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TOPICAL REVIEW

Review on heatwaves: a risk perspective

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Abstract

Current anthropogenic climate change is increasing the occurrence and magnitude of heatwaves causing closely interconnected and interdependent risks across multiple domains, such as environmental and human health, water and food security, etc. The following systematic literature review synthesizes the state of the art concerning risks related to heatwaves by analyzing 1459 publications. Since risks arise from the interaction of hazard, exposure, and vulnerability, publications were first classified by risk components and then further categorized by research fields: healthcare, society, ecosystem, agriculture, infrastructure, and heritage. The analysis allowed the identification of gaps in the current research with implications for policies and practical applications of risk assessments. First, only 3.1% of the revised literature integrates all three components in risk assessments. Second, most of the literature provides average risks over several heatwave events, thus neglecting critical factors like heatwave magnitude and duration. Third, the absence of standardized indices for identifying and classifying heatwaves hinders effective comparisons of results within the same field. It is recommended that future studies in the same field adopt a common methodology and that the above gaps are taken into account as this would enable building more robust and coherent scientific evidence while reducing ambiguities and uncertainties in risk estimates. Decisionmakers may otherwise struggle to develop effective heatwave adaptation and mitigation strategies if risk assessments are inconsistent or unreliable, and fail to account for risk interdependencies across different domains. More research is needed to develop quantitative frameworks that estimate heatwave risks by summing contributions from each affected domain. This is particularly important, as most of the papers reviewed only focused on healthcare (61.1%) or ecosystems (16.3%). However, we acknowledge that this literature review may have excluded some relevant studies, such as those in the heritage field, due to the specific search string applied in our methodology.

1. Introduction

Heatwaves are periods of abnormally hot weather that last from days to months and are often defined with reference to a relative temperature threshold as reported by the Intergovernmental Panel of Climate Change (IPCC, Masson-Delmotte *et al* 2021). This report shows heatwaves over the land have become more frequent and intense worldwide since the 1950s with medium or high confidence in human contribution to the observed changes. The current global warming of 1.1 K is equivalent to hot extremes (including heatwaves) that are 1.2 K more intense and 2.8 times more likely to occur than pre-industrial levels (i.e. period 1850–1900 when the human contribution to climate variability was not significant). Projections of extremes show a potential further increase proportionally to future global warming levels. A warming level of 4 K may result in projected increases in both magnitude and frequency of 5.1 K and 9.4 times, respectively. In addition, Luo *et al* (2024) report changes in the spatio-temporal evolutions of heatwaves leading to longer-lived, longer-traveling, and slower-moving events that contiguously affect large portions of lands and cause damage to human health and the environment. IPCC shows a significant excess of mortality in the last decades, especially in Europe, Asia, and Oceania (Pörtner *et al* 2022). This evidence is encouraging the scientific community to evaluate the healthcare risks resulting from heatwaves and how to improve human thermal comfort by developing emergency plans and implementing both engineering and nature-based solutions (NbS). However, this effort is often restricted to the direct connections between heat and health, providing a limited inclusion of the other research fields that may directly or indirectly affect human health and well-being. These research fields include the health of ecosystems, agro-food production, infrastructure safety, social relationships, and cultural and natural heritage. For instance, hot extremes during heatwaves can enhance sensible heat fluxes at the interface between the soil and the atmosphere exacerbating drought conditions (Perkins 2015). Water deficit can affect basins leading to mass die-offs of aquatic fauna (Carlson *et al* 2020) and a lower cooling efficiency of thermal and nuclear power plants (Rutten *et al* 2008, Linnerud *et al* 2011, Rübbelke and Vögele 2011). The subsequent reduction in energy production coincides with peak demands of electricity needed for active measures of ventilation such as air-conditioning systems (Morakinyo *et al* 2019). If demand exceeds supply, blackouts occur reducing access to food and water (Zeuli *et al* 2018) and active ventilation that exposes people to higher healthcare risks (Nunes *et al* 2011).

