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PERSPECTIVE

Attributing global impacts of local extremes to climate change for improving loss and damage estimates

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Supplementary material for this article is available online

1. Introduction

The historic agreement to establish a Fund for Responding to Loss and Damage ('the Fund') at the 27th United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP) in 2022 introduced a new financial mechanism to assist countries that are particularly vulnerable to the adverse effects of climate change in responding to loss and damage [1]. The momentum on the Fund continued in 2023 at COP28 in Dubai, where the Fund's operationalisation was decided, and in 2024 at COP29 in Azerbaijan, where it was made fully operational. While many questions regarding the Fund remain unanswered, attribution science continues to be proposed as a tool to measure losses and damages caused by human-induced climate change [2, 3].

Measuring loss and damage from climate change is an increasingly relevant issue in science and climate policy [2], yet there is still an ongoing debate on the definition of the term [4]. Loss and damage (L&D), broadly and within the UNFCCC climate policy discourse, often refers to the adverse economic or non-economic impacts of climate change that cannot and will not be mitigated or adapted to [4]. However, this definition can be at odds with the local priorities and realities of loss and damage from climate change in vulnerable countries. The L&D agenda, which includes scientific measurement of L&D and policy mechanisms like the Fund, is further complicated by practical and academic debates on climate justice [5], including compensation and liability for climate harms, and common but differentiated responsibilities [4].

While the Fund has not been communicated as a compensatory measure, the Fund's text (Decision 2/CMA.4) acknowledges the need for providing ex-post (including rehabilitation, recovery, and reconstruction) financial support following both slow onset and extreme events [1]. Though not explicitly mentioned in the Fund, ex-ante (climate risk management) financial resources are also important [4]. The evidence base required to inform these L&D funding needs is still unclear. Nonetheless, here, we specifically focus on the relevance of measuring loss and damage from extreme events, for which extreme event impact attribution ('impact attribution') could be informative.

Impact attribution quantifies human or natural impacts of extreme events rather than changes in meteorological hazards alone (known as 'event attribution') to (anthropogenic) climate change [6]. It is a multi-step, multi-model process requiring robust estimation of the link between climate change, a *specific* meteorological/climate hazard and the impact in question [6, 7]. Unfortunately, compared to impact attribution on natural systems (i.e. streamflow) [8], very few impact attribution studies on human and managed systems exist (see supplementary information 1), let alone in countries that are likely eligible for L&D funding. This is likely because of known challenges, including resource, data, and model limitations, and untangling non-climatic drivers from impacts [8, 9] (see [7] for a recent review). Therefore, improving impact attribution capacity in many vulnerable countries is essential.

However, accurately assessing the total impacts of climate change-induced extreme weather events requires considering that localised impacts of extreme weather can have significant consequences further afield due to international trade and supply chains. These local-to-global impact cascades are not currently considered in impact attribution research or in the L&D agenda, despite evidence on the unequal distribution of social, economic, and environmental impacts between countries [10, 11] and climate impacts and risks via trade and supply chains [12–16].

In this perspective, we show how considering the role of trade and global supply chains could help us identify the scope of impacts attributable to climate change, shedding light on additional impacts currently unaccounted for in the L&D discourse. To illustrate this point, we draw on a historical example of an extreme event with substantial direct and indirect economic and humanitarian consequences. Although estimating the global impacts of local extremes attributed to climate change will be challenging, it ensures that the quantification of attributable impacts is not underestimated in L&D research.

2. From attributing local to global impacts

Globalised, systemic shocks have been documented and analysed for many events. Food shocks are among the most researched examples because they can lead to devastating humanitarian consequences for vulnerable populations [17, 21]. Food shocks can be triggered by short-term events that disrupt supply, temporarily constraining the distribution of goods across borders and resulting in price hikes. Recent examples include the Russian invasion of Ukraine that disrupted global wheat supply, sparking a dedicated research effort to determine the drivers of its indirect ramifications [17].

Several studies have explored the distribution of climate-related impacts of slow onset and extreme events from local to regional [14, 16] and global scales [12, 18]. However, no study traces the chain of impacts attributable to anthropogenic climate change arising from locally occurring extreme events or what this means for impact quantification for L&D. As the Fund's text explicitly concerns providing financial resources to 'developing countries' (para 1, Decision 2/CMA.4) [1] that are often in the Global South, here, we explore a historic example of an extreme event in a developed Global North country with reported indirect consequences on the Global South. Consider the significance of the 2010 Russian heatwave event and what it might mean if we could determine the local and global impacts attributed to climate change.

