PLOS CLIMATE

REVIEW

Bridging evidence gaps in attributing loss and damage, and measures to minimize impacts

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Abstract

Losses and damages from climate change have been increasing as global temperatures continue to rise above pre-industrial levels. Low-income, climate vulnerable countries bear a disproportionate share of these losses and damages. After decades of international negotiations, the Loss and Damage Fund was established in late 2022, aiming at addressing both economic and non-economic losses arising from slow- and sudden-onset climate change events. Recognizing the complex nature of climate-related events, the establishment of the Loss and Damage Fund underscores an urgent need for precise attribution of these events to climate change, highlighting the fund's reliance on scientific evidence to guide its efforts. Attribution science, which decouples specific causes of changes in climate hazards and impacts, can support loss and damage negotiations. Low-income countries, which have contributed the least to climate change, are experiencing more severe impacts. However, data quality and coverage required for scientific studies to attribute loss and damage to climate change remain limited in these developing countries. In this paper, we highlight the challenges to attribute losses and damages to climate change in developing countries and underscore strategies to overcome those challenges using examples from the agrifood sector. These strategies have implications for the operationalizing of the Loss and Damage Fund. We emphasize how improving data availability and quality can lead to rigorous scientific conclusions, supporting evidence-based, inclusive, and effective interventions. We also indicated measures that enable strengthening climate resilience to avoid and minimize losses and damages.

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1. Introduction

People worldwide are increasingly experiencing the impacts of climate change from both long-term shifts and sudden onset events. The extreme conditions resulting from climate change have increasingly more pronounced impacts on both human and natural systems, resulting from greater intensity and frequency of extreme climate events, such as droughts, floods, heat waves, cyclones, and wildfires, as well as slow-onset events, such as biodiversity loss, rising temperatures, and sea level rise [1].

Climate change impacts have already caused human, social, environmental, and economic losses and damages [2–4], defined as "adverse observed impacts and/or projected risks [that] can be economic and/or non-economic" [1]. Climate-related losses and damages encompass both economic and non-economic aspects [2, 5], with economic losses involving market-traded resources, goods and services, while non-economic losses are often intangible and not commonly traded in markets, such as life, health, displacement and human mobility, territory, cultural heritage, indigenous/local knowledge, biodiversity and ecosystem services [6, 7].

The increasing losses and damages due to climate change have heightened policy dialogues on Loss and Damage, resulting in the establishment of the Warsaw International Mechanism (WIM) for Loss and Damage associated with climate change impacts at the 19th United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties (COP) in 2013 [8]. The WIM aims to address loss and damage associated with impacts of climate change in developing countries that are particularly vulnerable to the adverse effects of climate change. Since the establishment of the WIM, countries have made significant progress in dialogues and actions to avert, minimize, and address climate-related losses and damages. At COP27, the Loss and Damage Fund [9, 10] was established to assist climate vulnerable, developing countries to respond to loss and damage [11], with initial pledges at COP28 totaling 770.6 million USD. While these pledges were commended by many, they were also criticized for being insufficient when compared to the projected costs, anticipated to exceed 1 trillion USD by 2050 [12].

Climate policy dialogues underscore the critical needs for an inclusive and broad range of effective, science-based solutions that can be scaled to avert, minimize and address loss and damage in developing countries [9, 13, 14]. Attribution science, providing quantitative insights into the contributions of both anthropogenic and natural causes of climate change, can bolster actions and dialogues on Loss and Damage [15]. This review aims to highlight developments and challenges in attributing loss and damage to climate change, and identify strategies to address these challenges in developing countries, thereby enhancing evidence-based policy decisions regarding Loss and Damage. We illustrate the importance of addressing data gaps in attribution and avoiding loss and damage using the agrifood sector as an example due to its significant vulnerability to climate change impacts.

2. Attribution science for loss and damage

Attribution of climate change is defined as "the process of evaluating the relative contributions of multiple causal factors to a change or event with an assignment of statistical confidence" [16]. Building on robust methodological developments [17, 18] that detect and distinguish changes in climate variables from internal variability, attribution science has rapidly advanced. These methodological developments have been extended to analyze individual and classes of extreme event(s) [19]. Since then, attribution science has progressed to the point where it is now possible to make specific attribution statements about individual events. Researchers have conducted long-term change analyses and numerous extreme event attribution studies across the globe. In this section, we briefly explore the evolution of attribution science that has informed Loss and Damage negotiations.

