 in the atmosphere (Evans, 2021). The IPCC (2021) warns that the atmospheric concentrations of CO_2 are continuously increasing, and that in 2019, they reached their highest levels in more than two million years. While fossil fuel CO_2 emissions decreased in 2020 during the first waves of the COVID-19 pandemic, they have been climbing again, mainly due to a bump in economic activity in China and India (Friedlingstein et al., 2022).

Since the beginning of the industrial revolution, high-income countries (HICs) generated on average the largest share of global CO_2 emissions, while the contribution to global CO_2

[8] The causal link between anthropogenic polluting emissions and the probability and intensity of extreme weather events (e.g. hot extremes) has been proven by many studies (Herring et al., 2018; Tett et al., 2018; Peterson et al., 2012; van Oldenborgh, 2007).

emissions of poorer countries heavily affected by climate change remains marginal (Figure 1). In the 19th century, most CO_2 emissions were originating from land use changes due to the expansion of agriculture in HICs such as the United States. Near the end of the 19th century, with the worldwide takeoff of the industrial revolution, emissions from fossil fuels started to become the main components of global CO_2 emissions (Evans, 2021), and European countries such as the United Kingdom, France and Germany began to be at the top of CO_2 emitters. In the second half of the 20th century, and then during the 21st century, emerging economies such as China, Brazil and India significantly increased their share in global emissions. High-income countries are also the countries emitting the largest quantity of CO_2 in per capita terms. Indeed, over the 1850-2020 period, HICs have been responsible for more than 75% of all CO_2 emissions per capita (Sachs et al., 2022).

Figure 1. Cumulative production-based CO2 emissions from fossil fuels, by income group (% of global emissions)



Note: Production-based CO_2 emissions only.
Sources: Authors' elaboration based on The Global Carbon Project (2020) and Our World in Data (2021).

However, as of today, the financial burden of responding to climate impacts through adaptation and other initiatives to address L&D, still almost entirely falls on affected nations and not on countries that have been most responsible for climate change. In 1992, with the creation of the UNFCCC, all countries agreed on the principle of "common but differentiated responsibilities" and "distributive fairness". Yet, little has been done on the international scene. At COP27 in Egypt in 2022, countries called for funding arrangements including the establishment of a L&D Fund, but the consensus on the proposal for its operationalization is still fragile (Gabbatiss & Dunne, 2023). The Transitional Committee (TC) recommended in its co-chair's proposal voluntary contributions to the L&D Fund and full consistency among various components of the Financial Mechanism (TC, 2023b). However, up to now very few developed countries (e.g. Austria, Belgium, Canada, Denmark, Ireland, New Zealand, and Scotland) pledged or allocated funds to cover L&D in countries affected by anthropogenic climate change. Likewise, funding for adaptation in vulnerable countries remains dramatically insufficient and this will ultimately lead to more loss and damage. Despite the increase of 53% on average annually between 2017 and 2020, funding dedicated to adaptation programs only represent 7% of total climate finance (Buchner et al., 2021), which still mainly targets mitigation and green transitioning actions. Moreover, out of the USD 100 billion annual funding pledged to developing countries for climate adaptation and mitigation in 2009, only USD 28.6 billion have been mobilized for developing countries, and SIDS only had access to USD 1.5 billion (Akiwumi, 2022). Most of the finance went also to mitigation interventions rather than to adaptation projects. According to OECD preliminary data, it is only in 2022, two years after the deadline, that the commitment seems to have been fulfilled (Harvey, 2023). The under-financing for L&D and adaptation in poor or vulnerable countries often leads them to subscribe to new loans from the International Monetary Fund (IMF) to recover from the disasters they are inflicted with. Such new loans increase countries' burden of debt, reduce their capacity to recover, and have severe long-term consequences on their development and economic growth.

Poor and vulnerable countries, which are victims of climate-related disasters for which other nations are responsible, call for climate justice and ask for reparations. The concept of climate justice and the search for reparations are intrinsically linked with historical responsibility in GHG emissions and climate change. The UN General Assembly adopted the resolution A/RES/76/300 recognizing the right to a clean, healthy, and sustainable environment as a human right, and therefore indivisible from the right to life, mental health, adequate food, housing, water, and cultural life, among others (UN, 2021). Climate justice entails ensuring protection of this right for all and that the burden of climate change should not be born by the least responsible countries who tend to be the most vulnerable ones.

Countries that are historically more responsible for climate change should bear a fair share of global climate costs. While specific funding flows should be identified to share fairly the burden of the costs induced by climate change, increased global financing for the SDGs at large may offer great opportunities to strengthen resilience in vulnerable countries by investing massively in health systems, education, digital infrastructure, clean energy and other key services and infrastructure. This must of course be accompanied by further efforts in receiving countries to define long-term resilience and SDG pathways.

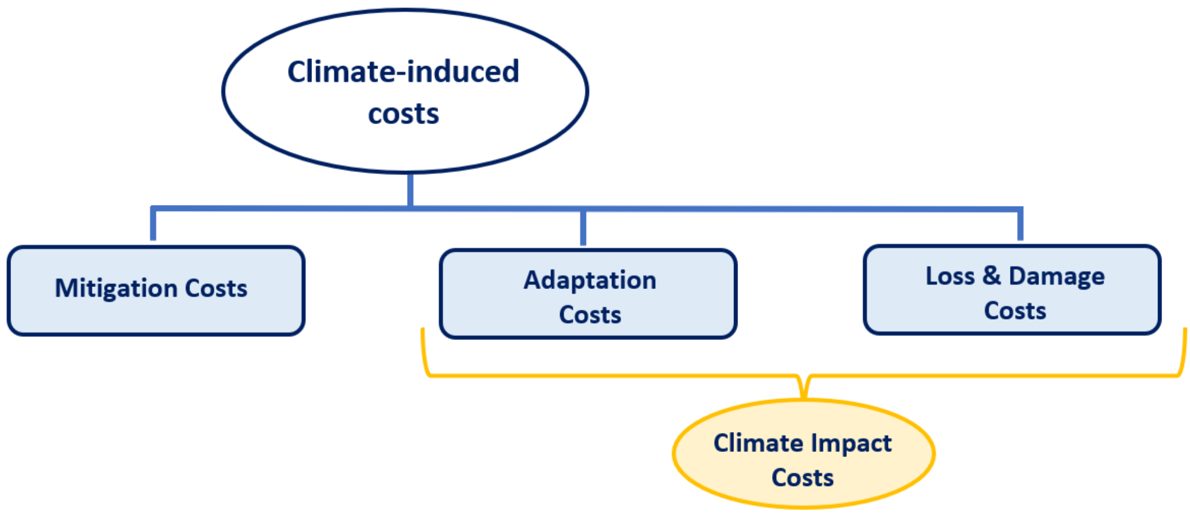
The support of the international community is also essential to pay the costs from both adaptation and L&D imposed by anthropogenic climate change in poor and vulnerable countries. Foreign public and private resources are more necessary than ever to build climate resilience in countries such as SIDS, where already small tax bases and domestic resources have shrunken due to the COVID-19 pandemic (Massa et al., 2023). Despite increasing climate finance provided by developed countries reaching USD 89.6 billion in 2021, and aside discussions for the operationalization of the L&D fund, efforts should be multiplied to strengthen adaptation finance in developing countries notably through scaling up the mobilization of private finance (OECD, 2023a; OECD, 2023b). In the effort of enhancing financial resources to build climate resilience, it is important to promote coherence and complementarity across new financing mechanisms such as the L&D Fund and existing funding arrangements, including climate finance with a focus on adaptation, disaster risk reduction (DRR), overseas development assistance (ODA), and humanitarian aid (Anisimov, 2023).

This paper stresses the need for climate justice at the international level and proposes an integrated framework to advance the discussions on how to quantify adaptation and L&D costs, and build a global fund to finance adaptation and L&D costs attributed to human-induced climate change. Section 2 provides a taxonomy of climate costs, clarifying their nature and highlighting key differences across them. Section 3 presents a pilot integrated conceptual and methodological framework to assess adaptation and L&D costs and individual countries' financial responsability. Section 4 makes an initial attempt to frame a new dedicated Global Climate Impact Fund to share fairly and globally the burden of financing for adaptation and L&D costs from human-induced climate change, among responsible countries. Section 5 concludes.

2. A taxonomy of climate costs

There are three types of investments needed for climate safety: mitigation, adaptation and L&D (Figure 2).

Figure 2. The three pillars of climate-induced costs



Source: Authors' elaboration.

For the purposes of this paper, we define Climate-induced Costs as the sum of Mitigation Costs and Climate Impact Costs, with the latter category including both the Adaptation and L&D costs. In this typology, we regard reparative (or restitutive) justice as applying to Climate Impact Costs faced by each country as the result of the global historical greenhouse gases (GHG) emissions. The Mitigation Costs are instead costs borne by countries for cutting emissions in order to avoid damaging the global climate.

Mitigation costs are related to "*human intervention to reduce the sources or enhance the sinks of greenhouse gases*" (IPCC, 2001). They are borne to address the root causes of anthropogenic climate change. Some examples are the costs for replacing greenhouse gas-emitting fossil fuels (e.g. coal, oil, and natural gas) with clean and renewable energies (e.g. solar, wind, and geothermal), making old buildings more energy-efficient, replacing traditional internal-combustion vehicles with electric options, decarbonizing food production or for planting trees and preserving forests to absorb and store more carbon dioxide from the atmosphere.

Adaptation costs are related to the "*adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects*" (IPCC, 2001). Therefore, they address the impacts of climate change. Adaptation costs include expenses for redesigning housing, building sea walls, elevating infrastructure, and promoting drought-tolerant crops, among many others. UNEP (2022) estimates that annual adaptation needs inflation adjusted are in the range of USD 160-340 billion by 2030 and USD 315-565 billion by 2050.