In 2010, western Russia experienced a long-lasting, intense heatwave, with temperature records broken from late July to the second week of August. A record area of more than 2 million km^2 registered unprecedented heat anomalies [19]. The local impacts of the Russian heatwave were severe and compounded by extensive fires and ongoing drought conditions [20]. Russia reported a death toll of 55 000, an annual crop failure of ∼25%, more than 1 million hectares of burned areas, and ∼US$15 billion (∼1% gross domestic product) of total economic loss [19]. Wheat, one of Russia's main cereal crops, was significantly impacted by underlying drought conditions and extreme heat, which occurred for the first time in recorded history over the planting and harvesting seasons [20].

The local impacts on Russia's wheat supply caused global concern because of Russia's status as a top wheat producer and exporter. During the period June-August, global demand for wheat remained constant, but with the impacts on Russia's wheat supply, global supply dropped. Wheat prices started to rise sharply ahead of speculation Russia might implement an export ban, which came to fruition on August 5th. The sharp drop in global wheat stocks and then Russia's absence from the international wheat supply, starting on August 15th when the ban came into force until July 2011, coincided with further increases in global wheat prices [20].

The price hikes catalysed widespread short-term indirect impacts that, if ignored, would underestimate the scope of impacts arising from local impacts on wheat in Russia [21]. In Egypt, one of Russia's top wheat importers, bread prices rose 300% by early 2011, which strained Egypt's bread subsidy scheme and led to bread riots [20]. Beyond Egypt, in 2010, many African countries were highly dependent on wheat imports (>95%), and their populations faced a high prevalence of undernourishment (>20%), emphasising the potential reach and indirect impacts of Russia's wheat losses on global hunger (figure 1, see caption for data).

3. Conceptually straightforward, practically complex

The reported global impacts of the 2010 Russian heatwave event demonstrate the significance of considering both the direct and indirect impacts of extreme events attributed to climate change. So, how could we approach attributing the local-to-global impacts of this event? The 'local' determination of attributable impacts could leverage and expand on existing wheat impact attribution methods applied in Kazakhstan (see supplementary information 1). The 'global' distribution of local attributable impacts could borrow from a diverse range of models that consider the direct and indirect effects of climate change [13–16]. However, the export ban enacted by Russia may prevent quantitatively linking and attributing local-to-global impacts. This is because policy responses like this one are driven by complex socio-political-economic decisions rather than climate change alone. Nonetheless,