Probabilistic event attribution (PEA) is the most frequently used attribution method. PEA allows a quantitative assessment of the extent to which human-induced climate change is affecting local weather events [20]. The methodology provides an opportunity and potential to ensure quantified accountability for loss and damage. The Storyline approach is an alternative method, defined as a "physically self-consistent unfolding of past events, or of plausible future events or pathways" [21]. This approach involves considering main driving factors of change and assessing their roles in a conditional manner [22]. As methodologies for attribution science evolved, this field unveiled the causal relationship between human activity and climate change. Attribution science has advanced our understanding of the causal chains within the climate system to establish the relationship between nature and humans' contributions to increasing concentration of atmospheric greenhouse gases [20]. This understanding extends to both slow- and sudden-onset climate change [23, 24], and their devastating impacts on natural and human systems. This connectedness is the foundation of decades-long Loss and Damage negotiations.

Climate change attribution also enabled shaping risk assessment discussions on Loss and Damage. Relating meteorological changes to the consequent loss and damage had been the focus of the Loss and Damage negotiation. Following robust developments in attribution methods, loss and damage discussions focus on impacts that are caused by only anthropogenic climate change [25].

The discussions have evolved include humans influence on climate change [25], with anthropogenic factors being identifiable in various climate extremes such as heat waves, droughts, and floods [26], though not all such events can be currently attributed to human actions.

The scope of attribution science has broadened to include the assessment of anthropogenic influence in observed climate hazard impacts, a field that is gaining traction. A growing body of impact attribution research is examining impacts in economic and non-economic areas, depending on the feasibility of allocating monetary values to losses and damages of climate change. Economic impacts refer to commonly traded goods and services in markets (e.g., impacts on agricultural production, see Section 3) while non-economic loss and damage refers to impacts of climate change on human and natural systems to which assigning monetary values is challenging. Examples of non-economic loss and damage include losses of life or health, territory, indigenous knowledge and identity, cultural heritage, and loss of biodiversity or entire ecosystems [27]. Studies have attributed impacts of climate change on non-economic impacts such as ecosystem health [28] and human health [29, 30]. Human-induced changes in weather patterns, particularly heat waves' influence on the Vibrio emergence in Northern Europe and Lyme disease in Canada, is evidence to adverse impacts of climate change on human health. Observed changes of adverse health outcomes both in rates and geographic are associated with climate change [29, 30]. In addition, human-induced unusual meteorological conditions in the Iberian Peninsula during winter and spring of 2015/16 contributed to unusually high anomaly in vegetation greenness, which is a proxy indicator for ecosystem productivity [28]. Studies have underscored that anthropogenic climate change disproportionately affects vulnerable countries. For instance, Smiley et al. [31] found that, among different socioeconomic classes within the spatial coverage of Hurricane Harvey, vulnerable populations are disproportionately affected by climate change-attributed impacts. Although attribution science has significantly evolved in recent decades, it has not kept pace with the increasing demand to attribute losses and damages in the regions that are already experiencing devastating impacts of climate change, particularly in the Global South.

3. Challenges in addressing losses and damages in developing countries

Attributing long-term and sudden-onset changes in the climate requires reliable observational data that are lacking in most of the developing countries. When available, data are often incomplete, spatially scarce, and have insufficient temporal coverage, which hampers reliably evaluating model simulations for attributing loss and damage. Despite progress towards operationalizing climate modeling that is more suited to the evolving needs of society, developing countries encounter obstacles in accessing and utilizing high-resolution, convective-permitting climate models [32]. Some of the state-of-art models running at high resolution (4.5 km) offer more accurate representations of hourly rainfall characteristics compared to the coarser 25 km resolution models that use convection parameterization. The convection-permitting models have the ability to predict future increase in the length of dry spells over West and Central Africa in the future [33]. The general lack of data limits model simulations, leading to inaccuracies in risk estimation and loss and damage attributions.

Scientific attribution studies also require reliable climate models and databases. Their limited availability has resulted in a geographic bias in the distribution of climate hazard attribution studies, with a notable dearth in developing countries [34]. Since 2003, several climate events such as heat waves, droughts, and floods occurred in developing countries. However, the disparities in available data and the absence of suitable tools for data collection in these regions have limited our understanding of these events [34]. Decisions on Loss and Damage require bridging the data and technological gap to foster the development of the necessary dataset and models for attribution.