In addition to their different objectives, mitigation and adaptation costs also differ in terms of spatial and time scale as well as concerned economic sectors (Tol, 2005). On one hand, mitigation costs are borne to respond to an *international* issue in the long-term, targeting sectors such as energy, transportation, industry, and waste management. On the other hand, adaptation costs are costs paid in response to *local* issues to get benefits in the short/long-term, mainly in the water and health sectors, as well as in coastal and low-lying areas.

Although a common definition of L&D still does not exist, L&D costs can be defined as costs related to the residual impacts of climate change which are not prevented or avoided by optimum adaptation and mitigation efforts[9]. The concept of L&D costs appeared for the first time in 1991, but only in 2015 L&D costs were recognized as a separate category from mitigation and adaptation (Sachs et al., 2022). L&D costs are incremental costs incurred because of climate-related disasters that can be reduced (but not eliminated) through adaptation and that persist even after optimal mitigation and adaptation (Shawoo et al., 2021; Jensen & Jabczyńska, 2022). L&D costs can be the consequence of severe weather events (e.g. cyclones, hurricanes, tornadoes, droughts, or heatwaves) or slow-onset processes (e.g. sea level rise, ocean acidification and salinization, land degradation, droughts, desertification, or glacial retreat).

When discussing L&D, a distinction is made between economic and non-economic costs (Thomas et al., 2018). *Economic* L&D costs are direct physical costs due to the negative impacts of climate change on resources, goods and services traded in markets. They can be easily quantified. Examples are costs related to damages to infrastructure, decreases in agriculture production or in services such as tourism, disruption of economic activities, etc. *Non-economic* L&D costs, instead, are indirect costs which are difficult to quantify and monetise, and refer to climate-induced impacts such as loss of life, biodiversity, social cohesion, and cultural

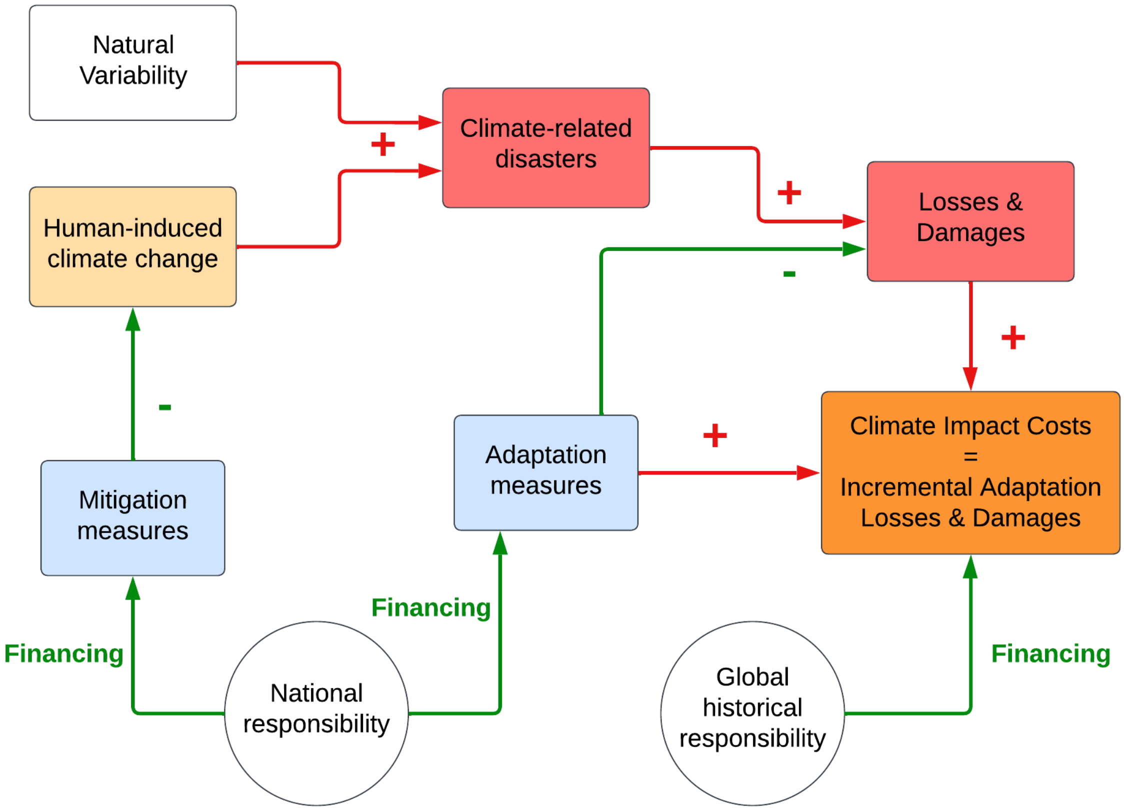
[9] Throughout the paper, this definition of L&D is preferred over the broader one stating that L&D refer to all negative consequences of climate change.

identity, or displacement and migration of communities[10]. Beside their direct and permanent consequences on people's lives, well-being, and health, non-economic L&D also have substantial impacts on economic growth and development.

Adaptation and L&D are costs induced by both natural variability and anthropogenic activities. However, only the financing of human-induced adaptation and L&D costs should be shared among polluting countries according to their historical responsibility in climate change (Figure *3*). Adapting to climate change helps reduce the amount of damages inflicted but represents substantial investment costs that add to the climate impact costs. As explained further in the paper, in addition to what is stated in the Paris Agreement (i.e. developed countries should provide financial, technical, and capacity building support to less developed and vulnerable countries), a climate justice regime would share the costs of incremental adaptation (i.e. additional adaptation spending due to anthropogenic activities despite an optimal level of adaptation to the share of climate events caused by natural variability) and L&D, but would require that each country is responsible for cleaning its energy system by funding its own mitigation measures. Each country should pay restorative justice funds in proportion to the share of its historical GHG emissions, relative to their population size and considering the effect of past emissions on current GHG concentrations based on climate modeling.

[10] Out of the total 59.1 million internally displaced people (IDPs) accounted at the end of 2021, around 38 million were displaced in the sole year 2021, and 23.7 million of them were displaced because of natural hazards (IDMC, 2022). More than half of the internally displaced people by disasters in 2021 were in the East Asia and the Pacific region (*Ibid*). At an estimated average cost of USD 390 per displaced individual annually, the total cost of the climate IDPs amounts to close to USD 10 billion per year. This estimated cost mainly refers to housing and schooling expenses and does not include the economic impact of displacement on host communities or IDPs in the process of returning, nor does it account for investments made by governments or development stakeholders to address the longer-term economic consequences of displacement such as unemployment and mental health issues.

Figure 3. From natural and anthropogenic climate change to climate-induced costs



Source: Authors' elaboration.

3. A pilot conceptual and methodological framework to assess adaptation and L&D costs and countries' financial responsibility

Determining who should pay for human-induced climate change adaptation and L&D is a key but complex exercise since several methodological issues arise. For example, should we start counting responsibility from the beginning of the industrialization period, or from the creation of the UNFCCC that marks the moment when countries and stakeholders started to be conscious about the consequences of their pollution patterns? While polluting countries should pay for both adaptation and L&D costs originating from anthropogenic climate change, should natural-induced costs be shared equally among all countries – including the less polluting ones – to ensure enough incentive to plan for greater resilience to climate change in affected regions or countries?

Moreover, the attribution of climate events to human-induced climate change requires first to correctly measure or predict adaptation and L&D costs and then to understand which share of climate impact costs is due to anthropogenic activities rather than to natural weather variability. Quantifying both adaptation and L&D costs is difficult due to the multidimensional nature of these costs – economic and non-economic, short- and long-term, historic and prospective – that challenges both the collection and the analysis of data. Moreover, nothwistanding the progress in the attribution literature, when a natural weather-related disaster hits, it is still difficult to assert that the given shock was due to long-term human-induced climate change rather than to natural weather variability. This challenge is even bigger for slow-onset processes that have more dispersed impacts.

Up to now, these challenges have been investigated by different streams of the literature. Existing studies can be categorized into three different group: (i) *quantification* studies trying to correctly quantify the total amount of adaptation and L&D costs that need to be covered for allowing countries and communities to recover from climate-related disasters; (ii) *attribution* studies identifying the respective role of human actions and natural variability in climate change, in the probability of climate disasters, and in the resulting adaptation and L&D costs; (iii) *contribution* studies identifying who (e.g. countries and/or economic sectors) contributed to human-induced climate change and resulting costs. Nevertheless, all these studies present numerous limitations due, for example, to the scarce availability of granular and timely data, and to the challenge of integrating non-economic variables into the used models (Sachs et al, 2022).