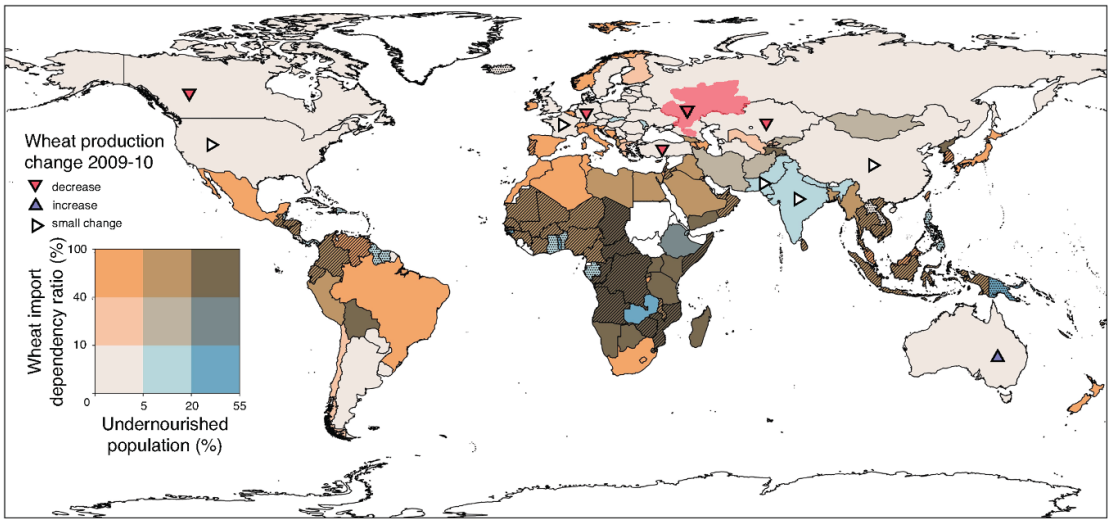

Figure 1. Undernourished population and wheat import dependency ratio (IDR), of the world to the 2010 Russian heatwave using data from the Food and Agriculture Organisation (FAOSTAT) (see supplementary information 2.1). The shaded red area represents key Russian wheat oblasts affected by the event [20]. Dots represent countries with no IDR values, stripes represent countries with greater than 95% dependence on wheat imports, and white represents no data. Triangles show major exporters and producers' change in production between 2009/10 from data in the United States Department of Agriculture (USDA) production supply and demand database and FAOSTAT data (see supplementary information 2.2). Red triangles show a production decrease, blue triangles show an increase, and white triangles show a small change (less than 5%) between 2009 and 2010.

linking local-to-global impacts could be qualitatively explored and responds to calls for attribution research to consider how 'emergency responses' mediate the impacts of extreme events [22].

While the local-to-global concept in an attribution context is straightforward, the practical and technical challenges that underpin this research agenda are substantial, requiring a concerted, transdisciplinary effort. To begin with, how do researchers decide what impacts of local extreme events that can be attributed to human-caused warming might have significant global consequences? The 2010 Russian heatwave is a well known example that demonstrates the significance of capturing local-to-global impacts, however, highlights the challenges of doing so if policy responses are involved. It is possible that other extreme events, which did not result in a trade policy response, cause direct *and* indirect impacts but have not attracted as much media attention or been less widely reported. As such, researchers may want to consult trade statistics data, other supply chain literature, and, ideally, knowledge from people in countries likely to experience indirect impacts. Testing case studies of existing food production shocks triggered by extreme events using established methods may be a good starting point for investigating this topic, given the research on teleconnected food shocks [21].

Concerning extreme event-related food production shocks, we focused on a case study on Global North–South impact transmission because the L&D discourse is based on principles of climate justice between the Global North and Global South [3] and because impact attribution may be easier to do in some Global North countries. However, exploring Global South–South impact pathways is vitally important. For example, India and Brazil are major producers and exporters of rice and corn, respectively, and have faced significant crop losses due to extreme weather events, respectively. As such, concerted efforts to improve impact attribution and supply chain methods, and data collection in and for the Global South is needed.

Finally, the technical challenges and data limitations inherent in impact attribution and modelling attributable impacts through global supply chains and trade are considerable. Climate events can trigger a cascade of impacts that spread through a highly interconnected and conditional network of causes and effects so quantitative analysis of cascading probabilities is exceedingly difficult [12]. Exploring qualitative, alternative approaches built on transdisciplinary collaboration will be necessary for the future of this research agenda.

4. Future directions

It is still unclear if and how attribution science can inform L&D funding discussions via the UNFCCC process. For example, evidence of catalogued impacts of extreme events attributed to anthropogenic climate change may be relevant for policymakers seeking to identify the losses and damages of a specific event, for which they seek payments from the Fund. However, making L&D payments conditional on having attribution statements available is problematic [3], given

the challenges in conducting event and impact attribution in many countries [2, 7, 9]. Emerging research suggests that evidence on attributing the impacts of event classes could more broadly inform funding discussions.

Research attributing the indirect impacts of extreme weather to climate change may be another way for attribution science to support L&D impact quantification and funding discussions. To do so, this agenda must involve scholars from the fields of social sciences and humanities (SSH), and, ideally, those with experience negotiating or informing L&D discussions. SSH scholars could help define what constitutes an indirect impact and climate justice in this context, and to whom or how far our duties of justice extend. Those directly involved with the L&D UNFCCC negotiation process could share whether accounting for indirect impacts could reshape the definition of the scope of climate change impacts in the UNFCCC process. Together, SSH scholars and L&D negotiators can contribute to understanding ethical debates on dimensions of justice and provide critical insight on technical decisions made to ensure the research design is just [5].

Moving forward, qualitative impact attribution across impact chains is possible and should be pursued. Exploring sectoral and regional impact cascades is needed to better understand how climate change influences the magnitude and distribution of impacts, and also policy responses to them (e.g. Russia's export ban). They are complex and more difficult to assess, but necessary for a complete picture (and ultimately end-to-end attribution) of how climate change is reshaping our world. Ignoring the indirect effects of extreme events within impact attribution research could underestimate L&D funding needs, which would be a step backward in measuring loss and damage for those most affected by the climate crisis.