There remains a pressing need to comprehend the impacts of climate change across various sectors and scales, ranging from national to subnational, and across temporal spans to capture all dimensions of economic and non-economic losses, including political and social aspects within developing countries. To date, the available data and advancements in loss and damage attribution in developing countries do not show the exact magnitude of direct impacts of climate change on different sectors. However, impact assessment studies have clearly indicated that agrifood systems are amongst those most heavily affected by climate change and variability [35]. For this reason, we use the agrifood sector as an example to highlight sector-specific losses and damages (in Section 3.1) as well as strategies to avoid or minimize such losses and damages (in Section 4).

Globally, there is a growing willingness to share climate-related data that can improve models and broaden data access for developing countries for their adoption. Yet, the tools for such data sharing must be tailored and scaled appropriately, and there is a need to build capacity for their effective use in tackling loss and damage within these countries [12, 36].

3.1. Losses and damages within the agrifood sector

Climate change and variability have extensively impacted agrifood systems. Adverse impacts of climate change on the agrifood sector exacerbate food insecurity, particularly in the Global South. This sector is highly vulnerable to climate change due to several limitations such as relying on rainfed practices. As a result, the agrifood sector is particularly vulnerable to extreme weather events like droughts and floods, which have resulted in significant losses, thus leaving millions of people under stress, crisis, emergency, and famine every year [37, 38]. In the past 30 years, 3.8 trillion USD worth of crops and livestock production have been lost due to climate-related events [26], equivalent to 5% of the annual global agricultural gross domestic product (GDP) [26]). The agrifood sector employs about 50% of workers in developing countries [39], including 500 million smallholder farmers who produce one third of the world's food yet are among the world's most climate-vulnerable. Consequently, the agrifood sector's dual role as a contributor to and a victim of climate change necessitates prioritized consideration within the Loss and Damage agenda.

Investment in agricultural research has played a substantial role in enhancing agricultural productivity across different parts of the world [40]. Yet, progress in enhancing agricultural productivity in other parts of the world has stymied [41] in large part due to the observed above 1˚C increase in global temperature which shifts rain belts and limits moisture availability through enhanced evapotranspiration [1, 42, 43]. With different levels of confidence, IPCC's Sixth Assessment Report (AR6) indicated that anthropogenic climate change has contributed to increasing adverse impacts on water availability and food production resulting in losses in crop production, livestock health and fisheries, with implications on human health and wellbeing [1]. The temporal evolution of the frequency of climate-related food production shows an increasing loss in crops, livestock, fisheries and aquaculture over the last decades [1].

Studies conducted on the yields of major cereal crops (wheat, maize, and barley) showed that climate change-induced warming caused losses of 5 billion USD per year, during 1981 and 2002 [44]. Comparatively, global production of maize and wheat has decreased by 3.8% and 5.5%, respectively, from 1980 to 2008, when assessed against a no-anthropogenic climate change scenario [45]. Moore et al. [46] extended these findings, showing a 5.7% annual reduction in global calorie production from maize, wheat, and rice since 1960, attributed to anthropogenic climate change [46]. However, such attribution studies largely focused only on major cereal crops, which only account for about 20% of agriculture's global net production value [47, 48].

The broader implications of climate change on agriculture are further underscored by the work of Ortiz-Bobea et al. [49] who examined the effect of anthropogenic climate change on agricultural total factor productivity (TFP). TFP—a measure of the aggregate output produced per unit of aggregate input—reflects the efficiency of agricultural production. It is determined by technological knowledge, the effect of weather (average temperature and total precipitation), and observed and unobserved inputs. According to Ortiz-Bobea et al.[49], anthropogenic climate change is responsible for about 21% decline in global agricultural TFP since 1961. This reduction is even more pronounced in the tropics, including regions like Africa, Latin America, and the Caribbean, where the slowdown in TFP growth ranges between approximately 26–34%. This highlights the disparate impact of climate change on agricultural productivity across different climatic zones, with tropical regions bearing a disproportionately higher burden.

4. Strategies toward addressing loss and damage

As the global community grapples with the escalating impacts of climate change, the concepts of adaptation and loss and damage emerge as complementary yet distinct aspects of the broader climate action framework. Adaptation strategies aim to mitigate the risks and reduce the vulnerability of communities to climate change, focusing on pre-emptive measures. However, the reality of exceeding adaptation limits has brought the issue of loss and damage to the forefront, highlighting the need for specific approaches to address the inevitable impacts that surpass adaptation capacities.