Frameworks proposed in the literature to estimate hydro-meteorological risks (e.g. Shah *et al* 2020) have found little application to heatwaves and are often restricted to human health (Tomlinson *et al* 2011, Buscail *et al* 2012, Aubrecht and Özceylan 2013). These assessments are usually based on the core definition provided by Pörtner *et al* (2022) in which the risk R is the potential for adverse consequences due to the dynamic interaction between the hazard, exposure, and vulnerability components. Hazard is the occurrence of an event that is potentially harmful causing loss of life, health, property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. Heatwaves are atmospheric hydro-meteorological hazards (UNDRR 2019). Exposure consists of the exposed elements located where a hazard occurs such as people, livelihoods, species or ecosystems, environmental functions, services, resources, infrastructure, economic, social, and cultural assets. Vulnerability is the propensity or predisposition of these elements to be impacted by hazardous events. A theory in agreement with the IPCC definition is Crichton's Risk Triangle (Crichton 1999) in which the risk is quantified as the product of hazard, exposure, and vulnerability. This theory is particularly adopted because the risk is null if events occur in an area without exposed elements that are predisposed to be affected by heatwaves. However, the literature has also proposed slight variants that substitute the product with the sum of these components (e.g. Busby *et al* 2014, Ramsey *et al* 2024).

It is worth noting that the identification and quantification of heatwaves as hazardous events can depend on the spatial location, the exposed elements, and the investigated risks (Perkins 2015). For instance, the heat stress felt by living beings can be affected by the usual climate conditions at which these elements are exposed (Curriero *et al* 2002) and by other weather variables in addition to temperature such as relative humidity and radiation (humans, Di Napoli *et al* 2018; livestock, Lallo *et al* 2018). The hazard characteristics (e.g. magnitude and frequency) are affected by the adoption of mitigation measures which are actions that mitigate climate change by preventing greenhouse-gas emissions or removing these gases from the atmosphere (Bashmakov *et al* 2022). The relationship between hazard and risk is also modified by adaptation measures, i.e. interventions that facilitate adjustment of the exposed elements to expected climate and its effects (Pörtner *et al* 2022).

This review synthesizes the current state of the art about heatwaves from the perspective of the IPCC definition of risk. Heatwave risks are analyzed in a broad range of research fields, namely, healthcare, society, ecosystem, agriculture, infrastructure, and heritage. The analyses of publication trends and approaches allow the identification of gaps in the current scientific literature and the provision of recommendations for future research. After this introductory section, the current paper is structured as follows. Section 2 describes the methodology used to carry out the review and classify the papers. Section 3 describes the hazard component. Section 4 describes the exposure and vulnerability components for each research field. Section 5 describes the heatwave risk estimates and frameworks proposed in the literature. Section 6 draws the conclusions. Finally, the appendix provides additional worthwhile references.

2. Methodology

A systematic literature review was carried out on the Web of Science by searching the combination of the words 'heatwave' and 'risk' in the title, abstract, and author keywords. The aim is to collect a broad range of scientific publications investigating heatwave risks in several research fields. This literature search was chosen under the hypothesis that contributions concerning risks integrate the concepts of hazard, exposure, and vulnerability by following the risk definition proposed by Pörtner *et al* (2022). The evaluation of factors beyond heatwaves that may affect these risks in complex systems is beyond the scope of this review. Only articles, review articles, and book chapters written in English were taken into account. The search yielded 1426 contributions published between 1989 and 2023, no limits were set for the starting date. A set of exclusion criteria is used to rule out a total of 206 publications focusing on other hazards, climate

