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A protocol for vulnerability and exposure assessment in rapid extreme event attribution studies

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Abstract. Over the past decade, the number of rapid extreme event attribution studies have increased substantially, both in frequency and speed of completion, often released in just a couple of weeks after an extreme weather event. Rapid analysis of vulnerability and exposure is a key complement to the hazard analysis in these studies in order to ensure a more holistic understanding of the drivers of observed impacts. In this paper, we present a method for rapid vulnerability and exposure assessment developed by the World Weather Attribution group. It focuses on the development and use of hazard-specific vulnerability and exposure assessment templates that are applied during a rapid literature review covering media, grey and academic literature. These templates are applied in conjunction with local expert judgement to elicit both breadth and depth of the assessment of potential drivers. This protocol supports the systematic integration of vulnerability and exposure into rapid attribution studies, strengthening their ability to inform the public about changing climate risks.

1 Introduction

Extreme event attribution has advanced significantly since Stott et al published their seminal 2004 paper on the potential role of human contribution to the 2003 European heatwave. Since then, the field has expanded substantially in both scope and speed, with the emergence of coordinated efforts to produce attribution analyses in a matter of weeks after the extreme weather event. In contrast, approaches for rapidly assessing vulnerability and exposure have received comparatively less methodological attention, despite their critical role in shaping impacts from extreme weather events.

A prominent example of rapid attribution studies is the World Weather Attribution (WWA) group, founded in 2014, which works to rapidly assess extreme weather events to determine the role climate change may have played in their frequency and intensity. To date, WWA has published over 100 rapid attribution analyses. WWA's approach detailed in "*A protocol for probabilistic extreme event attribution analysis*" by Philip et al. (2020), includes disaster surveillance and triggering, impact-based event definitions, model and observational assessment, hazard results synthesis and an analysis of vulnerability and

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exposure. Advancements to WWA's model and observational analysis approaches, including their synthesis, are further detailed in several scientific articles (e.g. Otto et al. 2020; van Oldenburgh et al. 2021; Clarke et al. 2023; Otto et al. 2024).

Following the IPCC risk framework, disaster risk is understood as the interaction between hazard, exposure, and vulnerability, rather than as a function of the hazard alone (IPCC, 2012; Cardona et al. 2021; IPCC, 2023). Within this framework, vulnerability is defined as the propensity or predisposition to be adversely affected and exposure is the presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected (IPCC, 2023). Since 2015, when WWA first started to produce rapid extreme event attribution studies there was a recognition that factors beyond changes to the hazard contribute to the impacts of the extreme weather events and it was important to include those factors when analysing the role of climate change in the extreme weather event. For example, in a study on the 2014-15 drought in Brazil, increasing trends in per capita water usage and population growth, rather than climate change, were found to be among the main drivers behind the water shortages (Otto et al., 2015).

Rapid vulnerability and exposure assessments differ from more comprehensive post-event or prospective analyses in both scope and purpose. While detailed vulnerability studies often rely on extensive datasets, fieldwork, and prolonged analysis, rapid assessments prioritize timeliness and the use of readily available information to inform interpretation while societal and policy attention remains high. As a result, rapid assessments are necessarily scoping in nature and do not aim to quantify impacts or exhaustively characterize vulnerability. Instead, they are designed to identify vulnerability and exposure factors that probably shaped observed impacts from extreme weather events.

WWA does not currently attribute disaster impacts directly to climate change (impact attribution), in part due to limitations in the robustness of methodologies across most disaster impact types, especially in the context of rapid attribution (Clarke et al, 2022; Perkins-Kirkpatrick et al., 2022; 2024). However, its studies are triggered by disaster impacts and event definitions used in the subsequent hazard analysis are primarily informed by the observed impacts (van Oldenburgh et al. 2021). The overarching aim of WWA's "rapid attribution" approach is to inform discussions about climate risk management, including both mitigation and adaptation, while the impacts of the extreme weather event are still fresh in the minds of the public and policymakers, and decisions about recovery and rebuilding are being made. In this context, the inclusion of a rapid assessment of vulnerability and exposure is essential to this goal, as it broadens the conversation beyond a binary framing of the climate change/no climate change, adding nuance on the human and societal factors that may have exacerbated or lessened disaster impacts.