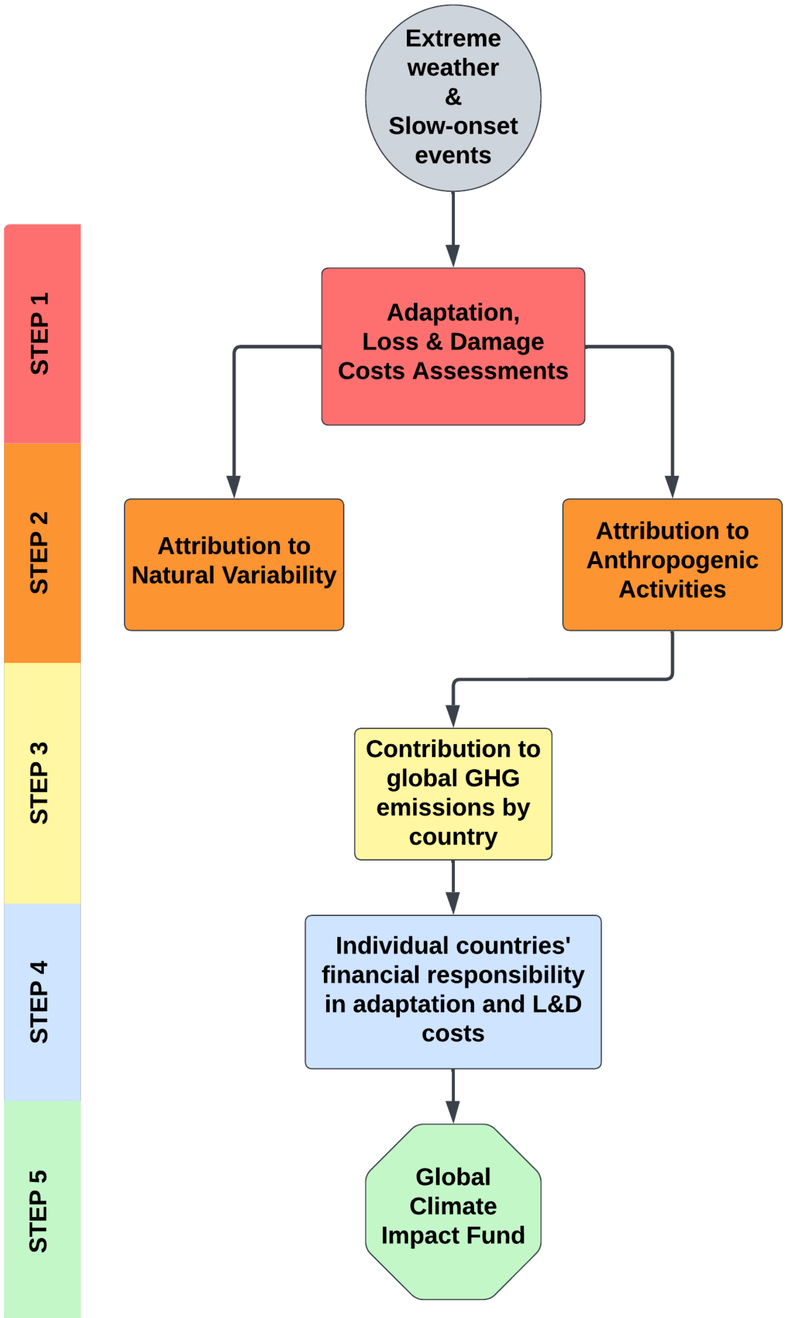
Although the existing literature provides useful guidelines, a harmonized and commonly accepted methodology to first quantify adaptation and L&D costs (including non-economic costs), and then to fairly split the burden of the costs among countries does not exist yet. As a consequence, estimates of climate impact costs provided by different entities are very diverse, although projected numbers are all considerable. For example, Baarsch et al. (2015) estimate economic L&D costs to be USD 400 billion in 2030 and USD 1–1.8 trillion by 2050, while Markandya and González-Eguino (2018) project L&D costs of at least USD 290-580 billion by 2030 for developing countries alone. More recent estimates obtained using data provided by the Climate Watch data platform of the World Resources Institute are likewise substantial, with identified total economic costs for current and future L&D of about USD 810 billion. The lack of precise estimates of climate impact costs and of a widely recognized criteria on how the burden of adaptation and L&D costs should be shared across countries leads to insufficient financial support for climate impact costs, especially in vulnerable countries such as SIDS (Massa et al., 2023), which risk to disappear under water if adequate resources are not allocated to support adaptation programs and cover L&D costs. Schäfer et al. (2021) highlight that existing financial support to address L&D is insufficient, with most climate finance addressing mitigation costs rather than adaptation and L&D costs (Buchner et al., 2021). Across the different types of L&D costs, financial support is particularly scarce for L&D costs caused by slow-onset processes as well as non-economic L&D costs[11].

This section proposes a pilot integrated framework that could be used by the international community to assess climate impact costs and allocate responsibilities for those costs

[11] See Künzel and Schäfer (2021) for evidence on Climate Vulnerable Forum (CVF) countries. CVF countries consist of 48 countries (including 17 SIDS) from the African, Asian-Pacific and Latin American and Caribbean region facing severe threats due to climate impacts.

(Figure 4). The framework also integrates the topic of adequate financing mechanisms and sources to deal with climate impact costs, that will be further discussed in Section 4. Partly building on OECD (2021), the pilot framework suggests that five steps are needed for assessing adaptation and L&D costs, and identifying specific countries' contributions to climate change and related climate impact costs. These steps are summarized by Figure *4* and described further below.

Figure 4. Pilot integrated framework to assess climate impact costs and third countries' contribution to adaptation and L&D costs in affected countries



Source: Authors' elaboration.

The first step of the framework is to assess adaptation and L&D costs. Indicator frameworks are useful tools readily applicable by policymakers to assess them. Although several institutions have been proposing series of indicators to measure L&D and adaptation, there is currently no harmonized and comprehensive indicator framework to support adaptation and L&D costing at the national level. Our proposed adaptation and L&D cost indicator frameworks aim to fill this gap. Although different in nature, the indicators selected in the frameworks for costing adaptation and L&D were identified according to the following criteria: indicators should be policy-relevant, measurable, globally relevant, no time or event-specific, and mutually exclusive.

The adaptation framework suggests a list of adaptation measures to be costed, paired with indicators useful for the costs assessment (Table 1 and Annex 1). Adaptation measures and indicators are classified around eight main sectors, including institutions and innovation, and cover both hard (e.g. infrastructure) and soft (e.g. laws and regulation) adaptation measures. Although not exhaustive, this list is comprehensive and useful to start an adaptation cost assessment. While some countries may need to consider all adaptation measures, others may prefer to focus on some of them, depending on their specific needs and available resources to adapt to climate change. Adaptation costing is usually ex-ante, and requires context-specific analysis and methods. Studies assessing adaptation costs are typically represented by partial equilibrium analyses based on sector-specific indicators (Soós et al., 2022; Parry et al., 2009; Bosch & Pásztor, 2012), or integrated assessments models (de Lucena et al., 2010). In both cases, some preliminary steps are essential to follow. This is why we complement the adaptation framework with a checklist which may provide guidelines to policymakers for costing their adaptation needs (Box 1).

The L&D framework reports impact and cost indicators, which are usually measured ex-post, using historical observable data, and not specific to a particular context (Table 1 and Annex 2). The framework accounts for L&D costs caused by either extreme weather events (e.g. floods) or slow-onset processes (e.g. sea level rise). Although a large share of losses and damages experienced in developing and vulnerable countries is caused by slow-onset climate change events, up to now most of the L&D costing methods that exist in the literature have focused on L&D from extreme weather events. In our framework, L&D that are typically occurring after a sudden shock and are easily measurable between two points close in time (e.g. loss in crops after a flood) are associated with "Extreme weather event", while L&D occurring on a more long-term basis (e.g. coral bleaching) are associated with "Slow-onset event". In some cases, both types of climate change events are associated with one impact or cost indicator (e.g. rise in food insecurity). The proposed L&D cost indicator framework relates to most of the Monitoring Sendai Framework targets and indicators, with the added value of integrating indicators capturing L&D due to slow-onset processes. Suggestions of useful potential data sources (global sources with open or restricted access, as well as local initiatives) to assess L&D costs at the country level are presented in Annex 3.

Both economic and non-economic L&D costs are considered in our framework. Taking non-economic costs into account is essential, especially in the context of climate justice and reparations. Non-economic costs are often neglected since they are more difficult to quantify as they refer to intangible climate-induced impacts on individuals, society and the environment (e.g. loss of life, loss of cultural identity), but they represent a significant and important part of L&D total costs. Economic costs are, on the other hand, easier to estimate, and can be decomposed between direct costs (i.e. damage to physical infrastructure or assets) and indirect costs (i.e. related losses in production).

A number of databases may enable L&D costs assessment at the global level. While these databases are useful to estimate global L&D costs, data availability and coverage at the local level remain limited and increased gathering of hazard and impact data is necessary. Some databases are managed by international organizations and their data are freely available (e.g. EM-DAT, DesInventar), while others are managed by private institutions such as insurance companies and their access is restricted (e.g. Sigma, NetCatService). Some initiatives such as the UNDP Bangkok Regional Hub, an effort to develop a taxonomy of L&D in 19 countries in the Asia Pacific Region, 9 countries in Africa, 3 Arab States and 4 countries in Europe and across the Commonwealth of Independent States, could lead to the creation of important data sources on L&D. Other examples of local L&D data collection efforts are cited in Bhuiyan et al. (2022). Digital technology could also be exploited more to gather data on L&D. In the assessment of adaptation costs, local data next to data already provided by various international organizations, such as FAO, WHO, the World Bank, and IMF, among others, are needed.

Following the costs assessments, a second step consists in estimating to what extent the anthropogenic drivers are responsible for climate change intensification. Climate events (slow-onset processes or extreme weather events) are due to both natural variability and human-induced drivers. Using the methodologies of attribution studies, the goal at this stage of the framework is to disentengle the influence of humans' activities on climate change from that of natural drivers. To do this, attribution studies usually use a combination of climate models comparing observed trends in specific climate variables (e.g. temperatures) with simulated trends of the same variables in alternative scenarios where anthropogenic drivers (e.g. GHG or aerosol emissions) are excluded. The next steps of the framework focus on the part of climate events due to anthropogenic drivers.

Measuring countries' individual contributions to climate events suffered by other countries is the third step of the framework. As CO_2 emissions have been identified as the largest source of anthropogenic climate change and are the best tracked over time, they can be used as a proxy to measure countries' individual contributions to human induced climate change. The aim is to estimate countries' historical responsibility in human-induced climate change. Relying on climate models and statistical methods, contribution methodologies enable to quantify the share of each countries in global GHG and aerosols emissions, and estimate their respective consequences on climate variables (e.g. global temperatures) and the probability of climate events.

After assessing the total adaptation and L&D costs, and estimating the share of climate change due to anthropogenic drivers as well as countries' individual responsibility in CO_2 emissions, **as a fourth step, the share of total adaptation and L&D costs that each country should bear**

as reparations to affected countries based on its contributions to human-induced climate change is identified.