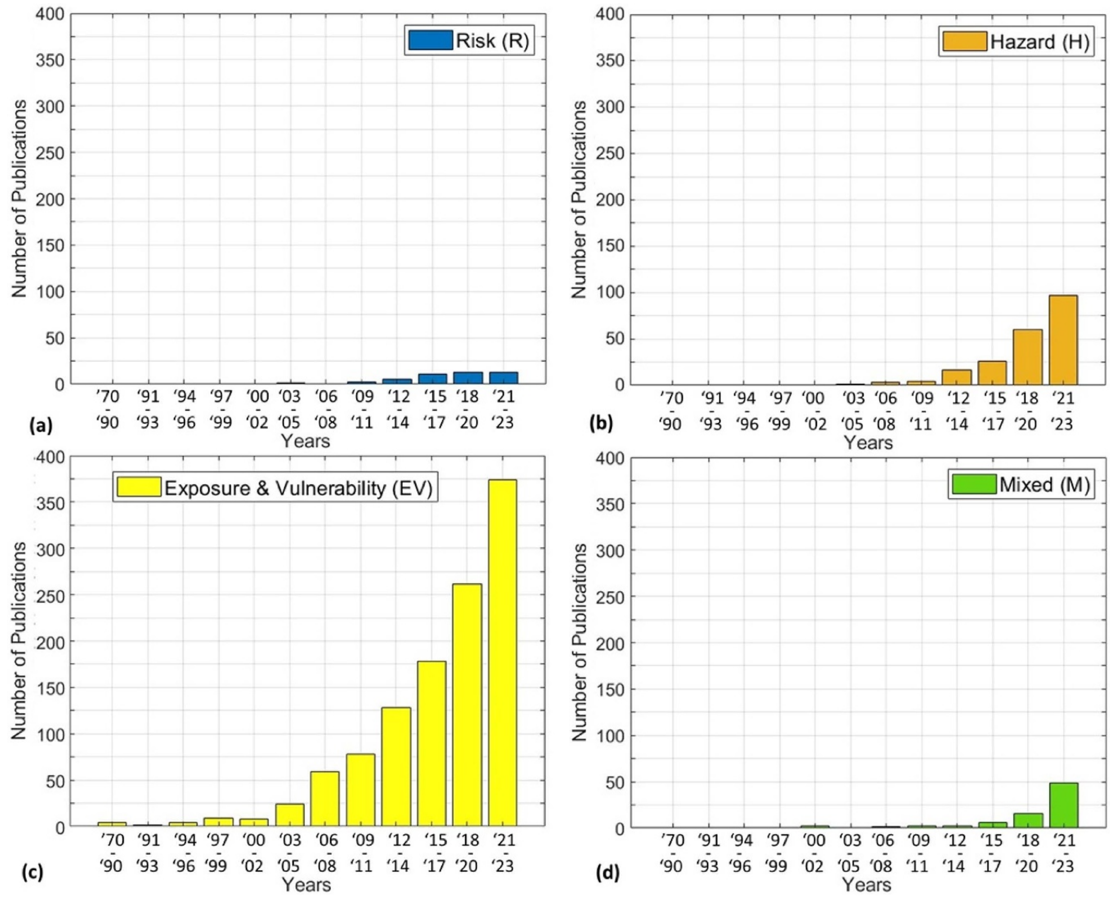

Figure 1. Time series of the number of publications concerning risk (a), hazard (b), exposure & vulnerability (c), and mixed (*M*) categories.

change, or non-risk related aspects of heatwaves. Most of the excluded publications are related to marine heatwaves (55 publications), heatwave forecasting and modeling validation (27), the general concept of climate change and hydro-meteorological hazards (25), cold waves (11), and drought (10). The excluded contributions were replaced by other 239 peer-reviewed articles and reviews already known by this paper's authors or found by snowballing citations. The final database includes 1459 publications subdivided into 1336 articles, 113 reviews, and 10 book chapters.

After a careful reading, the publications were classified according to the definitions provided by Pörtner *et al* (2022) (section 1) and divided into the following categories: (1) hazard (*H*), (2) exposure-vulnerability (*EV*), (3) mixed (*M*), and (4) risk (*R*). Publications were classified as *H* if the main topic is the analysis of heatwave characteristics (e.g. magnitude, duration, frequency) in both present and future climate scenarios. *EV* publications have investigated the to be affected by heatwaves. Exposure and vulnerability were combined in a single class because the analyses of the vulnerability component depend on the choice of the exposed elements to be analyzed. Since the vulnerability component includes the capacity to adapt and cope with hazards (Pörtner *et al* 2022), publications that have proposed measures to address heatwaves were classified as *EV*. On the other hand, *M* publications combined elements of both *H* and *EV* without a final quantification or discussion of risks as achieved by the *R* ones.

