Title: **Mitigating climate-driven animal mass mortality events with resilient native scavenger guilds.**

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Abstract: Climate-driven animal mass mortality events (MMEs) will increase as the magnitude and frequency of extreme weather and climate events worsens due to climate change. Besides resulting in demographic catastrophes for affected species, MMEs adds further pressure to vulnerable ecosystems in several ways. We suggest the protection and restoration of resilient native scavenging guilds are key strategies to build climate-resilient ecosystems. Incorporating this nature-based solution into biodiversity conservation policies will ensure the efficient breakdown and recycling of carcasses back into the environment, and minimise risks of disease spillover to human and wildlife. Policy makers are urged to recognise scavengers as allies in mitigating the negative impacts of climate-driven MMEs on our ecosystems.

Main Text: Human-induced climate change is placing increasing pressure on Earth's biodiversity by affecting weather and climate extremes and increasing the frequency and intensity of events such as drought and heatwaves (*1*). Every year, across different regions, the world witnesses the death *en masse* of hundreds, and sometimes thousands, of animals; these instances are known as mass mortality events (MMEs) and are affecting animal taxa indiscriminately across a range of biomes (*2*). Approximately 25% of MMEs reported between 1940 and 2012 were influenced directly by climate via thermal stress and weather events (*2*). The remaining events were attributed to disease, starvation, biotoxicity, and other factors often triggered by shifts in human-induced warming and anthropogenic land modification (*2*). Since 2012, several other MMEs have occurred globally and may be linked largely to extreme climate and weather events (***Figure 1***). As the magnitude of climate variability worsens and extreme weather events increase in frequency and intensity (*1*), the world is likely to witness ongoing and more frequent MMEs (*3*). Given the overwhelming evidence that the Earth's biosphere is undergoing unprecedented perturbations and the integrity of ecosystems worldwide is threatened (*4*), are our ecosystems prepared for more frequent mass mortality events? How can policy makers and land managers globally enable ecosystems to be resilient to MMEs in a changing climate?

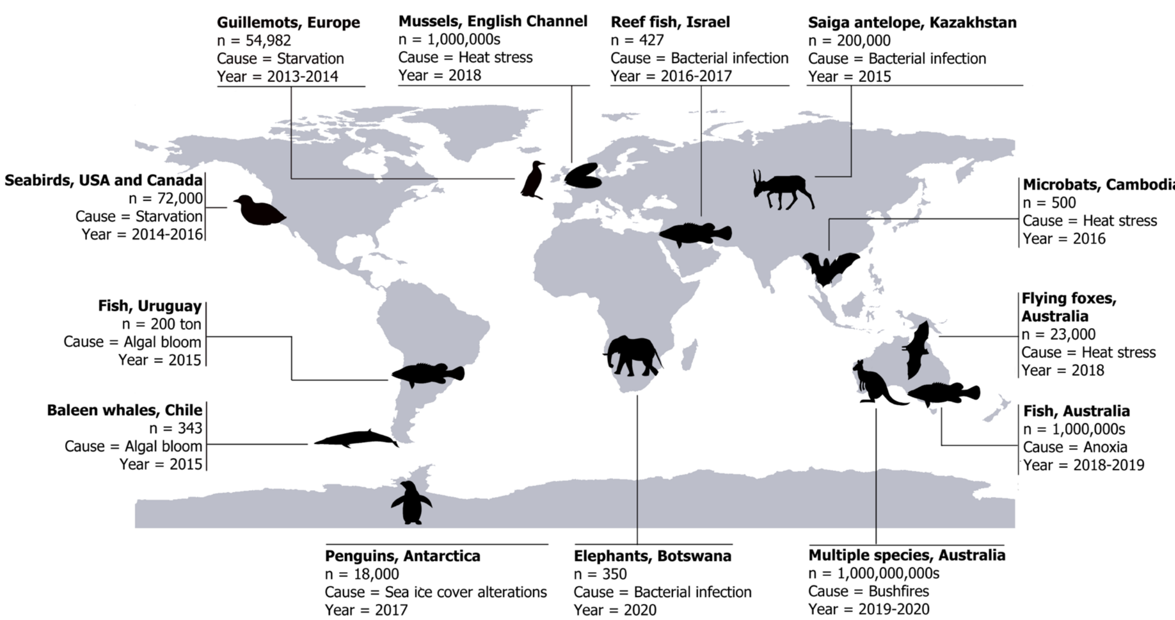

Figure 1. Examples of climate-related MMEs reported worldwide between 2013 and 2020 (S1-S15). MMEs linked to extremes in climate and weather events are occurring across multiple biomes and animal taxa (see Supplementary material). The number of animal deaths for each mass mortality varies from hundreds to billions of individuals in a single event, and the time frames range from days to weeks.

