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Learning from the past in moving to the future: Invest in communication and response to weather early warnings to reduce death and damage

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A R T I C L E I N F O

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A B S T R A C T

As climate change increases the frequency and intensity of extreme weather events, governments and civil society organizations are making large investments in early warning systems (EWS) with the aim to avoid death and destruction from hydro-meteorological events. Early warning systems have four components: (1) risk knowledge, (2) monitoring and warning, (3) warning dissemination and communication, and (4) response capability. While there is room to improve all four of these components, we argue that the largest gaps in early warning systems fall in the latter two categories: warning dissemination/communication and response capability. We illustrate this by examining the four components of early warning systems for the deadliest and costliest meteorological disasters of this century, demonstrating that the lack of EWS protection is not a lack of forecasts or warnings, but rather a lack of adequate communication and lack of response capability. Improving the accuracy of weather forecasts is unlikely to offer major benefits without resolving these gaps in communication and response capability. To protect vulnerable groups around the world, we provide recommendations for investments that would close such gaps, such as improved communication channels, impact forecasts, early action policies and infrastructure. It is our hope that further investment to close these gaps can better deliver on the goal of reducing deaths and damages with EWS.

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1. Introduction

Extreme weather events have already increased in frequency and severity in all regions of the world (Seneviratne et al., 2021). Even greater increases are projected for the future with greater climate change, including unprecedented heatwaves and heavy rainfall events. To avoid or reduce the deaths and damages that can be caused by these weather-related hazards, one of the most common adaptation strategies globally is investment in Early Warning Systems (EWS) (New et al., 2022). The official definition of an EWS is "an integrated system of hazard monitoring, forecasting and prediction, disaster risk assessment, communication and preparedness activities systems and processes that enables individuals, communities, governments, businesses and others to take timely action to reduce disaster risks in advance of hazardous events". Researchers have found large benefits from investments in EWS, such as investments in Europena flood early warning estimated to have an economic return of 400 to 1 (Pappenberger et al., 2015), and heatwave early warnings that have saved hundreds of lives in single cities (Ebi et al., 2004). The recent IPCC report on Impacts, Adaptation, and Vulnerability, mentioned EWS in every chapter (IPCC, 2022).

The community of practice working in this area is large and growing. EWS were recognized as a critical tools in tackling climate risks by both the Sendai Framework for Disaster Risk Reduction 2015–2030, which has a target of increasing "the availability of and access to multi-hazard early warning systems" (UNISDR, 2015) and the 2016 Paris Agreement, which commits to supporting EWS under the headings of both adaptation and loss and damage (United Nations, 2015). The 2019 UN Climate Action Summit led to the launch of the The Risk Informed Early Action Partnership (REAP) with a target of "1 billion more people covered by financing and delivery mechanisms connected to effective early action plans, ensuring they can act ahead of predicted disasters and crises". On World Meteorological Day in March 2022, the UN Secretary General announced the Early Warning For All Initiative, promising that the "United Nations will spearhead new action to ensure every person on Earth is protected by early warning systems within five years" (WMO, 2022).

Funding has also been allocated to support these ambitions. The Climate Risk and Early Warning Systems (CREWS) Initiative was launched in 2016 as a pooled funding mechanism, and the Green Climate Fund, a primary channel for multilateral climate finance, is currently developing a Sectoral Guide and Climate Information & Early Warning Systems. Most recently, in May 2022, the G7 Foreign Ministers committed to improve early warning systems via a significant increase in financial support to anticipatory action programming (German Federal Foreign Office, 2022).

2. How will these commitments on early warning translate into protection of vulnerable people?

Given these growing commitments globally, this perspective takes a step back and examines the role of early warning systems in the deadliest and costliest disasters of this century. Global weather models already exist, and therefore every-one on the planet is technically already "covered" by weather forecasts of varying quality. We notice that the largest gaps in early warning *systems* tend not to be in the forecast, but rather in risk communication and response capability, and we argue that targeted investments that focus on the ability of end users to access, understand and act upon warnings will be critical to the success of early warning systems in the coming years.