Figure 1 shows the number of contributions as a function of the year of publication classified according to the risk component. The number of *EV* (1128%, 77.3% of the total number in the final database), *H* (208%, 14.3%), and *M* (78%, 5.3%) contributions is significantly increasing over time leading to an exponential growth in the total number. Conversely, the trend of *R* contributions shows a plateau in the last decade. Despite the use of the word 'risk' as a keyword of the systematic literature review, only 45 publications (3.1%) are classified as *R*. We decided to exclude from *R* the publications that do not address both magnitude and duration of the heatwave, as it would be required by its definition. For example, several papers included in this review show the variation of risks versus temperature without any information about duration, or analysis of risks taking into account all past heatwave events over a certain threshold without allowing to discriminate between the magnitude of each single event. These papers were classified as *EV* due to the provision of valuable information concerning heatwave impacts in

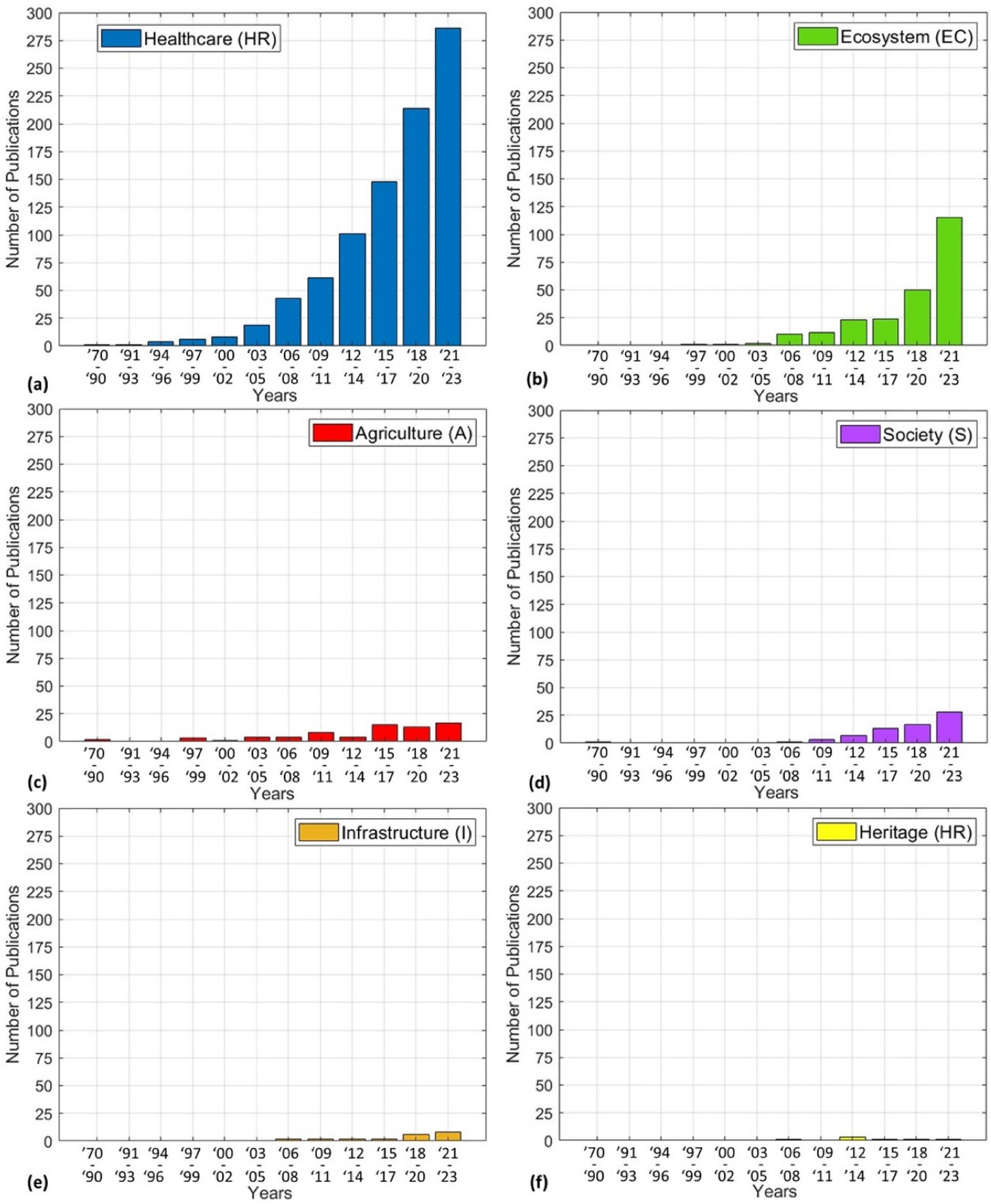

Figure 2. Time series of the number of publications concerning healthcare (a), ecosystem (b), agriculture (c), society (d), infrastructure (e), and heritage (f) research fields.

past events that help to understand the propensity or predisposition of elements to be adversely affected by heat stress.