This paper details the WWA approach to rapidly assessing vulnerability and exposure, including (1) a structured protocol, (2) hazard-specific vulnerability and exposure templates, and (3) empirical insights from application across diverse attribution contexts. The protocol is designed to enable standardized, transparent, and timely integration of vulnerability and exposure considerations into rapid extreme event attribution studies.

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2 WWA rapid vulnerability and exposure assessment method

The methodology is designed as a rapid, scoping-level "first look" at vulnerability and exposure factors that contribute to a disaster's impacts based on available literature, datasets and expert interviews in the weeks that follow the extreme weather event. By highlighting these factors, we aim to provide additional nuance that may not be a part of the existing public narrative on the disaster, as well as a basis for further research on these factors. The methodology has been developed and updated over the past 10 years of operationally applying it as part of WWA studies, evolving from a brief mention in the introduction, to a dedicated stand-alone section, to the systematized process described in this paper. The initial assessments were ad-hoc, based primarily on news reports, grey literature, and scientific literature. Over time, local experts were increasingly invited to contribute to help the team identify key themes and factors that likely contributed to impacts. As the volume of rapid studies released each year by WWA increased (from six in 2015 to 15 in 2023), the need for a more consistent, efficient, and transparent approach became apparent, resulting in further explicit development of the methodology described here as of 2023.

2.1 Rapid evidence scan

Once an event is identified for study, a rapid scan of relevant news articles, disaster impact summaries, and government websites is undertaken to obtain information on the impacts of the event. This helps to define the scope of WWA's analysis of the hazard, as well as important choices on how to cover vulnerability and exposure factors. For example, when studies cover a large area including multiple countries, we may focus the vulnerability and exposure only on the region(s) with the greatest impacts. If impacts are not fully clear, we may focus on providing an overview of each country's context with anecdotal examples from each country to illustrate factors that make each context unique.

2.2 Engaging local partners

In addition, as soon as the event is identified for study by WWA, local partners are identified who can provide local knowledge about the event and help identify factors that may not be well covered in the literature, English language news reporting or disaster impacts summaries. We rely on the Red Cross Red Crescent Movement's global humanitarian network to rapidly reach partners with disaster expertise from almost every country in the world. Over time, we developed an international roster of experts with varying geographic, hazard-specific, or thematic expertise to rapidly reach out to relevant experts from research and practitioner communities. These experts, where possible, are familiarized with the assessment process in the "cold phase," prior to the occurrence of an event. The aim is to include a range of 2-8 local partners in order to integrate varied perspectives and maintain operational efficiency, but experts engaged have varied from 0-30. For example, in the 2025 Fennoscandian heatwave assessment over 30 experts were consulted from a range of national and regional actors (Barnes et al. 2025), while the 2025 analysis of heavy rainfall and flooding in Sri Lanka and the Malacca Strait included five local experts (Kew et al., 2025).

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2.1 Rapid literature review using hazard-specific vulnerability templates

Operationally, a team from WWA and local experts gather to develop a first draft outline of the vulnerability and exposure assessment, discussing key themes based on a mix of the existing template, the rapid evidence scan and local expertise to identify a set of themes to explore. Based on this, experts are allocated to research evidence on the key themes and any additional expertise needed for the study is identified. Each expert conducts a rapid review of grey and scientific literature using the vulnerability factors and questions as a guide to write an initial rough draft of each theme.

In order to guide the inquiry and quickly identify relevant vulnerability factors after an extreme weather event, a series of "vulnerability and exposure templates" per hazard type (heat, cold, drought, flood, storm, wildfire) were developed. The templates, available in supplemental material, include a series of guiding questions that are clustered under themes such as "risk management" or "sociodemographics" that act as a point of departure for the assessment. These hazard-specific vulnerability templates were developed inductively in 2023 based on authors' expertise in disaster risk and by reviewing past WWA studies. In 2025, the templates were further improved through a review of literature on vulnerability factors related to each hazard type. This process and the updated templates are described in section 4.