Table 1. Adaptation and L&D cost indicator frameworks

Selected examples of adaptation indicators useful to cost adaptation*	L&D Indicators to be costed
Agriculture, fisheries, and forestry	
Share of agricultural production issued from climate-resilient seeds (%)	Volume of crops, livestock and timber lost after natural hazards
Degree of crop and livestock diversification	Area of productive land and forest damaged by natural hazards or affected by salinization
Fishes caught that are then discarded (%) Number and levels of fishing quotas	Number of fish farms lost after natural hazards
Area affected by salinization (% arable land) Irrigated area (% arable land)	Agriculture, aquaculture and forestry machinery, equipments and systems destroyed or damaged by natural hazards
Average rainwater harvesting tanks capacity (liters) Freshwater withdrawal (% of available freshwater resources)	Number of jobs in the agriculture, fisheries and forestry sectors lost after natural hazards
Environment	
Share of coastal area at risk of flooding protected with sea walls or advanced shoreline (%)	Change in tree cover, species abundance, coral bleaching
Forest area treated with prescribed fire (%)	Area affected by desertification
Human and cultural	
Share of the population living in climate-related risk areas that has been relocated (%)	Number of people who died, went missing or were injured or affected by natural hazards
Household cash transfers (% GDP) Share of food surpluses that is stored (%)	Number of people suffering from mental health issues after natural hazards (per 100 000 population)
Surviving infants who received 2 WHO-recommended vaccines (%)	Number of persons whose house was destroyed or severely damaged by natural hazards
Share of patients admitted in trauma services who died within 24 hours after hospitalization (%)	Number of people who fell below the national poverty line or into food insecurity
Number of adaptation initiatives sourced from indigenous knowledge	Loss of tangible and intangible cultural heritage (including historical assets and cultural identity)
Climate change is included in primary and secondary education national curricula (Yes: 1; No: 0)	
Industry	
Share of private companies issuing sustainability reports (%)	Number of raw materials, machinery and equipment destroyed or damaged by natural hazards
	Number of jobs lost after natural hazards
	Loss of production after natural hazards
Infrastructure	
Expenditure on road maintenance (% GDP)	Number or length of houses, ports, airports, schools, healthcare facilities, government buildings, industrial facilities, and electrical power plants destroyed or damaged by natural hazards
Share of municipal waste collected and safely treated (%)	Number of schools, medical and industrial material and equipment destroyed or damaged by natural hazards
Share of buildings resilient to climate hazards (%) (e.g. seismic risk, floating housing, etc.)	Length of roads, railways, electrical distribution lines, WASH grids and telecommunications grids destroyed or damaged by natural hazards

Source: Authors' elaboration. *Notes*: * Additional indicators useful to cost adaptation (including those in the Financing, Innovation and Institutions categories) are reported in Annex 1.

Box 1. A checklist for adaptation costs assessments

1- ***Identify the event for which adaptation is needed.***

It is essential to be precise in the description of the climate change event to which we want to adapt. For instance, instead of referring to "sea level rise", it is better to specify "flood caused by a surge from the sea", "erosion of beaches and cliffs" or "saltwater intrusion", since the adaptation tools to address these effects are different. While hard adaptation is required for inundations, sediment or beach nourishment, soft adaptation is more adapted in case of erosion (Parry et al., 2009).

2- ***Assess the probability of occurrence of the event and quantify its current scope.***

Determine the frequency and probability of occurrence of the event (e.g. floods are estimated to happen *X* times during the following *N* years). If the event is directly measurable, quantify its effects (e.g. measuring the volume of plastic waste entering in the ocean per year) and differentiate them by source (e.g. plastic generated inland, plastic generated on coastal areas) (see examples in Soós et al., 2022).

3- ***Identify the relevant and specific adaptation measure, especially distinguishing between hard and soft measures.***

Describe the different elements of the measure, its performance characteristics, its expected implementation time horizon, and potential side effects. At this stage, several adaptation options can be listed. Costs of each option must be calculated separately and compared afterwards.

4- ***Identify the status of the current infrastructure, technological, and political environment.***

This step is essential to understand context-specific variables (e.g. countries with high and low existing infrastructure do not face the same adaptation needs nor have the same adaptative capacity).

5- ***Identify the exhaustive list of costs' components of the selected measure and compute the total cost to implement the measure.***

The adaptation indicators of our proposed framework can guide the quantification of the different costs' components (e.g. measuring the share of coastal area needing flood protection is necessary to estimate the total costs of flood protection measures).

Decompose the adaptation measure costs between: capital costs (i.e. initial investment and capital recovery), and operating and maintenance costs (i.e. costs of labor, energy, material, services). Depending on the data required, global databases can be used, or local data collection can be required.

The following formula approximates the calculation of adaptation investment costs:

$$adapt\ costs = \sum_{year=1}^{N} (capital\ costs + operating\ \&\ maintenance\ costs) * proba$$

where the aggregated investment costs ($capital\ costs$ and $operating\&maintenance\ costs$), adjusted for inflation, are multiplied by the probability of the event. The total is then summed over the number of years by the time horizon of the adaptation measure.

This is the starting point to design a new dedicated Global Climate Impact Fund (GCIF) to share fairly on the global scale the financing of adaptation and L&D costs generated by human-induced climate change. Up to now, traditional and innovative financing mechanisms as well as a number of national and international financing sources have been identified to address L&D costs, but they are still insufficient and in some cases difficult to apply (Sachs et al, 2022). For example, risk retention financing instruments, which refer to contingency finance such as disaster relief funds, have the advantage to be rapidly disbursed. However, they can also divert funds from other key spending needs, can not be used for slow-onset processes and may even worsen a country's fiscal burden. Other innovative financing instruments, such as debt for loss and damage swaps, can provide debt relief following a climate disaster, but they can also disincentivize to reduce risks and can not provide additional resources to respond to immediate needs stemming from the impacts of natural hazards (Sachs et al, 2022). To align with the concept of climate justice, we propose to complement the existing financing mechanisms and sources with a dedicated GCIF. The GCIF would be a targeted instrument to finance incremental adaptation and L&D costs caused by human-induced climate change, and would prevent countries from contracting new loans (e.g. with the IMF) that increase their burden of debt and jeopardize their capacity to recover and build resilience to climate change (Walsh & Ormond-Skeaping, 2022).

Nevertheless, there are multiple methodological obstacles to achieving each step of the proposed pilot integrated framework. Starting with cost assessments (step 1), the main limitations are: the lack of robust, granular, and timely data on both current and historic climatic variables; the imperfect collection of data on economic impacts; and the lack of measurements of non-economic impacts. Weak data governance and underdeveloped digital technology are also key obstacles for data gathering and sharing at the national, regional, and global level. Data is difficult and costly to collect, and when it is collected it is often either on paper (not digitalized) and therefore difficult to share, or it is not freely and openly available. Initiatives such as PARIS21's Climate Change Data Ecosystem (CCDE), SDSN's Thematic Research Network on Data and Statistics (TReNDS) and the Global Partnership for Sustainable Development Data, are key examples of efforts that need to be multiplied and scaled-up to close the existing data gaps. The attribution of climate events to natural variability and anthropogenic activities (step 2) also suffers from similar limitations, notably in developing and vulnerable countries, where there are limited availability of long-term and disaggregated data. In addition to data related obstacles, the assessment of the contribution of each country to GHG emissions as well as the identification of the proportion of adaptation and L&D costs caused by specific countries (steps 3 and 4) also suffer from sensitivity to emissions data and methodological choices (Sachs et al, 2022). For example, there is no consensus on the starting date that should be used to measure countries' contribution to anthropogenic climate change, notably through CO_2 emissions. Therefore, it can be challenging to identify countries' individual contribution to human-induced climate change and subsequently assess their financial responsibility in other countries' adaptation and L&D costs.

4. A Global Climate Impact Fund for adaptation and L&D costs

COP27 marked a turning point in climate justice, as countries agreed on the creation of a specific Loss and Damage Fund. The Fund aims at providing financial resources to nations that are affected by the consequences of climate change, based on the principle of cooperation and facilitation, and not of liability or compensation (TC, 2023b). While the adoption of the Loss and Damage Fund represents a historic decision in favor of climate justice, countries must ensure that its implementation is fair and rapidly effective. The Loss and Damage Fund can be a pivotal innovative mechanism to increase global liquidity and leverage resources for sustainable development in the context of the call for a global SDG Stimulus (United Nations, 2023). In 2023, the Transitional Committee (TC)[12] responsible for the design and operationalization of the Fund, held multiple meetings to define its nature, institutional arrangements, as well as the rules defining countries' contribution and resources allocation[13]. The TC co-chair's proposal to COP28 suggested the Fund would be managed by a Board (with legal personality and capacity) and hosted for an interim period of four years by the World Bank as a Financial Intermediary Fund (FIF) (TC, 2023b). However, despite this agreed proposal, the consensus seems to be still fragile (Gabbatiss & Dunne, 2023). Besides, although L&D costs are incremental costs whose magnitude also depends on adaptation measures (Shawoo et al., 2021; Jensen & Jabczyńska, 2022), the current Fund model does not integrate adaptation costs.

The framework presented in this paper provides additional perspectives on how the Fund should operate.

To align with the concept of reparative justice, the Global Climate Impact Fund (GCIF) should cover both incremental adaptation and L&D costs that are caused by human-induced climate change. Costs that emerge both after sudden extreme weather events and slow-onset processes should be considered. While total climate-related costs linked to anthropogenic activities (i.e. incremental adaptation and human-induced L&D) should be shared among polluting countries only, proportionally to their contribution to GHG emissions and the consequent change in climate, the remaining costs caused by natural variability and inadequate adaptation should be covered individually by all countries, including those non responsible but affected by climate change. This could provide the right incentive to affected countries to continue investing in their efforts to adapt to climate change. In other words, adaptation expenditure necessary to cover for climate change caused by natural variability

[12] The Transitional Committee is composed of 14 members from developing countries and 10 representatives from developed countries. The geographical representation among developing countries is: 3 countries from Africa, 3 countries from Asia and the Pacific, 3 countries from Latin America and the Caribbean, 2 SIDS, 2 countries from the Least Developed Countries group, 1 developing country not belonging to any of the previous group (UNFCCC, 2022).