3. What does an effective early warning system require?

Often when people think about early warnings, they tend to focus on hazard forecasting and modeling (e.g. Vogel and O'Brien, 2006), but the concept of an "Early Warning System" (EWS) does include other elements. These are broadly defined as: (1) risk knowledge, (2) monitoring and warning, (3) warning dissemination and communication, and (4) response capability (UNISDR, 2006). This system spans many institutions with different roles and responsibilities, who need to coordinate in responding to feedback on how well the system is working.

Defining "success" in EWS has been an elusive concept, but we would echo existing literature proposing that success should include the recognition of benefits by local communities (Glantz, 2004), rather than success in forecasting accuracy alone. There is an increasing push to frame EWS as "people-centered", which requires strong integration across sectors and scales. People-centered EWS are co-developed with the participation of people who will ultimately receive the warnings, and ensure that information and warnings do reach these vulnerable communities (CREWS, 2016, CREWS and IFRC, 2021). Many systems incorporate multiple relevant risk factors, including both climate hazards and social vulnerabilities (Dash and Walia, 2022, Marchezini et al., 2018, Kelman and Glantz, 2014).

This perspective builds on an existing literature base calling for greater attention to the "last mile" in EWS by both practitioners and scholars. For example, in 2009, the International Federation of Red Cross and Red Crescent Societies World Disasters Report called for attention to better communication to vulnerable and under-reached communities (IFRC, 2009). Research over the past 15 years has documented the need for early warning messages to have content tailored to specific communities, and delivery channels informed by their unique needs (e.g. Shrestha et al., 2021, Vogel and O'Brien, 2006).

4. How have early warning systems performed in recent years?

Here, we analyze the six deadliest and six of the costliest hydro-meteorological disasters categorized in the EM-DAT database. We downloaded all disasters in the database from the year 2000 until the first 6 months of 2022. We then subsetted the dataset to include only disasters classified as climatological, hydrological, or meteorological. For this analysis, we selected the six disasters with the highest numbers of reported deaths in the EM-DAT database (Table 1), and the three disasters with the highest total monetary damages (adjusted to for inflation to the year 2020). Given that these were all storms in the US and Puerto Rico, we also include the three disasters with highest monetary damages outside of the US. For each disaster, we reviewed secondary sources that described the four

Table 1
The 6 deadliest disasters in the EM-DAT database between 2000 and 2022. For each event, we characterize the performance of the four components of early warning systems: risk knowledge, monitoring and warning, warning dissemination and communication, and response capability.