2.4 Triangulation of evidence

Gaps in evidence and new themes that emerge based on the review are noted and shared amongst the group. Additional experts may be brought in as needs arise. The authors come together to review one another's rough drafts, share initial key messages, ask critical questions, and discuss gaps in evidence or missing thematic areas. Based on this feedback, authors update the drafts, including a discussion of the available evidence, possible missing evidence and further areas of research.

2.5 Quality assurance

The written assessment is shared with a set of reviewers who often have geographic or thematic expertise in the subject of the study. There is also at least one internal reviewer who was not part of the drafting. The reviewers are asked to review the section for comprehensiveness, check for appropriate relative balance of the factors being highlighted, share additional evidence sources that may be missing, check for factual errors and provide comments on the robustness of key messages based on literature cited and their expert judgement. The authors respond to and integrate the review comments.

2.6 Rapid quantitative exposure assessment

In parallel to this process, WWA also conducts a basic quantitative exposure analysis by estimating the number of people exposed to the hazard. This is done by summing the population in the shapefile for the agreed spatial event definition (the development of the event definition is described in Philip et al., 2020) using the WorldPop 2020 dataset (Tatem et al., 2017). Where data is available, additional aspects of exposure may be included, for example, in the case of Hurricane Melissa,

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hospitals, schools and populations exposed to three categories of extreme winds along the path of the hurricane were mapped (Clarke et al., 2025).

3 Case studies

The combination of expert consultation and judgement, alongside a rapid review of media, grey and academic literature is essential to the rapid nature of WWA's vulnerability and exposure analysis, as outlined in section 2. We present here three illustrative case studies of this approach.

3.1 2019-2021 Madagascar drought

The rapid attribution study of drought in Southern Madagascar from 2019 to 2021 involved local experts with knowledge on southern Africa and Madagascar's climate and economy (Harrington et al. 2022). Despite the lower-than-average rainfall, WWA's analysis of observations and climate models determined that climate change had not significantly increased the likelihood of drought in the study region (Harrington et al., 2022). Rather, a variety of vulnerability and exposure drivers had a compounding effect on the lower-than-average rainfall period leading to high food insecurity in Southern Madagascar. These factors included: a particularly high portion (90%) of the population living below the poverty line, land use changes negatively impacting traditional pastoralist coping mechanisms, subsistence agriculture in marginalized lands, inadequate road infrastructure that limited market access and increased food prices, and an invasion of locusts and armyworms. The COVID-19 pandemic was an additional compounding factor, reducing casual labor options in urban centers across industries such as tourism, mining and textiles. Local expertise was critical to understanding the real-time factors that played a role in the impacts of this drought.

3.2 2024 Rio Grande do Sol floods

The vulnerability and exposure section of the Clarke et al. 2024, rapid attribution study of the April-May 2024 floods in Rio Grande do Sul, Brazil, was structured around an impact-based understanding of the event. Early scoping focused on the spatial concentration of severe impacts in the metropolitan region of Porto Alegre and along major river basins, which informed the prioritization of urban flooding, river overflow, and cascading infrastructure failures in the assessment. A small interdisciplinary team at the Red Cross Red Crescent Climate Centre undertook a targeted literature review of land-use change, urban development patterns, housing conditions, and social vulnerability, drawing on Portuguese-language sources, government reports, academic literature, and post-event impact summaries. This process highlighted how long-term urban expansion into informal and low-income settlements intersected with the extreme rainfall to amplify losses. Rather than aiming for an exhaustive account, the analysis sought to identify the key risk drivers, with particular attention to factors that help explain differential impacts across population groups and areas.

The draft findings were reviewed and iteratively refined with input from Brazilian experts and humanitarian practitioners. Two scholars from the Brazil Lab at Princeton University - a Brazilian anthropologist and a Brazilian historian - provided

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comprehensive feedback, strengthening the analysis of historical land governance, social inequality, and the legacy of development decisions in the state. Their contributions helped situate present-day exposure patterns within longer socio-political contexts, adding depth to the analysis. This collaborative and iterative process allowed for triangulation across academic, practitioner, and locally grounded perspectives within a limited timeframe.