[13] In its third meeting, the TC identified different sources of financing for the Loss and Damage Fund including contributions from multiple stakeholders and innovative sources such as the voluntary carbon market or international pricing mechanisms (TC, 2023a).

should not be covered by the GCIF. The Fund should not finance L&D that are caused by natural variability in climate and inadequate adaptation measures in affected countries.

The TC's final proposal ahead of COP28 "urges developed country Parties to continue to provide support and encourage other Parties to provide, or continue to provide support, on a voluntary basis, for activities to address loss and damage" (TC, 2023b).

Our proposal is that contributions to the GCIF could be based on the principle of *historical responsibility* in climate change and could cover all types of climate impact costs (adaptation and L&D). Half of the amount covered by polluting countries should be based on their current GHG emissions and the other half should be based on their cumulative historical GHG emissions. A price could be assigned to each ton of CO_2 emitted based on total outlays needed and the volume of emissions. On the long-run, other financial inputs from private sector and potential innovative instruments could be considered to diversify the sources of funding.

Nevertheless, rather than being a post-disaster recovery scheme based on a disaster-by-disaster compensation approach, the GCIF should work as a *global insurance mechanism*, where the premia would be paid according to polluting countries' historical and current responsibilities in CO_2 emissions. A post disaster fund would leave aside most L&D costs inflicted by slow-onset processes, to which countries such as SIDS are disproportionately vulnerable (Massa et al., 2023), and would introduce a moral hazard issue as it reduces the incentive for adaptation measures that could reduce loss and damages. Countries would indeed engage very low preventive measures and expect a post-disaster fund to cover all their costs in the wake of climate disasters. In the case of the proposed global insurance model, in order to reduce the moral hazard issues typically associated with insurance schemes, the GCIF should ensure that beneficiary countries do take adaptation and prevention measures, for example by including a precondition to enter the insurance scheme based on countries' efforts to prevent damages (e.g. to prohibit new constructions in floodplains). The fact that the share of L&D caused by natural processes is planned to be shared among all countries (not only polluting countries) is an additional guarantee to reduce the moral hazard issue.

Allocations from the GCIF should be in the form of restorative payments equal to the costs of human-induced adaptation and L&D a country is bearing, net of the costs for which they are responsible towards other countries. Every country is considered as a contributor and a recipient of the Fund. If a country faces as many costs as it is responsible for vis-à-vis the rest of the world, then it should receive no net payments from the GCIF. If its responsibility in climate adaptation and L&D costs is greater than the costs it faces (as will be true for most HICs), then the country will pay more to the GCIF than it will receive from the GCIF. If its share of priced historical emissions is lower than its adaptation and L&D costs (as most of the SIDS, Low-Income Countries (LICs) and Lower-Middle-Income Countries (LMICs)), then it will receive more from the GCIF than it will pay to the GCIF. A double track could be envisioned to apply for funding from the GCIF. On one hand, countries could apply for funding their incremental adaptation costs, based on their long-term resilience plans and SDG pathways. The GCIF would be therefore more than an insurance scheme, incentivizing planning and ensuring quality spending. On the other hand, countries affected by human-induced L&D from both extreme weather events and slow-onset processes could receive funding to compensate for the costs.

The GCIF should operate as a new, independent, stand-alone institution, as stressed in the TC's final institutional arrangement proposal (TC, 2023b), to avoid tipping the balance of power toward developed countries parties. Hence, the GCIF will decide on its own for contribution, eligibility, and allocation criteria, among others. Access to the funds should be simplified and countries should be able to use their existing reporting and accounting systems to prevent delays and additional costs to adapt to new settings. Major multilateral development banks (MDBs) (e.g. the World Bank, the IMF, or regional MDBs) would be in charge of the disbursements of funds allocated by the GCIF to affected countries, without adding any form of conditionality. The MDBs could also oversee the spending of the funds and make sure beneficiary countries comply with the requirements on adaptation spending to avoid moral hazard issues associated with insurance payments. The Global Fund to fight HIV/AIDS, tuberculosis and malaria, and its eight design principles[14], stand as a model of inspiration for designing the GCIF. The Global Fund has indeed proved that pooled international financing could accelerate progress in addressing global challenges (Sachs & Schmidt-Traub, 2017).

5. Conclusion

Anthropogenic activities have been the main driver for climate change since the industrial revolution. GHG emissions, notably carbon dioxide (CO_2), are the largest contributors to human-induced climate change. The consequences of climate change are extreme weather events and slow-onset processes threatening the universal human right to a clean, healthy, and sustainable environment. While high-income countries historically produce the most significant proportion of GHG emissions, climate change is disproportionally impacting vulnerable countries whose contribution to anthropogenic climate change has been marginal. The financial burden of climate responses through adaptation and initiatives addressing L&D largely falls on affected nations, raising calls for reparations and climate justice.

Measuring costs related to adaptation and L&D, and determining who should pay for their human-induced share, is a key but complex exercise. Currently, there is no universally accepted framework to quantify these costs and determine fair sharing mechanisms among nations. As a starting point, building on the literature, this paper provides a taxonomy defining climate-induced costs as the sum of mitigation costs and climate impact costs, with the latter category including adaptation and L&D costs. While mitigation costs are defined as costs for

[14] The Global Fund has eight design principles: (1) country-led, (2) multistakeholder, (3) independent, transparent, technical review and evaluation; (4) political independence; (5) needs-based pooled financing; (6) funding for programs integrated in broader health systems; (7) performance-based funding; (8) financing only (Sachs & Schmidt-Traub, 2017).

cutting emissions to diminish the anthropogenic pressures over climate change, the taxonomy highlights that the concept of reparative justice should apply to adaptation and L&D costs.

Using useful guidelines from the existing literature, the paper presents then a pilot integrated methodological and conceptual framework to quantify and fairly split the burden of climate impact costs from anthropogenic climate change, among responsible countries. As a first step, the framework proposes to assess total adaptation and L&D costs using harmonized indicator frameworks that could be readily used by policymakers. The second step is to identify the share of climate impact costs due to anthropogenic activities versus natural weather variability. The third step consists of measuring countries' individual contribution to global GHG emissions. The fourth and final step builds on previous steps, and estimates the share of adaptation and L&D costs for which countries are individually responsible toward affected countries, given their contribution to global anthropogenic climate change.

The framework leads to the proposal of a Global Climate Impact Fund (GCIF) seeking to restore climate justice by relying on countries' individual contributions linked to their historical and current responsibility in GHG emissions. The Fund should be established as an independent institution aiming to cover adaptation and L&D costs derived from human-induced climate change. It should also offer access to countries on the basis of standardized criteria, and by simplifying processes and averting additional costs. The GCIF should work in the form of a global insurance mechanism where countries should receive restorative payments equivalent to the costs of human-induced adaptation and L&D costs net of the share of global costs they are responsible toward the rest of the world. Beneficiaries would in turn be responsible for preparing science-based and credible long-term resilience and SDG pathways as well as detailed project proposals to show precisely how the additional funds will be invested for long-term adaptation.

Areas for future research and policy action include applying the proposed cost indicator frameworks in country-case studies with the aim of further selecting, prioritizing, and refining the indicators presented in the paper. In this regard, the issue of data availability is of paramount importance. There is an urgent need for robust, granular, and timely data to obtain reliable estimates of adaptation and L&D costs. Efforts are needed to measure non-economic costs as well as L&D costs due to slow-onset processes that tend to be underestimated. Moreover, as we propose to build the Fund on the principle of historical and current responsibility in global GHG emissions, further research should lead to a commonly agreed starting date to account for countries' emissions. The price per ton that would be defined is another area for future research, as one could argue that the price per ton of CO_2 emissions could be higher for richer countries. Finally, the current mechanisms of the Loss and Damage Fund proposed by the Transitional Committee, or the GCIF proposed in this paper, may not be sufficient to cover for the financing gaps in addressing adaptation and L&D costs. Therefore, future research and policy action should look at the role of private sector and innovative financing in the overall financing scheme for climate impact costs.

Annexes

Annex 1. Proposed adaptation indicator framework

Sector	Adaptation measures to be costed	Examples of adaptation indicators useful to cost adaptation
Agriculture, Fisheries and Forestry	Adopt climate-smart agriculture techniques	Share of agricultural production issued from climate-resilient seeds (%) (e.g. salt-tolerant seeds)
	Increase crop and livestock diversification	Degree of crop and livestock diversification
	Reduce overfishing	Fishes caught that are then discarded (%) Number and levels of fishing quotas
	Improve soil management (e.g. desalinization methods, efficient irrigation)	Area affected by salinization (% arable land) Irrigated area (% arable land)
	Improve water management (e.g. rainwater harvesting)	Average rainwater harvesting tanks capacity (liters) Freshwater withdrawal (% of available freshwater resources)
	Improved storage and processing to reduce post-harvest losses	Penetration rate of metal silos technology among small farmers (%)
Environment	Improve flood protection	Share of coastal area at risk of flooding protected with sea walls or advanced shoreline (%)
	Improve wildfire protection	Forest area treated with prescribed fire (%)
	Reforestation	Tree density Change in tree cover (%)
	Invest in protected areas	Mean area that is protected in terrestrial and freshwater sites important to biodiversity (%)
	Promote green areas in cities	Share of the urban population with access to green area within 15 minutes' walking distance (%)
Financing	Enhance international financing for adaptation	Amount of ODA and private financing received and allocated to climate change adaptation (USD per capita)
		Amount of financing received from catastrophe-bonds and disaster-contingency funds (USD per capita)
	Enhance internal financing for adaptation	Number of financial incentives for climate adaptation including taxes and subsidies
		Public expenditure allocated to climate change adaptation (% GDP)
		Public expenditure allocated to resilient infrastructure (% GDP)
		Share of credit to households using micro-finance schemes (e.g. to support resilient housing) (%)
		Share of key assets protected by insurance in the energy, WASH, and agriculture sectors (%)
Human and cultural	Relocate people living in climate-related risk areas (e.g. low-lying areas)	Share of the population living in climate-related risk areas that has been relocated (%)
	Enhance social safety nets and social protection (e.g. food banks)	Household cash transfers (% GDP) Share of food surpluses that is stored (%)
	Invest in public health services (e.g. vaccination programs, emergency services)	Surviving infants who received 2 WHO-recommended vaccines (%) Share of patients admitted in trauma services who died within 24 hours after hospitalization (%)
	Promote sharing of local and traditional knowledge	Number of adaptation initiatives sourced from indigenous knowledge
	Improve education on adaptation and climate change (e.g. school programs, media communications)	Climate change is included in primary and secondary education national curricula (Yes: 1; No: 0)