Event	Risk knowledge	Monitoring and warning	Warning dissemination and communication	Response capability	References
Myanmar, 2008: Tropical cyclone Nargis was responsible for 138,000 deaths, and more than $5 billion in damages.	Nargis made landfall in a region with known cyclone risk but with infrequent experience of cyclones.	International forecasts accurately predicted the location of landfall despite rapid intensification. Warnings were sent by the Indian government to the Myanmar government before landfall.	Limited warning communication to the public is widely considered to have contributed to the large death toll.	There was little infrastructure prepared to help people avoid the impacts of the storm; greater investment in cyclone shelters and protocols could help save lives.	(Salleh, 2008) (DEMS, 2008)
Russia, 2010: a heatwave killed 56,000 people, and caused $500,000,000 in damages.	Heat waves are increasing in Russia with climate change. This was an unusually intense and widespread heat wave.	Seasonal forecasts did not show a strong signal of an extremely warm summer. However, heatwaves in Russia are generally well captured by short-term weather forecasts.	Information was not readily available on short-term weather forecasts before the event.	Differential vulnerabilities of certain groups, and lack of response tools such as air conditioning in hospitals are blamed for high mortality.	(Katsafados et al., 2014) (Dole et al., 2011)
Europe, 2003: a heatwave killed 64,000 people (estimates are as high as 70,000) across Italy, France, Germany, and Spain, and caused $17 billion in damages.	Heat waves are increasing in Europe with climate change. Temperatures were unusually high.	The heatwave was caused by an anticyclone over Western Europe, which was forecasted by the European Centre for Medium-Range Weather Forecasts.	TV news, internet and newspapers informed the public on how to cope with the heat: drink plenty of water, wear cool clothing, and stay in the shade during hottest temperatures.	From effects on agriculture and transportation to dehydration and heat stroke, people were not prepared for the heat wave.	(Robine et al., 2008, Mitchell et al., 2019)
Somalia, 2010: death estimates from a drought range from 20,000 to 250,000 people.	Droughts are common in this region. This event was complicated by conflict, constraints on access, and a global food price spike.	FSNAU and FEWS NET predicted drought and food security impacts months before the full onslaught was felt. This was forecasted because of the well-known effects of La Nina.	The threats were well communicated. Action was prevented by constraints on access and the heavy legal and reputational risk to agencies operating on the ground.	Response capability was hobbled by the fact that the two largest agencies with food security capacity (WFP and CARE) had pulled out of Somalia in 2010 and 2009.	(Maxwell & Majid, 2016) (Checchi and Robinson, 2013) Hillbruner and Moloney (2012)
Philippines, 2013: Typhoon Haiyan killed more than 7,000 people, and damage estimates are $11 billion.	Haiyan struck the Philippines, a country that has an established typhoon risk, during the latter portion of the rainy season.	Forecasts predicted landfall in central Philippines. Storm surge warnings were also made 2 days prior to Haiyan's landfall by the Philippine Atmospheric, Geophysical and Astronomical Services Administration.	Despite early warnings from the government, many locals did not understand the term "storm surge." Those aware of the term and warning underestimated the severity of the hazards, especially with respect to inland inundation, hindering them from evacuating in a timely and effective manner.	Response capability was constrained by governance challenges, such as the absence of national government entry and exit protocols, incapacitated/inactive local governments and councils, and lack of experience working with non-government actors.	(Dy & Stephens, 2016) (Jibiki et al., 2016)
India, 2013: a flood killed 6,000 people and caused more than $1 billion in damages.	June rains in northern India have been increasing in magnitude since the late 1980 s. This increase is well documented.	Uttarakhand received a forecast of "extremely heavy rains" 24 h prior to the event by India Meteorological Department (IMD). The warning did not indicate which regions would be adversely impacted.	The Uttarakhand government issued a disaster alert over 30 h after the IMD issued an alert; another disaster alert and rescue activities were launched 24 h later. Communities claimed that warnings from other community members and environmental cues were their primary sources of information.	Most individuals instantly evacuated, but some lingered to learn more, confirm their warnings, or start preparing for the evacuation. Final evacuations had to be postponed as a result of milling behaviors.	(Cho et al., 2016) (Uttarakhand government ignored Met warning., 2013)

components of EWS relating to that disaster, and summarize these perspectives in the following tables.

The stories in the following tables show mixed results in the effectiveness of the components of early warning systems. The deadliest disasters of this century have happened across geographies, from a heatwave in Europe to drought in Somalia. Table 1 presents the six deadliest climate or weather-related disasters in the Emergency Events Database (EM-DAT) between 2000 and 2022 (Guha-Sapir et al., 2022). Table 2 presents six of the costliest climate or weather-related disasters, to offer a slightly different perspective. In all cases, we

Table 2
The first three rows are the three costliest disasters in the EM-DAT database between 2000 and 2022, which were all storms in the US and Puerto Rico. This is followed by the three costliest non-US disasters in the same timeframe. For each event, we characterize the performance of the four components of early warning systems: risk knowledge, monitoring and warning, warning dissemination and communication, and response capability. Notably, many of these disasters occur in high income countries which may be attributed to costly infrastructure in these locations but does not discount the need for global EWS protection.