3.3 2025 Fennoscandian heatwave

The vulnerability and exposure analysis of the 2025 Fennoscandian heatwave study by Barnes et al. (2025), focused on understanding how prolonged heat interacted with social systems, the built environment, and institutional capacity across Norway, Sweden, and Finland. The analysis was structured around observed impacts and known risks, both generally and from previous Nordic heat events (the 2018 heatwave in particular), while incorporating early evidence from health services, emergency response actors, and government agencies during and immediately after the event. The assessment synthesized peer-reviewed literature, government reports, and grey literature across the three countries, alongside consultation with more than 30 national and regional actors, including public health authorities, social services, labor organizations, and environmental agencies. A subset of 12 local experts contributed to the writing and review of the vulnerability and exposure analysis.

This analysis identified key vulnerability and exposure pathways shaping risks and impacts, notably population ageing, limited heat adaptation in housing and care facilities designed for cold climates, seasonal reduction in healthcare and social service capacity during the summer holiday period, and uneven risk awareness among frontline care providers. Particular attention was placed on how these factors combine to increase risk in settings such as elderly care facilities, hospitals, preschools, and private homes, where indoor overheating and staffing constraints amplified heat-related health risks. It also spotlighted the role of cultural practices such as summer cabin use and increased swimming activity, and the specific vulnerabilities faced by Sámi communities whose livelihoods are closely tied to highly climate-sensitive ecosystems. Iterative feedback from these reviewers strengthened the analysis of governance and preparedness, highlighted persistent gaps like fragmented responsibilities across government actors, as well as areas of progress since 2018, including expanded heat action planning and the integration of equity considerations into urban greening and land-use planning.

4 Updating and strengthening hazard-specific vulnerability templates

In 2025, the hazard-specific vulnerability templates were updated through a literature review with the aim of validating the factors included and filling potential gaps. The literature review was conducted by searching Google Scholar for combinations of the specific hazard (heat/cold, drought, flood, storm, wildfire) and the term “vulnerability factors”. The hazard categories are intentionally kept broad and operationally modified to fit the actual extreme weather events (e.g. flash floods or riverine). The flood and storm categories are largely similar, but storm also encompasses storm surge and wind related impacts and drivers. To ensure the material was current and relevant, the time frame was restricted to publications from 2000–2025. The first twenty English-language, peer-reviewed entries sorted by relevance were selected for review. Exposure factors were not treated separately, as they are included in most vulnerability studies. The articles were then scanned for mentions of

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vulnerability or exposure factors. The usefulness of the cold-spell studies identified through these search parameters is limited, as they primarily focus on medical vulnerability, mortality, and China as a case study. To address this limitation, we added the next ten studies from outside China that met the search criteria.

The factors collected through the literature review represent a mix of outcomes, drivers, and states that relate to disaster risk. For example, for floods, the analysis yielded factors as varied as 'number of floods' (hazard characteristics), 'soil characteristics' (environmental conditions), 'floodplain development' (exposure), 'evacuation ability' (susceptibility), 'social cohesion' (coping capacity) which can all play a role in driving disaster risk. They were clustered by the authors according to existing and new themes in order to systematically categorize the drivers of risk for each hazard type. Some factors could be categorized under multiple themes but included under one for conciseness, and could be moved when the templates are operationally used. Synonyms or overlapping entries were removed or consolidated. Guiding questions from the prior (2023) template were mapped to the new themes and lists of factors, and new questions added in case of gaps. The updated templates can be found in the Supplementary Materials.

Extreme Heat/Cold	Drought	Wildfires	Floods	Storms
Hazard characteristics and impacts . Geophysical	**Hazard characteristics and impacts** . Geophysical	**Hazard characteristics and impacts**	**Hazard characteristics and impacts** . Geophysical	**Hazard characteristics and impacts** . Storm surge
Sociodemographics . Health . Cultural	**Sociodemographics** . Health	**Sociodemographics** . Health and air pollution	**Sociodemographics** . Health . Cultural or systemic	**Sociodemographics** . Health
Economic context, capacity and livelihoods . Agriculture	**Economic context, capacity and livelihoods**	-	**Economic context, capacity and livelihoods**	**Economic context, capacity and livelihoods**
Urban built environment . Infrastructure . Informality	-	**Wildland-urban interface** . Built environment . Structures	**Spatial planning and exposure** . Shelter (formal and informal)	**Spatial planning and exposure** . Land use changes . Shelter
-	**Agriculture** . Food security . Rural-urban interface . Land cover and ecological condition	**Landscape and fuel availability** . Ecological condition	**Land use and landcover change**	-
Critical Systems and services	**Critical systems and services** . Water and energy systems	-	**Critical systems and services**	**Critical systems and services**