Industry	Increase due diligence	Share of private companies issuing sustainability reports (%)
Infrastructure	Transport and road infrastructure adaptation	Expenditure on road maintenance (% GDP)
	Adjusting power plants infrastructure and electricity grids to climate events	Share of underground electricity cabling (%)
	Enhance waste management	Share of municipal waste collected and safely treated (%)
	Ensure climate-resistant housing infrastructure	Share of buildings resilient to climate hazards (%) (e.g. sismic risk, floating housing, etc.) Share of buildings with improved insulation (%)
Innovation	Contribute to the diffusion of climate change adaptation technologies	Triadic patent families filed in the field of climate protection (per million population)
	Invest in the development of early warning systems (e.g. hazard mapping and monitoring technology, remote sensing)	Use of early warning systems for short-, medium- and long-term decisions in the agricultural sector
	Improve hazard data collection (e.g. integrate indigenous climate observations)	Statistical Performance Index (worst 0-100 best)
	Development and adoption of easy-to-use risk assessment tools	Risk assessment processes are built on a multi-governance approach (Yes: 1; No: 0)
Institutions	Creation and implementation of national, regional, subnational and local adaptation plans	The national government has issued an adaptation plan (Yes: 1; No: 0) Share of regional and subnational authorities having issued local adaptation plans (%)
	Creation and implementation of city-level, district-level and sectoral adaptation plans	Number of local authorities having issued sectoral adaptation plans (%)
	Include indigenous and traditional knowledge in the design of adaptation plans at all levels	Share of indigenous people members of subnational public administrations (%)
	Expand laws and regulations promoting adaptation (e.g. building standards, protected areas, land zoning)	Share of new laws and regulations that were adopted during the year in relation to adaptation to climate change (%)

Sources: Authors' elaboration based on Noble et al. (2014); OECD (2022); Mycoo et al. (2022); Government of Fiji (2017); Goonesekera and Olazabal (2022).

Annex 2. Proposed L&D cost indicator framework

Sector	Loss & Damage Indicator	Cost indicator	Type of cost	Climate event
Agriculture, fisheries and forestry	Volume of crops already produced and expected to be sold that were destroyed by natural hazards, by type of crop (tons)	Value of crops destroyed (USD per capita): multiply the volume of each crop c by its market value and aggregate the total value; divide by the population size loss_crop = (SUM(vol_c * price_c)) / pop	Economic Direct	Extreme weather event
	Area of productive land damaged by natural hazards (hectares)	Loss of production (USD per capita): for each type of crop, multiply the area of land destroyed by the crop yield per hectare and the crop price ; aggregate the total value ; divide by the population size loss_land = (SUM(area_c * yield_c * price_c))/pop	Economic Indirect	Extreme weather event
	Land surface affected by soil salinisation (hectares)	Estimated value of production loss (USD per capita): multiply the area of land affected by salinisation by the crop yield loss in tons per hectare and the market price of each crop c ; divide by the population size loss_salin = (SUM(area_c * yield_c * price_c)) / pop	Economic Indirect	Slow-onset process
	Number of irrigation or other drainage system items destoyed by natural hazards	Replacement cost of irrigation or other drainage systems (USD per capita): multiply the number of items destroyed (resp. damaged) by their price (resp. repair cost) and aggregate the total value; divide by the population size repl_irrig = ((n_dest * price) + (n_dam * repair_cost)) / pop	Economic Direct	Extreme weather event
	Number of livestock lost after natural hazards, by type of livestock	Value of livestock (USD per capita): multiply the number of each livestock ls by its market value and aggregate the total value; divide by the population size loss_livestock = (SUM(n_ls * price_ls)) / pop	Economic Direct	Extreme weather event
	Number of fish farms lost after natural hazards	Loss of fish production (USD per capita): Multiply the average number of fishes in fish farms by their market value ; divide by the population size loss_fish = (nfish * price) / pop	Economic Indirect	Extreme weather event
	Volume of timber loss (tons)	Value of timber destroyed (USD per capita): multiply the volume timber lost by its market value ; divide by the population size loss_timber = (vol_timber * price) / pop	Economic Indirect	Extreme weather event
	Area of productive forest damaged by natural hazards (hectares)	Forest restoration cost (USD per hectare): Multiply the seeds cost per kg by the seeds needed per hectare of land forest_restore = cost_seeds * n_seeds	Economic Direct	Extreme weather event
	Number of agriculture, aquaculture and forestry machinery and equipments destroyed or damaged by natural hazards	Replacement cost of machinery and equipments (USD per capita): multiply the number of items destroyed (resp. damaged) by their price (resp. repair cost) and aggregate the total value; divide by the population size	Economic Direct	Extreme weather event

		repl_agri_machine = ((n_dest * price) + (n_dam * repair_cost)) / pop		
	Number of jobs in the agriculture, fisheries and forestry sectors lost after natural hazards	Loss of income in the agriculture, fisheries and forestry sectors (USD per capita): Multiply the number of jobs lost by the average individual income in each sector s ; divided by the population size loss_inc = (SUM(njobs_s * avincome_s)) / pop	Economic Indirect	Extreme weather event
Environment	Change in tree cover (unexploited forest) (%)	Proxy - Forest restoration cost (USD per hectare): Multiply the seeds cost per kg by the seeds needed per hectare of land forest_restore = cost_seeds * n_seeds	Non-economic	Extreme weather event Slow-onset process
	Change in species abundance and occupancy	Cost of conserving endangered species (IUCN Red List) (USD per capita): the Conservation Opportunity Index measures the costs of achieving conservation of species in their natural habitat and in zoos (See methdology source)	Non-economic	Extreme weather event Slow-onset process
	Area affected by desertification (hectares)	Cost of land rehabilitation (USD per hectare): by type of land (e.g. irrigated land, rainfed, rangeland), multiply the land affected by desertification with the average rehabilitation cost per hectare. The average rehabilitation cost per hectare varies according to the local availability of trained technical workers, equipment, transportation, among other elements	Non-economic	Slow-onset process
	Coral reef area affected by coral bleaching (hectares)	Cost of coral bleaching (USD per capita) proxied by the economic loss in the fishery sector, tourism sector, and loss of flood protection (See methodology source)	Economic & Non-economic	Slow-onset process
Human and cultural	Number of people who died or went missing after natural hazards (per 100 000 population)	Cost of fatalities and missing population (USD per capita): Multiply the number of fatalities or missed persons by the Value of Statistical Life ; divide by population size cost_fatalities = (n_fatalities + n_missing) * VSL / pop	Non-economic	Extreme weather event
	Number of people who were injured during natural hazards (per 100 000 population)	Cost of injuries (USD per capita): Multiply the number of injured people by the average hospital cost for injuries per capita ; divide by population cost_injuries = n_injured * av_hospcost / pop	Non-economic	Extreme weather event
	Number of people who fell below the national poverty line (per 100 000 population)	Social safety cost (USD per capita): multiply the number of people who fell into poverty by the average public expenditure on social protection per capita ; divide by the population size cost_poverty = n_pov * av_expsocial / pop	Economic Indirect	Extreme weather event Slow-onset process
	Number of persons whose house was destroyed or severaly damaged by natural hazards	Relocation cost (USD per capita): Multiply the number of people whose house was destroyed by the average relocation cost per capita in the area ; divide by the population size cost_relocation = n_houses * av_reloccost	Non-economic	Extreme weather event Slow-onset process