Event	Risk knowledge	Monitoring and warning	Warning dissemination and communication	Response capability	References
USA, 2005: Hurricane Katrina killed almost 2,000 people, and caused damage of $173 billion.	Katrina hit a region with a known risk for hurricanes and history of hurricane destruction.	The storm was named 6 days before striking Louisiana. The storm made landfall in Florida as a Category 1 hurricane and was forecasted to hit New Orleans as a Category 5 hurricane.	President Bush and FEMA issued emergency declarations before landfall; public warnings were widespread 3 days before. Louisiana carried out the largest evacuation in US history.	Staff and budget shortages and planning difficulties included inadequate evacuation plans, lack of boats for search and rescue teams, communication shortfalls, and limited human and financial capacity.	(United States, 2006)
USA, 2017: Hurricane Harvey killed 88 people, and was responsible for damage of $105 billion.	Texas is vulnerable to hurricanes forming in the Atlantic Ocean and Caribbean Sea. 21 % of all hurricanes making landfall in the US occur in Texas.	The Hurricane weather Research and Forecasting (HWRF) predicted rainfall amounts and location, which were the most devastating impacts of the storm's landfall in Texas.	A combined total of 372 tornado, flash flood, and severe thunderstorm warnings were issued from August 25–30. It is unclear how many warnings were issued before landfall.	The Texas Department of Emergency Management has a recovery mission in its legal mandate with the majority of staff and funding focused on the emergency response phase.	(Nasios, n.d.) (NOAA Hurricane Model)
Puerto Rico, 2017: Hurricane Maria killed 64 people and was responsible for damage up to $75 billion.	Maria struck the center of the Caribbean hurricane belt, the area in which hurricanes are most likely to form.	The National Hurricane Center began to forecast Maria making landfall on the island of Puerto Rico as a category 4 hurricane about 54 h in advance. Peak water levels were on the lower end of the forecast range.	A Hurricane Warning was issued a little over a little over 37 h before landfall in Puerto Rico, and social networks urged residents to prepare at least 2 days before landfall.	Early action was hampered by the fact that Puerto Rico was recovering from Hurricane Irma a few weeks before, but healthcare facilities and others did prepare for landfall.	(María Se Fortalece y Se Convierte En Huracán, *Hurricane* Maria, 2017, Rodriguez de Arzola, 2018)
Thailand, 2011: A flood killed 813 people and caused damage of $48 billion.	Floods are common occurrences in the Chao Phraya River, although the 2011 floods were caused by unusually high rainfall (143 % higher than average).	There was no real-time flood warning system, and oscillating advice from government agencies was confusing for residents.	Flood and landslide warning systems and channels (e.g., television, radio) existed, but clear warnings and two-way communications were found lacking.	Among other factors, response capability was influenced by political challenges, such as problematic coordination between local and central governments.	(Prathumchai & Bhula-or, 2020) (Gale & Saunders, 2013)
Germany, 2021: Floods killed 200 people and caused damage of $40 billion.	While the affected parts of Rhineland-Palatinate and North Rhine-Westphalia have occasionally seen flooding, this was more severe than previously experienced. (E.g. 148L of rain per m^2 in 2 days where average totals are 80 L for the full month of July.)	Forecasts showed a high probability of flooding in the affected regions, with certainty a few days before the event. Alerts were issued to national and local authorities and regional warnings were issued in several states. More than 150 warnings were issued to the public.	An online survey found that 29–35 % of respondents did not receive any warning. Of those who did receive warnings, 85 % did not expect very severe flooding and 46 % did not know how to respond. Other analyses found a lack of adequate recommendations to at-risk populations.	An investigation is ongoing, and there has been criticism of lack of investments in robust early warning systems, a strong expectation of functioning infrastructure supplies, and lack of flood protection plans for smaller streams.	(Smith et al 2021) (Fekete & Sandholz, 2021) (Thieken et al., 2022)
China, 2008: A winter storm killed 129 people and caused damage of $27 billion.	This storm hit areas of southern and central China which does not have frequent experience with snow and cold.	Continuous cold weather warnings spanning a period of 26 days were issued from 24 January to 18 February 2008.	China Meteorological Administration's issued "red alerts", the most severe weather warning category.	Early action was limited by lack of knowledge of behavior to adopt and limited attention paid to user needs for extreme weather forecasts and content of warning messages.	(Zhou et al., 2011)

document that weather forecasts did exist before the event happened, and major failures of communication and early action were drivers of some of the biggest impacts.

Our analysis of these disasters is limited to a review of secondary sources that have documented these events, and therefore does not go into depth into the complex story of each disaster. Readers can find further contextual analysis in the citations, as well as review papers that compare warning systems and disasters across regions (e.g. Cools et al., 2016, Macherera and Chimbari, 2016). In addition, the reporting of deaths and damages in the EM-DAT database is not consistent across time or across hazards (e.g. heatwave events report excess deaths rather than deaths from heat stroke alone), and damage estimates tend to be higher in wealthy regions with large infrastructure. These reporting biases should be taken into account when reading the sample of disasters that we present here.