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Heat/cold risk management	**Drought risk management**	**Wildfire risk management**	**Flood risk management**	**Storm Risk management**
. Governance . Policies and plans . Early warning and early action . Emergency response . Individual and household coping behavior . Insurance and social protection	. Governance . Policies and plans . Early warning and early action . Emergency response . Individual and household coping behavior . Insurance and social protection	. Governance . Policies and plans . Prevention . Detection and communication . Protection . Containment and extinguishment . Insurance	. Governance . Policies and plans . Early warning and early action . Emergency response . Individual and household coping behavior . Insurance and social protection	. Governance . Policies and plans . Early warning and early action . Emergency response . Individual and household coping behavior . Insurance and social protection

Table 1: An outline of the key headings and subheadings developed in each of the hazard-specific vulnerability templates showing similarities and differences amongst templates.

Across all hazard types a number of consistent themes emerge including a description of hazard characteristics and impacts; sociodemographics; and risk management for each hazard (Table 1). Under 'hazard characteristics and impacts' the guiding questions focus on understanding the timing, location, intensity of the hazard as well as its impacts. Under 'sociodemographics' the questions focus on understanding who is most vulnerable amongst the population, and the social and demographic characteristics that may drive that vulnerability. Under 'risk management' there are common subheadings including governance, policies and plans, early warning or early action, emergency response, household coping behaviors, and insurance and social protection. The section focuses on understanding the current state of each of these aspects of risk management, and how they may contribute to or alleviate disaster impacts. The wildfire template uses a different but analogous framing for the risk management section loosely based on the International Fire Safety Standards common principles (International Fire Safety Standards Coalition, 2020).

The heading of "economic context, capacity and livelihoods" captures the impact of the macro-economic conditions on people and the country's ability to cope, household economic coping capacity, as well as the drivers of differential impacts of the hazard on some livelihoods. The heading of "critical systems and services" contains guiding questions to elicit the extent to which systems such as water, energy and transport and services such as healthcare or utility are able to withstand the hazard and meet the needs of people, and the reasons for possible gaps. Both of these headings were common across hazards except wildfires, likely due to the limited nature of the literature review, and were subsequently added in order to capture these aspects of risk. Lastly, there was a common theme of human interaction with and modification of the physical landscape, although the heading itself varied by template and including using phrases such as 'spatial planning', 'land use land cover changes', or 'built environment' depending on the perceived unique emphasis for each hazard type. For example, under the wildfire template the term "wild-land urban interface" is used while under storm "spatial planning and exposure" is used.

Across hazards the guiding questions are similar, although some reference hazard-specific nuances. For example, the heat/cold template under the sub-heading of 'Geophysical' specifically references the impact of the urban heat island effect, while in the floods template it references the impact of the topographic and hydrologic characteristics of the region.

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5 Discussion: lessons learned and limitations

Vulnerability and exposure analysis is key to providing a more holistic perspective on the drivers of disaster impacts in extreme event attributions studies. The rapid analysis methodology developed by WWA, which combines three key inputs of media monitoring, a streamlined set of literature review questions and local expert judgement, helps to ensure that rapid extreme event attribution studies incorporate this critical perspective in a pragmatic yet standardized manner.