The establishment of mechanisms like the Warsaw International Mechanism for Loss and Damage under the UNFCCC framework reflects a growing acknowledgment of these inevitable impacts. This approach encompasses both economic and non-economic losses, addressing the immediate and residual effects of climate change events that adaptation measures cannot fully prevent or mitigate. In the early days of the UNFCCC, there was concern that the increasing attention to adaptation in the climate agenda would detract from mitigation efforts [50]. Climate negotiators soon recognized both mitigation and adaptation are needed. The same is true for adaptation and loss and damage. While there are limits to adaptation that cause some losses and damages to be unavoidable, adaptation is still undoubtedly necessary to minimize and avoid losses and damages in the first place.

This section explores how strategies for addressing loss and damage can be effectively integrated with ongoing adaptation efforts for both planning and post-event recovery, using examples from the agrifood sector. We highlight the synergies between these approaches and emphasize the importance of a cohesive strategy that includes financial mechanisms, policy support, and equity considerations to assist those most affected by climate change.

4.1. Enhancing data availability through climate services

Climate service involves "the production, translation, transfer and use of climate knowledge and information in climate-informed decision-making and climate-smart policy and planning" [51]. Challenges in data availability can be improved through investing in timely observational data collection, digitization and access; enhancing climate data translation and transfer; building capacity of local stakeholders, and building trust among regional, national, and institutional stakeholders to share the best available data.

Delivering demand-driven and policy-relevant climate information at a national and regional level can accelerate data availability. Digital climate service platforms have been used to provide country-specific early warning and agro-advisory services in countries such Angola, Colombia, Guatemala, Ethiopia, Malawi, Peru, Tanzania, and Zambia [52]. Successful collaborations with national meteorological institutions enable the utilization of national data together with scientific global tools to produce the required climate information to support countries to minimize climate-related loss and damage.

Nevertheless, climate services should be improved and scaled to enhance data quality and availability which can support evidence-based Loss and Damage decision making. Improvements include making climate information relevant for decision-making [53], enhancing collaboration between scientists and target users [54], developing tools for climate monitoring [55], and enhancing access to institutional data repositories and databases for climate hazards to provide data for Loss and Damage decisions and interventions.

The robustness of observation-based attribution results in data scarce regions can be assessed using reanalysis [56] and remote sensing [57]. Non-commercial and commercial climate-related remote sensing data, which also covers developing countries has been available since the 1980s. Some climate variables have over 30 years of historical records, which can be used to complement observational data gaps in data-scarce parts of the world. Advancing utilization of these resource-efficient technologies enables monitoring long-term climate change and climate hazards as they unfold, as well as non-climate drivers of hazards [58]. Combining these spatial technologies with smartphones can improve timely data collection on extreme events and inform Loss and Damage decisions [59].

4.2. Enhancing climate resilience

IPCC defines Resilience as "the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure while also maintaining the capacity for adaptation, learning and transformation" [1]. Enhancing climate resilience is one of the efficient ways to minimize and avert loss and damage. Adaptation approaches, such as transformative adaptation options, enable significant changes in structure or function beyond adjusting existing practices, allowing large-scale adoption, new strategies, and the transformation of places. Transformative adaptation embraces the systemic inclusion of social equity, enabling comprehensive, multidisciplinary, and inclusive approaches to address economic and non-economic loss and damage. This enhances the use of new strategies, models, digital tools, and processes with attention to social equity to comprehensively plan and implement adaptation actions. The focus on adaptation being context-specific, inclusive of various stakeholders and vulnerabilities within communities, and outcome-oriented limits maladaptation [60] and its associated loss and damage, which includes current or potential negative consequences of adaptation-related responses that exacerbate or shift the vulnerability or exposure of a system, sector, or group of the population, or that erode sustainable development [1].

Approaches such as incremental adaptation can also contribute to transformative adaptation and they play a key role in building climate resilience and limiting climate-related losses and damage [38], such as loss of crops and livestock within the agrifood value chains. Therefore, identifying and scaling up efficient climate adaptation solutions and creating enabling political, social and economic environments are important to mobilize and invest funds for Loss and Damage [61].