	Number of people suffering from mental health issues after natural hazards (per 100 000 population)	Mental health costs (USD per capita): Multiply the number of people affected by natural hazards by the average public mental healthcare expenditure per capita ; divide by the population size cost_mental = n_affected * av_mentalexp / pop	Non-economic	Extreme weather event Slow-onset process
	Number of people who fell into food insecurity (per 100 000 population)	Cost of humanitarian assistance (USD per capita): Multiply the number of people who fell into food insecurity by the average humanitarian assistance received per capita in the area ; divide by the population size fis = (n_fis * av_humassist) / pop	Economic Indirect	Extreme weather event Slow-onset process
	Number of tangible cultural heritage (incl. Cultural or historical assets, monuments or sites destroyed or damaged by natural hazards) (per 100 000 population)	Value of cultural heritage lost (USD per capita) estimated through the repair costs aggregated to the estimated economic impact of the loss of cultural sites (e.g. degree of damage of its historical or touristic function) (See methodology source)	Economic (indirect) & Non-economic	Extreme weather event Slow-onset process
	Loss of intangible cultural heritage (incl. Cultural identity, cultural practices and traditions, sense of place)	Assess through local surveys the population willingness-to-pay for the preservation of a set of cultural traditions (See methodology source)	Non-economic	Extreme weather event Slow-onset process
Industry	Number of raw material, machinery and equipments destroyed or damaged by natural hazards	Replacement cost of industrial machinery and equipment (USD per capita): Multiply the number of items destroyed (resp. damaged) by their price (resp. repair cost) and aggregate the total value; divide by the population size repl_ind_machine = ((n_dest * price) + (n_dam * repair_cost)) / pop	Economic Direct	Extreme weather event
	Number of jobs lost after natural hazards	Loss of income in industry (USD per capita): For each industry "ind", multiply the number of jobs lost by the average individual income; aggregate the total value and divide by the population size loss_inc = (SUM(njobs_ind * avincome_ind)) / pop	Economic Indirect	Extreme weather event
	Loss of production after natural hazards	Change in GDP per capita in each productive sector (%) (e.g. manufacture, tourism, trade, services)	Economic Indirect	Extreme weather event
Infrastructure	Number of houses destroyed or damaged by natural hazards (per 100 000 population)	Housing replacement cost (USD per capita): Multiply the number of houses destroyed (resp. damaged) by the cost to build new houses (resp. to repair houses); aggregate the total value and divide by the population repl_housing = ((n_dest * cost_build) + (n_dam * cost_repair)) / pop	Economic Direct	Extreme weather event
	Length of roads and railways destroyed or damaged by natural hazards (km)	Roads and railways replacement cost (USD per capita): Multiply the number of kilometers of roads (resp. railways and bridges) destroyed by the cost to build one kilometer of road (resp. railways and bridges); aggregate the total value; divide by the population size. The different types of roads can also be taken into account (e.g. highway, secondary road) repl_roadsrails = ((km_roads * cost_kmroad) + (km_rails * cost_kmrail) + (km_bridge cost_kmbridge)) / pop	Economic Direct	Extreme weather event

Number of airports and ports destroyed or damaged after natural hazards	Airports and ports replacement cost (USD per capita): Multiply the number of airports and ports destroyed (resp. damaged) by the average cost of reconstruction (resp. cost of reparation); divide by the population size repl_transp = ((n_dest * av_construct) + (n_dam * av_repair)) / pop	Economic Direct	Extreme weather event
Number of schools destroyed or damaged by natural hazards	Schools replacement cost (USD per capita): Multiply the number of schools destroyed (resp. damaged) by the average cost of reconstruction (resp. cost of reparation) in the area; divide by the population size repl_schools = ((n_dest * av_construct) + (n_dam * av_repair)) / pop	Economic Direct	Extreme weather event
Number of school material and equipments destroyed or damaged by natural hazards	Scool material replacement cost (USD per capita): Multiply the number of schooling material and equipment "me" destroyed (resp. damaged) by their respective price (resp. cost of reparation) in the area; divide by the population size repl_material = ((n_dest_me * price) + (n_dam_me * repair_cost)) / pop	Economic Direct	Extreme weather event
Number of healthcare facilities destroyed or damaged by natural hazards	Healthcare facilities replacement cost (USD per capita): Multiply the number of healthcare facilities destroyed (resp. damaged) by the average cost of reconstruction (resp. cost of reparation) in the area; divide by the population size repl_hosp = ((n_dest * av_construct) + (n_dam * av_repair)) / pop	Economic Direct	Extreme weather event
Number of medical material and equipment destroyed or damaged by natural hazards	Medical equipment replacement cost (USD per capita): Multiply the number of healthcare material and equipment destroyed (resp. damaged) by their price (resp. cost of reparation) in the area; divide by the population size repl_material = ((n_dest_me * price) + (n_dam_me * repair_cost)) / pop	Economic Direct	Extreme weather event
Number of government buildings destroyed or damaged by natural hazards	Government buildings replacement cost (USD per capita): Multiply the number of government buildings destroyed (resp. damaged) by the average cost of reconstruction (resp. cost of reparation) in the area; divide by the population size repl_govbuild = ((n_dest * av_construct) + (n_dam * av_repair)) / pop	Economic Direct	Extreme weather event
Number of industrial facilities destroyed or damaged by natural hazards	Industrial facilities replacement cost (USD per capita): Multiply the number of industrial destroyed (resp. damaged) by the average cost of reconstruction (resp. cost of reparation) in the area; divide by the population size repl_indfaci = ((n_dest * av_construct) + (n_dam * av_repair)) / pop	Economic Direct	Extreme weather event
Number of industrial material and equipment destroyed or damaged by natural hazards	Industrial material replacement cost (USD per capita): Multiply the number of industrial material and equipment destroyed (resp. damaged) by their price (resp. cost of reparation) in the area; divide by the population size repl_material = ((n_dest_me * price) + (n_dam_me * repair_cost)) / pop	Economic Direct	Extreme weather event
Length of electrical distribution grids and lines destroyed or damaged by natural hazards (km)	Electrical grid replacement cost (USD per capita): Multiply the number of kilometers of electrical grids destroyed (resp. damaged) by the cost to build (resp. repair) one km of grid; aggregate the total value; divide by the population size	Economic Direct	Extreme weather event

	repl_electgrid = ((km_dest * av_construct) + (km_dam * av_repair)) / pop		
Number of electrical power plants destroyed or damaged by natural hazards	Electrical plants replacement cost (USD per capita): Multiply the number of electrical power plants destroyed (resp. damaged) by their construction cost (resp. reparation cost) in the area; divide by the population size repl_elecplant = ((n_dest * av_construct) + (n_dam * av_repair)) / pop	Economic Direct	Extreme weather event
Length of water, sanitation and hygiene (WASH) grid destroyed or damaged by natural hazards (km)	WASH grid replacement cost (USD per capita): Multiply the number of kilometers of WASH grids destroyed (resp. damaged) by the cost to build (resp. repair) one km of the grid; aggregate the total value; divide by the population size repl_wash = ((km_dest * av_construct) + (km_dam * av_repair)) / pop	Economic Direct	Extreme weather event
Length of telecommunication infrastructure destroyed or damaged by natural hazards (km)	Telecommunication grid replacement cost (USD per capita): Multiply the number of kilometers of telecommunication grids destroyed (resp. damaged) by the cost to build (resp. repair) one km of the grid; aggregate the total value; divide by the population size repl_wash = ((km_dest * av_construct) + (km_dam * av_repair)) / pop	Economic Direct	Extreme weather event

Sources: Authors' elaboration based on De Groeve et al.(2015); UNESCAP (2017); Youth Innovation Lab (2020); Jovel and Mudahar (2010); Serdeczny et al. (2016); IRDR (2015); Bahinipati and Gupta (2022).

Annex 3. Suggestions of potential useful data sources to assess L&D costs

Sector	Cost indicator	Potential useful data source (global, open access)	Potential useful data source (global, restricted access)	Potential useful data source (local initiatives)	Data download link	Notes on the cost indicator
Agriculture, fisheries and forestry	Value of crops destroyed (USD per capita): multiply the volume of each crop c by its market value and aggregate the total value; divide by the population size loss_crop = (SUM(vol_c * price_c)) / pop	EM-DAT DesInventar FAO UN Stats		Local survey		
	Loss of production (USD per capita): for each type of crop, multiply the area of land destroyed by the crop yield per hectare and the crop price ; aggregate the total value ; divide by the population size loss_land = (SUM(area_c * yield_c * price_c))/pop	DesInventar FAO UN Stats		Local survey		
	Estimated value of production loss (USD per capita): multiply the area of land affected by salinisation by the crop yield loss in tons per hectare and the market price of each crop c ; divide by the population size loss_salin = (SUM(area_c * yield_c * price_c)) / pop	Ruto et al. (2021), "Economic Impact of Soil Salinization and the Potential for Saline Agriculture", In: Future of Sustainable Agriculture in Saline Environments		Local survey	https://northsearegion.eu/media/14789/chap2-economic-analysis-of-salinization.pdf	Other (economic and non-economic) costs associated with soil salinisation exist, including: environmental costs, land value, investment, employment, food supply chains, etc.
	Replacement cost of irrigation or other drainage systems (USD per capita): multiply the number of items destroyed (resp. damaged) by their price (resp. repair cost) and aggregate the total value; divide by the population size repl_irrig = ((n_dest * price) + (n_dam * repair_cost)) / pop	DesInventar FAO UN Stats		Local survey		
	Value of livestock (USD per capita): multiply the number of each livestock ls by its market value and aggregate the total value; divide by the population size loss_livestock = (SUM(n_ls * price_ls)) / pop	DesInventar FAO UN Stats		Local survey		
	Loss of fish production (USD per capita): Multiply the average number of fishes in fish farms by their market value ; divide by the population size	FAO UN Stats		Local survey		

	loss_fish = (nfish * price) / pop				
	Value of timber destroyed (USD per capita): multiply the volume timber lost by its market value ; divide by the population size loss_timber = (vol_timber * price) / pop	DesInventar FAO UN Stats	Local survey		
	Forest restoration cost (USD per hectare): Multiply the seeds cost per kg by the seeds needed per hectare of land forest_restore = cost_seeds * n_seeds	DesInventar FAO UN Stats	Local survey		
	Replacement cost of machinery and equipments (USD per capita): multiply the number of items destroyed (resp. damaged) by their price (resp. repair cost) and aggregate the total value; divide by the population size repl_agri_machine = ((n_dest * price) + (n_dam * repair_cost)) / pop	DesInventar EM-DAT FAO UN Stats	Local survey		
	Loss of income in the agriculture, fisheries and forestry sectors (USD per capita): Multiply the number of jobs lost by the average individual income in each sector s ; divided by the population size loss_inc = (SUM(njobs_s * avincome_s)) / pop	DesInventar World Bank	Local survey National statistical office		
Environment	Proxy - Forest restoration cost (USD per hectare): Multiply the seeds cost per kg by the seeds needed per hectare of land forest_restore = cost_seeds * n_seeds	OECD FAO World Bank		Example: http://mneguidelines.oecd.org/draft-oecd-fao-handbook-on-deforestation-forest-degradation-and-due-diligence-in-agricultural-supply-chains.pdf	Other (economic and non-economic) costs associated with the loss of tree cover exist, including: the health-related costs of tree loss in urban environment, the costs of tree loss on species survival and biodiversity, the costs for growing trees rather than costs for planting trees, etc.
	Cost of conserving endangered species (IUCN Red List) (USD per capita): the Conservation Opportunity Index measures the costs of achieving conservation of species in their natural habitat and in zoos (See methdology source)	Conde et al. (2015), "Opportunities and costs for preventing vertebrate extinctions", Current Biology Correspondance, Vol. 25, Issue 6		https://www.cell.com/current-biology/fulltext/S0960-9822(15)00080-9?_returnURL=https%3A%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS0960982215000809%3Fshowall%3Dtrue	