Mass mortalities add further pressure to fragile ecosystems

Habitat fragmentation and degradation are biodiversity's pandemic and weaken the resilience of ecosystems to shocks and disturbances. MMEs are exceptional events consisting of the sudden death of hundreds to billions of individuals from one or a few animal species in a defined geographic location (*2*). More than 70% of MMEs are caused by drivers beyond extreme weather and climate (*2*), but similarly, they are often related directly to human activities, such as pollution, habitat destruction and land modification (*2, Figure 1*). The negative impacts of such "demographic catastrophes" (*5*) are threefold. Firstly, the simultaneous death of several individuals from a local population is detrimental to the affected species' genetic pool and possibly its long-term survival (*6*). Secondly, ecosystem equilibria are tightly linked to species population numbers and a major shock to the abundance of one or few species can have cascading effects on the functional interactions across entire landscapes, particularly when keystone species are affected (*5*). Thirdly, the large number of carcasses resulting from MMEs can shift ecological interactions with largely unknown and unpredictable consequences on food webs and plant communities (*3, 5*). This last point is also relevant for 'deliberate' MMEs, such as culling of overabundant species, because this management strategy can produce carcass quantities beyond natural mortality rates in the affected landscape. Thus, the efficient breakdown and recycling of carcasses is critical to manage and mitigate the impacts of MMEs, particularly in landscapes where biodiversity and ecosystem services are already under threat by the pressures of fragmentation and degradation.

In nature, this nutrient recycling service is provided by scavenging guilds that can include a wide range of species, from large apex scavengers to smaller avian, mammalian and insect taxa, and microbial communities (*7*). In fact, regular inputs of animal carcasses are important for maintaining ecological and evolutionary processes and enhancing biodiversity, and several animal species have specialised to consume carrion and detritus (*8*). Examples of ecosystems receiving regular inputs of MMEs exist, including spawning salmon (*Oncorhynchus* spp.) in western Canada and wildebeest (*Connochaetes* spp.) in Kenya (*3*). In these landscapes, carrion is an important source of nutrients and contributes to the dynamics of ecosystem productivity, structure, and function.

However, MMEs are a risk to ecological equilibria and human wellbeing where such events are not the result of millennia of evolution and adaptation (*2, 3, 5*), and where scavenging food webs have become severely altered or are largely absent due to landscape modification or direct persecution by humans (*9*). Modified and dysfunctional scavenger guilds can result in longer carcass persistence in the landscape (*9*), with microbes dominating decomposition processes (*7*). Slower nutrient recycling can alter the structure and composition of scavenger communities (*9*) and, in turn, influence patterns and processes of disease transmission (*10*). Thus, following MMEs, pathogen development and disease spillover may become serious risks from wildlife to humans (*11*). And while the links between COVID-19 and animal sources are still debated (*12*), several historical cases of zoonotic spillover exist and increased habitat fragmentation allows for greater likelihood of contact between people and wildlife (*11*). Thus, resilient scavenger communities can assist us in mitigating the risks of MMEs to ecosystems and to our wellbeing.

Scavenger restoration and conservation to mitigate climate-driven MMEs

Climate change is a global problem and so are animal mass mortalities. The importance of climate change adaptation, beyond mitigation, is now recognised globally (*1, 4, 13*) and there is political commitment appearing internationally (*14*). However, multiple reports highlight the widespread lack of preparedness, and the UNEP Adaptation Gap Report 2020 (*13*) stresses the importance of ecosystem-based solutions to mitigate the impacts of climate change on biodiversity. Accordingly, we suggest that addressing the expected increase of MMEs under climate change starts with systematically managing scavenging food webs to boost ecosystem resilience to shocks and pressures stemming from more frequent and large carcass inputs. This entails three key steps: i) Understanding and recognition of the key role of scavengers as natural providers of nutrient cycling services across ecosystems; ii) Protection and conservation of extant scavenger species and communities, and reintroduction of locally extinct ones; and iii) Planning mitigation actions to assist scavenger communities not adapted to deal with MMEs, particularly in ecosystems already facing multiple threats and stressors.

To the best of our knowledge, the role of scavengers is rarely addressed to achieve goals of ecosystem adaptation to climate change. For example, the Action Plan for vultures in Africa and Europe (*15*) highlights the potential impacts of climate change on the species but does not mention vultures as potential key species for resilient ecosystems. Steering management plans towards the protection and conservation of native and functional scavenging food webs consists of a nature-based solution to mitigate and adapt to the negative impacts of climate change.

Conclusions and the way forward

As 2021 marks the beginning of the UN Decade on Ecosystem Restoration, it is critical that the emerging problem of animal mass mortalities is recognised. Globally, there is a need for greater awareness of MMEs and their link to extreme weather and climate events stemming from climate change. Regionally, greater efforts should be dedicated to assessing the level of resilience of ecosystems and species to extreme climate and weather events, as this can contribute to the identification of animal populations vulnerable to both being the subject of MMEs or being most affected by their negative impacts. Locally, existing management plans should be scrutinised for appropriate policies that address MMEs and acknowledge the value and key role of scavengers as providers of both supporting and regulating ecosystem services. As a first step, assessments of the status and health of ecosystems must include assessment of scavenger biodiversity, their conservation status and contribution to carcass removal and nutrient cycling across ecosystems. Scavenger conservation should be promoted (including reintroductions) to encourage adaptation and resilience to perturbations resulting from MMEs under climate change. In our view, incorporating functional scavenger communities into regional climate adaptation strategies provides a nature-based solution to the emerging global carcass problem.

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Supplementary Materials: Table S1; Supporting references to Figure 1 and Table S1 (S1-S30)