Heatwaves, for example, are well forecasted in most extra-tropical regions like Europe and Russia; more than 5 billion people live in areas where heatwave forecasts are very accurate (Coughlan de Perez et al., 2018). However, the 2003 (Europe) and 2010 (Russia) heatwaves were two of the deadliest disasters of this century, even though the affected countries have access to excellent weather forecast models. Both events were unprecedented in the historical record, and therefore appropriate levels of risk awareness and capacity to respond were likely lacking among the affected populations (See Table 1 for details). Since those events, major efforts in risk awareness, risk communication, and response capacity have reduced heatwave deaths in more recent events (Fouillet et al., 2008).

The event with the earliest forecasts was the 2011 famine in Somalia, which was forecasted months before conditions deteriorated. The most important barrier to early action was the lack of an adequate response in a complex context of insecurity, deteriorating purchasing power, distress migration and extreme constraints on access (Maxwell and Majid, 2016).

Cyclones and storms dominate these lists of disasters. The deadliest event was Cyclone Nargis in Myanmar in 2008, widely attributed to a lack of forecast communication to the public, lack of response capability and the refusal by the government of Myanmar to allow any international assistance. Typhoon Haiyan (Yolanda) in the Philippines in 2013 also appears in Table 1, with questions of whether storm forecasts were understood correctly by the public and weather response capability was sufficient. Table 2 contains the three costliest disasters of the 21st century, which are also storms: Hurricanes Katrina and Harvey in the USA, and Hurricane Maria in Puerto Rico. Residents were often surprised by these record-breaking events even in regions where such storms are common, because hazard maps and anecdotal accounts from the past might not accurately represent the full range of possibilities for how a future event could unfold. This was also part of the story in the unprecedented 2021 floods in Germany.

In terms of forecasts, however, all of these storms were forecasted in advance, and strong evacuation systems contribute to the fact that many of these are on the “costliest” rather than the “deadliest” list. Today, there are coordinated regional forecasting centers for tropical storms, with mandated authorities for the production and national dissemination of forecasts. Areas for improvement in forecasting and modeling include cyclone rapid intensification to extend lead times and better forecasting of cyclone sub-hazards, such as rainfall and storm surge.

In many of these cases, poor communication to the public is a theme in the retrospective analyses. This was also the case in Germany in 2021, where people reported not receiving flood warnings, and in China in 2008, where people did not understand the potential impacts of a forecasted snowstorm (Thieken et al., 2022, Zhou et al., 2011).

While these short tables of high-impact disasters are not representative of all the smaller, recurrent, and under-reported disasters experienced worldwide, they can shed some light on major gaps and opportunities for improvement in Early Warning Systems.

5. How can we improve early warning systems?

Based on Tables 1 and 2 and the diverse experience of the author team in EWS, we reflect on several critical areas for investment in the different components of EWS.

5.1. Risk knowledge

Education and preparedness programs can ensure people are aware of hazard risks in their region and behaviors to take to reduce their impact. As the intensity of some hazards are changing with climate change, we recommend planning workshops around hazard scenarios that are different from the historical record, helping people imagine what has never before happened. These future scenarios can take into account the increasing frequency and intensity of extreme events, not simply past experience. Based on our review of these historical disasters, we found that many locations were not imagining large and unprecedented events in their planning processes. We recommend developing probabilistic multi-scenario exercises that go beyond worst case scenarios from historical records.

Long-term resilience investments in areas that are highly vulnerable to disaster will help avoid future impacts, as seen in several of the disaster case studies in Table 1 and Table 2. France invested in heatwave awareness and preparedness, and impacts of recent heatwaves, such as one in 2006, have been lower than in 2003 (Fouillet et al., 2008). After Hurricane Katrina, the US government invested billions in infrastructure and preparedness to protect New Orleans, which saved lives and protected assets during a similar storm, Tropical Storm Ida, in 2021.

5.2. Forecasting and warning

Much has been written about the forecast “usability” gap, which can inform future investments in weather forecasting (Lemos et al., 2012). The disasters in Table 1 and Table 2 highlight specifically how multi-hazard forecasting can save lives. During tropical storms, people often focus on wind speed forecasts, and might be unaware of rainfall forecasts (e.g. Hurricane Harvey) or storm surge forecasts (e.g Typhoon Haiyan). We recommend further investment in multi-hazard forecasting as well as impact-based forecasting.