Media monitoring has proven key to identifying novel drivers as they emerge through on the ground interviews and reporting during disaster response efforts, for example the potential role of the federalized nature of early warning systems in Germany during the 2021 floods in Western Europe (Tradowsky et al. 2023). The hazard specific templates developed by WWA in 2023 and refined in 2025, have helped ensure a streamlined approach to academic and grey literature analysis, encouraging exploratory breadth and easing the ability to 'onboard' a broader range of experts to the rapid attribution studies. However, there is a potential for the templates to lead to path dependencies, for example, frequently identifying land use or cover changes, which are often well-documented in literature and data, as a key driver of the disaster risk over other factors that don't have their own section in the templates. Complimenting these templates with local expertise via interviews, co-authorship or expert reviewing helps ensure studies are also grounded in the necessary depth of understanding in order to capture local dynamics, nuances or potentially anomalous factors that are not captured by the templates. Illustrative examples of this are outlined in the case studies in section 3.

The rapid nature of WWA studies also results in various limitations and challenges. Existing peer-reviewed and grey literature may contain important gaps in potential key drivers in understudied locations. During the 2019-2021 drought in Southern Madagascar expert judgement pointed toward the compounding effects of COVID-19 which was not yet captured in the peer-reviewed literature (Harrington et al., 2022). In other cases, the event may still be unfolding when it is being studied, for example, Hurricane Melissa in 2025 (Clarke et al., 2025). This can limit the ability to draw weighted conclusions, assess cascading impacts, or incorporate key documents such as after-action reviews into the analysis. Accepted methodologies to fill these gaps such as household surveys or systematic key informant interviews are not feasible in the rapid timeline (typically weeks) of WWA studies.

WWA includes review of media reporting as a proxy for more extensive key informant interviews. While this is a novel approach, it can also lead to a 'newsworthy bias' which tends to focus on what went wrong, and thus focused on what may have exacerbated impacts, rather than also capturing what may have lessened impacts – which is also crucial to a holistic understanding. The depth and breadth of media coverage can also vary based on the type of event, its impacts and its location. Rapid onset events, with large death tolls or economic impacts, and closer to media hubs tend to garner more attention and in-depth coverage, for example (Sufi and Alsulami 2025, Yan and Bissell 2015, Berlemann and Thomas 2018). For example, when WWA was studying the 2025 floods in eastern Mexico the rapid evidence scan yielded a focus on urban areas, but local disaster experts equally emphasized the less-reported impacts on rural indigenous communities (Barnes et al., 2025). Extreme

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weather events in conflict contexts may demonstrate extreme vulnerability, but may also be especially difficult in terms of full insight into all risk dynamics at play (Pinto et al., 2023).

The current WWA approach to vulnerability and exposure analysis is generally highly qualitative. In that regard, one area for further development is the inclusion of standardized quantitative information sources. This could range from quite basic, such as systematically integrating available maps of vulnerability indices, to more complex such as economic damage assessment. While this development is beyond the scope of this paper, it is important to note that the ability to rapidly assess quantitative vulnerability and exposure dimensions is highly dependent on data availability and quality which is variable across regions. This may lead to an effect of "looking under the lamppost": focusing the analysis not on the most important factors but on those for which data are available. It will be important to explore whether dimensions that are easier to quantify may be inadvertently elevated in media reporting, over dimensions that cannot be robustly quantified, even if expert judgement indicates the latter as a more critical driver. Finally, the integration of a similar approach into other hazard-focused operational attribution services may be useful to explore.

6 Conclusion

Rapid extreme event attribution studies are growing in frequency and are informing a range of contexts including media reporting, disaster response and recovery efforts, Loss and Damage discussions, and support for national climate change policy (IPCC, 2023; Cologna et al., 2025). World Weather Attribution's focus in this landscape is informing the public about changing climate risks to enhance adaptation efforts through public awareness raising via the media, engagement in disaster recovery and facilitating policy dialogues. Across these contexts a holistic understanding of the drivers of disaster impacts in the context of climate change is crucial to reducing future impacts. This paper presents a novel, structured approach for incorporating a rapid assessment of vulnerability and exposure factors into rapid extreme event attribution studies, enabling more comprehensive, transparent, and policy-relevant yet still rapid interpretations of climate-related disasters.

Supplement link

The link to the supplement will be included by Copernicus, if applicable.

Author contributions

AB, MV literature review; JA, RS, MV, CPM, MvA paper drafting; MV, RS, JA template design; RS study design.

Competing interests

No competing interest to declare.

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