4.3. Reducing climate risk

Addressing climate risk in the agrifood sector requires a multifaceted approach, drawing upon a range of strategies to preempt, minimize, and manage the adverse impacts of climate variability and extreme events. The selection of examples discussed herein—ranging from decision-support models and early warning systems to insurance mechanisms—is guided by their proven effectiveness, scalability, and direct relevance to the agrifood sector's unique vulnerabilities. These strategies are illustrative rather than exhaustive, highlighting innovative approaches that have shown substantial promise in various contexts.

Climate-informed agronomic decision support models. The complexity of climate impacts on agriculture necessitates sophisticated tools for informed decision-making. Decision-support models that incorporate climate-food-emissions projections offer tailored advice for crop diversification and land use, enhancing resilience to climatic shifts [62, 63]. Models also utilizes spatial, crop and population data to provide suitable sites for specific crops minimizing crop losses associated with changing growing conditions due to climate change in a specific area [64, 65], providing a critical bridge between climate science and practical agronomy.

Early warning systems and early action services. The deployment of early warning systems (EWS) and early action services represents a vital strategy for reducing climate risk. These systems provide anticipatory alerts for extreme weather events, enabling timely preparedness and response actions that can significantly mitigate potential damages [66, 67]. Recent advancements have seen the integration of EWS with disaster management protocols and financial mobilization strategies, thereby enhancing the capacity to avert and address loss and damage effectively. The bundling of these services has demonstrated considerable success in minimizing the impacts of floods and other climate extremes, showcasing the value of proactive intervention [68].

Climate and conflict nexus. The intricate linkage between climate change and sociopolitical conflicts necessitates a nuanced approach to risk reduction [69, 70]. As climate extremes exacerbate resource scarcity, the resultant stress can fuel conflict and displacement [71, 72], underscoring the need for solutions that address the intersection of climate, peace, and security. Tools and methodologies designed to provide evidence-based insights on climate risks, particularly in vulnerable regions like Africa, are crucial for crafting strategies that mitigate both direct and indirect impacts of climate change, including non-economic losses such as displacement and social unrest [73, 74].

Farm-scale financial access. Financial tools such as climate risk insurance schemes, sometimes bundled with agricultural credits [24], enable smallholder farmers to adapt and recover from loss and damage within the agrifood sector. These tools, coupled with satellite data for rapid assessment and compensation, offer a buffer against the financial shock of climate extremes, providing a safety net for affected communities [5, 24, 60]. The effectiveness of these products depends on supportive policies and a conducive environment for their adoption and scaling. While promising, these solutions must be carefully tailored to address the full spectrum of climate events, including slow-onset disasters, to ensure comprehensive coverage [75–77].

Reducing climate risk through these diversified strategies is foundational to any comprehensive effort to address loss and damage. By integrating decision-support models, early warning and action services, conflict mitigation strategies, and financial mechanisms, stakeholders can significantly enhance the agrifood sector's resilience to climate change.

5. Conclusion

Lack of quality observational data in the Global South has been a challenge, and there are only a few climate hazard attribution studies that have covered developing countries. Therefore, there is a need to increase investments in gathering, storing, and processing data to facilitate loss and damage attributions, especially in the Global South. Improving data sharing platforms and establishing new ones, capacity building, and delivering demand-driven and policy-relevant climate information at national and regional levels can be used as strategies to accelerate data availability. Synergies and cross-border collaborations are necessary for data sharing, and for experience and knowledge exchange. Existing cooperations between developing and developed countries could be leveraged to build synergies for timely data sharing. It is also necessary for policy makers and for data and technology owners to improve laws and policies so that they can support data and technology sharing. Furthermore, reanalysis, remote sensing, and station-satellite blended data can be used to assess the robustness of attribution findings in data-scarce regions of the Global South.

Building climate resilience, due to its systemic approach, can minimize climate change-related losses and damages. Further harmonization of loss and damage interventions with broader categories of climate action can minimize tradeoffs and maladaptation, and at the same time enhance resource-use efficiency. Policy makers should continue to invest in solutions for transformative adaptation, such as climate services, early warning systems, and insurance to enhance climate resilience and minimize, or when possible, avert losses and damages in the agrifood sector. Given existing limitations in attributing losses and damages, researchers and policy makers should bolster data availability on climate events and their impacts in developing countries, as well as increase Loss and Damage funds to strengthen climate resilience within developing countries.

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