Forecasting improvements that offer longer lead times for extreme events can enable more action in the future, especially during cyclones that undergo rapid intensification (e.g. Typhoon Haiyan and Cyclone Nargis), or events that include fast/flash flooding (e.g. 2011 Thailand floods and 2021 Germany floods). Improved forecast coordination and communication across national borders can also improve outcomes.

5.3. Communication

Breakdowns in communicating weather information to the public were cited as major problems in most of the big disasters of this century. To close this gap, we recommend investments in multiple communication channels that provide location-specific warning messages and impact-based forecasts. For example, in Bangladesh, people away from river banks will not automatically translate forecasts of river levels into personal impacts, and historical experience might not serve them well if the flood is unusually large. Cellphone messaging can help disseminate information with localized contents and improved mobilization of the public.

The information that is communicated needs to enable the public to fully comprehend the severity or possible impacts of an event. "People-centered" and "impact-based" warnings that translate weather information into impacts and scenarios can help bridge this gap, especially for events that we have never before experienced. Impact-based forecasts move from forecasting what the weather will be (e.g. 10 mm of rainfall) to what the weather will do (e.g. road closures). Such forecasts can also include details on possible severity and probability (Harrowsmith et al., 2020). These detailed forecasts should communicate multiple aspects/hazards of a weather event clearly to the public, which can help enable organic responses to protect people and assets. Two-way communication channels between officials and the public are essential to clarify and support mobilization.

5.4. Response capability

We need to first and foremost invest in infrastructure to enable early action, such as evacuation shelters or cooling centers. Human capacity is also critical; local emergency response offices need to be adequately staffed and equipped and have appropriate coordination mechanisms for pre-disaster action within and outside government. Many countries find themselves unprepared with limited capacity to act based on forecasts. Using an example from our own experience outside of Tables 1 and 2, in Namibia, there was a severe drought in 2012/2013 that left 400,000 people at risk of hunger, and supportive interventions were only implemented after the President declared a 'state of emergency'.

Secondly, we recommend the development of appropriate policies and plans to react to a forecasted event. These plans should designate responsibilities to take action based on a forecast. In the Philippines, for example, local protocols detail what should be done by local government agencies in the case of a disaster warning, and there are different steps contextual to the area. These protocols should align with pre-arranged financing and cross-border contingency planning, especially among territories with shared risks, and must be written in simple language for government officials and the public to understand. For an effective response, not only is capacity required, but also a good contingency plan, prearranged finance, and an agreed mechanism for triggering the response (Lentz et al., 2020).

Outside of government agencies, civil society actors can also develop such plans and protocols, for example Early Action Protocols by the Red Cross Red Crescent Movement and UN Organizations. These plans allocate funding and responsibilities to guide responses to an early warning. A mapping process within the humanitarian sector, for example, counted humanitarian early action plans/protocols that covered more than 2 million people in 57 countries in 2021 (REAP, 2021). Coordinated early action between the Bangladesh Red Crescent and UN agencies benefitted people who experienced a flood in 2017 and 2020 (Gros et al., 2019, Pople et al., 2021).

Beyond these four categories, we acknowledge that there are limitations to framing EWS in these simple components. Scholars have suggested that the standardization of these four components of an EWS can reduce opportunities for local knowledge to inform and contextualize an EWS and the links between the categories (Garcia and Fearnley, 2012). Others have proposed the integration of citizen science (Marchezini et al., 2018) and focusing on the match between risk information and response capability, rather than evaluating them separately (Cools et al., 2016). We would encourage further research comparing historical disasters and non-disasters to identify points of success and isolating areas for investment and improvement.

6. Conclusion

While there are areas for improvement in each of the four components of an EWS, simply improving the accuracy of weather forecasts will not result in better outcomes for vulnerable people. In fact, most of the deadliest and costliest hydro-meteorological disasters of this century have happened during events that were forecasted before they happened. To close the largest gaps, we recommend that EWS initiatives for adapting to climate change focus on the categories of communication and response capability in the least-served communities of the world.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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