The *EV*, *M*, and *R* publications were further classified into the related fields of research, i.e. healthcare (*HC*), society (*S*), ecosystem (*EC*), agriculture (*A*), infrastructure (*I*), and heritage (*HR*). 55 (3.8%) *EV* and 3 (0.2%) *R* publications fit into two different fields (i.e. a multiple *EV* publication) and have been classified as belonging to both fields. Figure 2 shows the time series of the number of publications for each field. The exponential trend of both *EV* and *M* contributions is driven by the research in the two predominant fields, i.e. *HC* and *EC*. The time series of the other fields do not show a clear trend or seem to have reached a plateau as *A*. Further details are provided by figure 3 which reports an info-graphic to summarize the subdivision of research fields in sub-categories and the related statistics. *HC* contributions dominate the literature review by covering 892 publications (61.1%), followed by *EC* (238%, 16.3%), *A* (71%, 4.9%), *S* (70%, 4.8%), *I* (22%, 1.5%), and lastly *HR* (7%, 0.5%). The research on heatwave risks shows a disparity in focus, with significantly more studies on healthcare than on other domains. This disparity can also have repercussions on the most

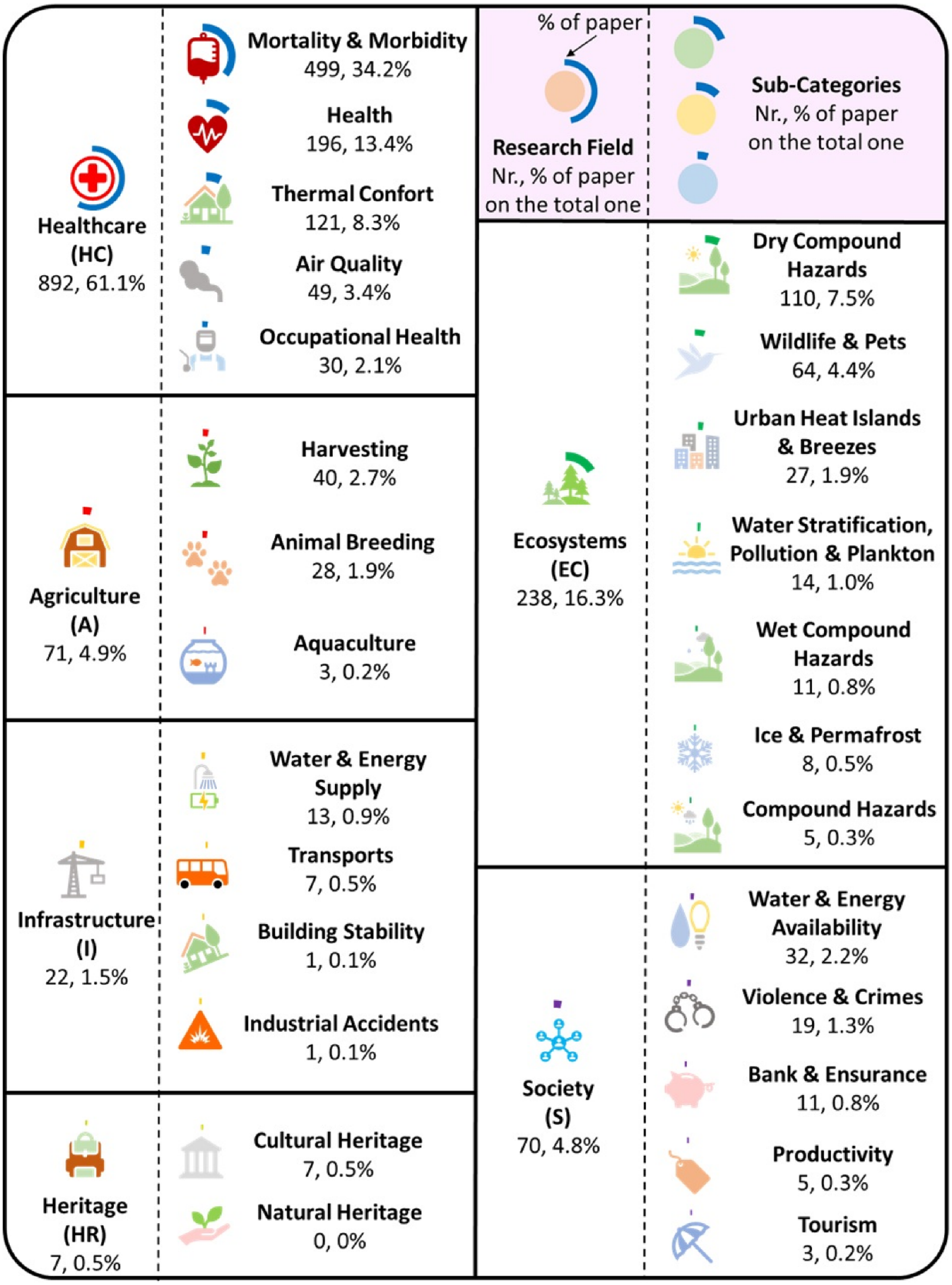

Figure 3. Info-graphic that shows each research field and its sub-categories. Each field was associated with a color, i.e. healthcare (blue), ecosystem (green), agriculture (red), society (purple), infrastructure (orange), and heritage (yellow). The arc length around each icon is regulated according to the percentage of the total number of publications.