Data availability statement

All data that support the findings of this study are included within the article and any supplementary files.

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Conflict of interest

The authors have no competing interests to declare.

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References

[1] United Nations 2022 Funding arrangements for responding to loss and damage associated with the adverse effects of climate change, including a focus on addressing loss and damage *Decision 2/CMA.4 (10th Plenary Meeting)*
[2] Coumou D *et al* 2024 How can event attribution science underpin financial decisions on loss and damage? *PNAS Nexus* **3** 277
[3] Huggel C, Wallimann-Helmer I, Stone D and Cramer W 2016 Reconciling justice and attribution research to advance climate policy *Nat. Clim. Change* **6** 901–8
[4] Boyd E *et al* 2021 Loss and damage from climate change: a new climate justice agenda *One Earth* **4** 1365–70

[5] Zimm C et al 2024 Justice considerations in climate research Nat. Clim. Change 14 22–30
[6] IPCC 2022 Climate change 2022: impacts, adaptation and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press)
[7] Perkins-Kirkpatrick S E et al 2024 Frontiers in attributing climate extremes and associated impacts Front. Clim. 6 1–24
[8] Cramer W, Yohe G W, Auffhammer M, Huggel C, Molau U, Silva Dias M A F, Solow A, Stone D A and Tibig L 2014 Detection and attribution of observed impacts Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change
[9] Otto F E L, Harrington L, Schmitt K, Philip S, Kew S, van Oldenborgh G J, Singh R, Kimutai J and Wolski P 2020 Challenges to understanding extreme weather changes in lower income countries Bull. Am. Meteorol. Soc. 101 E1851–E60
[10] Hickel J, Dorninger C, Wieland H and Suwandi I 2022 Imperialist appropriation in the world economy: drain from the global South through unequal exchange, 1990–2015 Glob. Environ. Change 73 102467
[11] Malik A, Lenzen M, Li M, Mora C, Carter S, Giljum S, Lutter S and Gómez-Paredes J 2024 Polarizing and equalizing trends in international trade and sustainable development goals Nat. Sustain. 7 1359–70
[12] van den Hurk B J J M et al 2023 Climate impact storylines for assessing socio-economic responses to remote events Clim. Risk Manage. 40 100500
[13] Sun Y et al 2024 Global supply chains amplify economic costs of future extreme heat risk Nature 627 797–804
[14] Malik A et al 2022 Impacts of climate change and extreme weather on food supply chains cascade across sectors and regions in Australia Nat. Food 3 631–43
[15] Li M, Meng B, Geng Y, Tong F, Gao Y, Yamano N, Lim S, Guilhoto J, Uno K and Chen X 2025 Inequitable distribution of risks associated with occupational heat exposure driven by trade Nat. Commun. 16 537
[16] Garcia-Leon D, Casanueva A, Standardi G, Burgstall A, Flouris A D and Nybo L 2021 Current and projected regional economic impacts of heatwaves in Europe Nat. Commun. 12 5807
[17] Alexander P, Arneth A, Henry R, Maire J, Rabin S and Rounsevell M D A 2023 High energy and fertilizer prices are more damaging than food export curtailment from Ukraine and Russia for food prices, health and the environment Nat. Food 4 84–95
[18] Baldos U L C, Chepeliev M, Cultice B, Huber M, Meng S, Ruane A C, Suttles S and van der Mensbrugghe D 2023 Global-to-local-to-global interactions and climate change Environ. Res. Lett. 18 053002
[19] Barriopedro D, Fischer E M, Luterbacher J, Trigo R M and García-Herrera R 2011 The hot summer of 2010: redrawing the temperature record map of Europe Science 332 220–4
[20] Hunt E et al 2021 Agricultural and food security impacts from the 2010 Russia flash drought Weather Clim. Extremes 34 100383
[21] Bren d'Amour C, Wenz L, Kalkuhl M, Christoph Steckel J and Creutzig F 2016 Teleconnected food supply shocks Environ. Res. Lett. 11 035007
[22] Jézéquel A et al 2024 Broadening the scope of anthropogenic influence in extreme event attribution Environ. Res. Clim. 3 042003