	Cost of land rehabilitation (USD per hectare): by type of land (e.g. irrigated land, rainfed, rangeland), multiply the land affected by desertification with the average rehabilitation cost per hectare. The average rehabilitation cost per hectare varies according to the local availability of trained technical workers, equipment, transportation, among other elements	FAO World Bank			Example: http://www.ciesin.org/docs/002-186/002-186.html
	Cost of coral bleaching (USD per capita) proxied by the economic loss in the fishery sector, tourism sector, and loss of flood protection (See methodology source)	Cesar et al. (2003), "The economics of worldwide coral reef degradation", Cesar Environmental Economics Consulting Beck et al. (2018), "The global flood protection savings provided by coral reefs", Nature Communications, Vol. 9, n°2186			https://www.wwf.or.jp/activities/lib/pdf_marine/coral-reef/cesardegradationreport100203.pdf https://www.nature.com/articles/s41467-018-04568-z
Human and cultural	Cost of fatalities and missing population (USD per capita): Multiply the number of fatalities or missed persons by the Value of Statistical Life ; divide by population size cost_fatalities = (n_fatalities + n_missing) * VSL / pop	EM-DAT DesInventar	SIGMA NetCatSer	Local survey	
	Cost of injuries (USD per capita): Multiply the number of injured people by the average hospital cost for injuries per capita ; divide by population cost_injuries = n_injured * av_hospcost / pop	EM-DAT DesInventar	SIGMA NetCatSer	Local survey	
	Social safety cost (USD per capita): multiply the number of people who fell into poverty by the average public expenditure on social protection per capita ; divide by the population size cost_poverty = n_pov * av_expsocial / pop	World Bank		Local survey	
	Relocation cost (USD per capita): Multiply the number of people whose house was destroyed by the average relocation cost per capita in the area ; divide by the population size cost_relocation = n_houses * av_reloccost	EM-DAT		Local survey	
	Additional expenses for justice and security (USD per capita)	IMF COFOG UNDOC IMF COFOG	Gallup World Poll		https://ga.gallup.com/ https://dataunodc.un.org/content/homicide-country-data

	Mental health costs (USD per capita): Multiply the number of people affected by natural hazards by the average public mental healthcare expenditure per capita ; divide by the population size cost_mental = n_affected * av_mentalexp / pop	WHO (proxy: mental hospital admissions)		Local survey	https://www.who.int/data/gho/data/indicators/indicators-index	
	Cost of humanitarian assistance (USD per capita): Multiply the number of people who fell into food insecurity by the average humanitarian assistance received per capita in the area ; divide by the population size fis = (n_fis * av_humassist) / pop	WHO, WFP, DAC, OCHA		Local survey		Other (economic and non-economic) costs associated with food insecurity exist, including: decreased educational attainment, decreased incomes on the long-term, increased social protection expenditure, decreased well-being, higher expenses spent on food imports, etc.
	Value of cultural heritage lost (USD per capita) estimated through the repair costs aggregated to the estimated economic impact of the loss of cultural sites (e.g. degree of damage of its historical or touristic function) (See methodology source)	See costing methodology by Romão and Paupério (2018), "An indicator for the economic loss in value of damaged cultural heritage properties", 8th ICBR - International Conference on Building Resilience		Local survey	https://repositorio-aberto.up.pt/handle/10216/119545	
	Assess through local surveys the population willingness-to-pay for the preservation of a set of cultural traditions (See methodology source)	Example: Vondolia et al. (2022), "Valuing Intangible Cultural Heritage in Developing Countries", Sustainability, Vol. 14, Issue 8, p. 4484		Local survey	https://doi.org/10.3390/su14084484	
Industry	Replacement cost of industrial machinery and equipment (USD per capita): Multiply the number of items destroyed (resp. damaged) by their price (resp. repair cost) and aggregate the total value; divide by the population size repl_ind_machine = ((n_dest * price) + (n_dam * repair_cost)) / pop					
	Loss of income in industry (USD per capita): For each industry "ind", multiply the number of jobs lost by the average individual income; aggregate the total value and divide by the population size			Local survey		

	loss_inc = (SUM(njobs_ind * avincome_ind)) / pop			
	Change in GDP per capita in each productive sector (%) (e.g. manufacture, tourism, trade, services)			
Infrastructure	Housing replacement cost (USD per capita): Multiply the number of houses destroyed (resp. damaged) by the cost to build new houses (resp. to repair houses); aggregate the total value and divide by the population repl_housing = ((n_dest * cost_build) + (n_dam * cost_repair)) / pop	EM-DAT DesInventar	NetCatSer	Local survey
	Roads and railways replacement cost (USD per capita): Multiply the number of kilometers of roads (resp. railways and bridges) destroyed by the cost to build one kilometer of road (resp. railways and bridges); aggregate the total value; divide by the population size. The different types of roads can also be taken into account (e.g. highway, secondary road) repl_roadsrails = ((km_roads * cost_kmroad) + (km_rails * cost_kmrail) + (km_bridge cost_kmbridge)) / pop			Local survey
	Airports and ports replacement cost (USD per capita): Multiply the number of airports and ports destroyed (resp. damaged) by the average cost of reconstruction (resp. cost of reparation); divide by the population size repl_transp = ((n_dest * av_construct) + (n_dam * av_repair)) / pop	EM-DAT DesInventar	NetCatSer	Local survey
	Schools replacement cost (USD per capita): Multiply the number of schools destroyed (resp. damaged) by the average cost of reconstruction (resp. cost of reparation) in the area; divide by the population size repl_schools = ((n_dest * av_construct) + (n_dam * av_repair)) / pop	EM-DAT DesInventar	NetCatSer	Local survey
	Scool material replacement cost (USD per capita): Multiply the number of schooling material and equipment "me" destroyed (resp. damaged) by their respective price (resp. cost of reparation) in the area; divide by the population size repl_material = ((n_dest_me * price) + (n_dam_me * repair_cost)) / pop	EM-DAT DesInventar	NetCatSer	Local survey
	Healthcare facilities replacement cost (USD per capita): Multiply the number of healthcare facilities destroyed (resp. damaged) by the average cost of reconstruction (resp. cost of	EM-DAT DesInventar	NetCatSer	Local survey

reparation) in the area; divide by the population size repl_hosp = ((n_dest * av_construct) + (n_dam * av_repair)) / pop			
Medical equipment replacement cost (USD per capita): Multiply the number of healthcare material and equipment destroyed (resp. damaged) by their price (resp. cost of reparation) in the area; divide by the population size repl_material = ((n_dest_me * price) + (n_dam_me * repair_cost)) / pop	EM-DAT DesInventar	NetCatSer	Local survey
Government buildings replacement cost (USD per capita): Multiply the number of government buildings destroyed (resp. damaged) by the average cost of reconstruction (resp. cost of reparation) in the area; divide by the population size repl_govbuild = ((n_dest * av_construct) + (n_dam * av_repair)) / pop	EM-DAT DesInventar	NetCatSer	Local survey
Industrial facilities replacement cost (USD per capita): Multiply the number of industrial destroyed (resp. damaged) by the average cost of reconstruction (resp. cost of reparation) in the area; divide by the population size repl_indfaci = ((n_dest * av_construct) + (n_dam * av_repair)) / pop	EM-DAT DesInventar	NetCatSer	Local survey
Industrial material replacement cost (USD per capita): Multiply the number of industrial material and equipment destroyed (resp. damaged) by their price (resp. cost of reparation) in the area; divide by the population size repl_material = ((n_dest_me * price) + (n_dam_me * repair_cost)) / pop	EM-DAT DesInventar	NetCatSer	Local survey
Electrical grid replacement cost (USD per capita): Multiply the number of kilometers of electrical grids destroyed (resp. damaged) by the cost to build (resp. repair) one km of grid; aggregate the total value; divide by the population size repl_electgrid = ((km_dest * av_construct) + (km_dam * av_repair)) / pop	EM-DAT DesInventar	NetCatSer	Local survey
Electrical plants replacement cost (USD per capita): Multiply the number of electrical power plants destroyed (resp. damaged) by their construction cost (resp. reparation cost) in the area; divide by the population size repl_elecplant = ((n_dest * av_construct) + (n_dam * av_repair)) / pop	EM-DAT DesInventar	NetCatSer	Local survey

WASH grid replacement cost (USD per capita): Multiply the number of kilometers of WASH grids destroyed (resp. damaged) by the cost to build (resp. repair) one km of the grid; aggregate the total value; divide by the population size repl_wash = ((km_dest * av_construct) + (km_dam * av_repair)) / pop	EM-DAT DesInventar	NetCatSer	Local survey
Telecommunication grid replacement cost (USD per capita): Multiply the number of kilometers of telecommunication grids destroyed (resp. damaged) by the cost to build (resp. repair) one km of the grid; aggregate the total value; divide by the population size repl_wash = ((km_dest * av_construct) + (km_dam * av_repair)) / pop	EM-DAT DesInventar	NetCatSer	Local survey

Sources: Authors' elaboration based on EU (2015); UNESCAP (2017); Youth Innovation Lab (2020); Jovel and Mudahar (2010); Serdeczny et al. (2016); IRDR (2015); Bahinipati and Gupta (2022).

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