widely analyzed fields such as human health which is closely connected to the health of animals and ecosystems (one health concept, Destoumieux-Garzón *et al* 2018). For instance, heatwaves can exacerbate drought conditions (Perkins 2015; dry compound hazards, *EC*). The lack of water affects vegetation leading to tree die-off events (Mitchell *et al* 2014; dry compound hazards, *EC*), a reduction in pasture growth (Harrison *et al* 2017; animal breeding, *A*), and losses in crop yields (Potopová *et al* 2017; harvesting, *A*). Production losses can contribute to geopolitical instabilities (d'Amour *et al* 2016; Violence & Crimes, *S*), worsening both human health and well-being.

Even the sub-categories of each research field show a different interest (figure 3). All research fields have a predominant sub-category covering about

50% of the contributions: *HC*) human mortality and morbidity (mortality & morbidity, 55.9% of total *HC* contributions) followed by analyses of health policies and people's perception, knowledge, and awareness (Health, 22.0%), *S*) the availability of water and energy to meet demand (Water & Energy Availability, 45.7%) followed by the occurrence of traffic crashes and violent behaviors (Violence & Crimes, 27.1%), *S*) compound events of heatwaves, drought, and wildfires (dry compound hazards, 46.2%) followed by the animal health (Wildlife & Pets, 26.9%), *A*) crop failures (Harvesting, 56.3%) followed by mortality and morbidity of livestock and production losses (animal breeding, 39.4%), and *I*) production and distribution of water and energy (Water & Energy Supply, 59.1%) followed by damage to transport networks (Transports, 31.8%). The *HR* field shows the worst situation in which 100% of analyzed contributions are related to cultural heritage neglecting the natural one.

3. Hazard

Heatwave events are becoming more intense, long-lasting, and frequent in most continental lands and these characteristics may further increase in the next century. Several studies have investigated these events in present (*p*) and future (*f*) climate for Africa (e.g. *p*, Ceccherini *et al* 2017, van der Walt and Fitchett 2021; *f*, Russo *et al* 2016, Zittis *et al* 2021), Artic (e.g. *p*, Dobricic *et al* 2020, Yu *et al* 2021), Asia (e.g. *p*, Khan *et al* 2019, Luo *et al* 2022b; *f*, Das and Umamahesh 2022, Hua *et al* 2023), Europe (e.g. *p*, Chapman *et al* 2019, Kew *et al* 2019; *f*, Lhotka *et al* 2018, Smid *et al* 2019), North America (e.g. *p*, Habeeb *et al* 2015, Hulley *et al* 2020; *f*, Zou *et al* 2022, Chen *et al* 2023b), Oceania (e.g. *p*, Gergis *et al* 2020, Jyoteeshkumar Reddy *et al* 2021; *f*, Nishant *et al* 2022), and South America (e.g. *p*, Ceccherini *et al* 2016, Rusticucci *et al* 2016; *f*, Giorgi *et al* 2014, Dosio *et al* 2018). Low-income regions are experiencing the highest heatwaves trends and will be the most exposed to future changes due to their limited adaptive capacities (Lee *et al* 2021, Alizadeh *et al* 2022). The higher the greenhouse-gas concentration and warming rate are, the higher these changes will be (Almazroui *et al* 2021, Fischer *et al* 2021).

Several papers have analyzed the drivers of past heatwave events attributing their characteristics (e.g. frequency of occurrence, magnitude, and duration) to the internal climate variability (20 out of 49 papers, 41%), the external anthropogenic contribution to climate change (14%, 29%), or both (15%, 31%). Depending on the geographical area of interest, climate patterns that affect heatwaves include El-Nino Southern Oscillation (ENSO, e.g. Chase *et al* 2006, Hoerling *et al* 2013, Panda *et al* 2014), Indian Ocean Dipole (Akihiko *et al* 2014, Loughran *et al* 2017, Reddy *et al* 2021), Interdecadal Pacific Oscillation (Imada *et al* 2017), Atlantic Multi-decadal Oscillation (Keellings and Waylen 2015), North Atlantic Oscillation (Yoon *et al* 2020), Madden–Julian Oscillation (Guigma *et al* 2021). These patterns can trigger persistent high-pressure blocking events which are long-lasting at high latitudes and are increasing at mid-latitudes (Pfleiderer and Coumou 2018). Blocking events induce land-atmosphere feedback that can contribute to the occurrence of daytime heatwaves resulting in high daily maximum temperature (e.g. Kornhuber *et al* 2017, Ren *et al* 2020, Rousi *et al* 2022). Atmospheric subsidence during blocking events leads to cloud-free sky conditions (Kautz *et al* 2021). Lack of precipitation and larger incoming short-wave radiation at the ground can contribute to soil-moisture depletion. As a consequence, a lower portion of the incoming solar energy is used for evapotranspiration lowering its cooling effect on the atmosphere. The available energy is converted into more sensible heat fluxes resulting in heating. As a loop, a warmer atmosphere further dries out the soil contributing to further heating of the atmosphere (e.g. Schumacher *et al* 2019, Zhang *et al* 2020, Dirmeyer *et al* 2021). This loop can be worsened during the daytime by large-scale horizontal advection that can promote the entrainment of warm air into the atmospheric boundary layer (e.g. Sousa *et al* 2019, Röthlisberger and Papritz 2023). Although this warming can be reduced by convection in mountain areas and sea-breeze circulations (Stéfanon *et al* 2014), this warm air is stored in anomalously deep and warm nocturnal residual layers where stagnation conditions occur (Miralles *et al* 2014), leading to a progressive accumulation of heat over several days.

Gershunov *et al* (2009) found similar driving mechanisms for nighttime heatwaves (i.e. high daily minimum temperature). However, these events are typically associated with an increase in both cloud cover and humidity. This anomalously moist atmosphere can affect minimum temperature by enhancing downward longwave radiation during the night and intensifying greenhouse-gas effect. Compound heatwaves (i.e. both high daily minimum and maximum temperature) are usually a combination of the atmospheric conditions that occurred during daytime and nighttime heatwaves (Luo *et al* 2022a). The frequency of occurrence of both nighttime and compound heatwaves increased faster than daytime heatwaves over land regions in the period 1979–2020 (Wu *et al* 2023).

Along with the natural drivers, these processes can be triggered by the increasing trend of air temperature due to climate change (e.g. Stott *et al* 2004, Perkins *et al* 2014, Vogel *et al* 2019, Rivera *et al* 2023). Otto *et al* (2012) reported that the same heatwave event may be mostly driven by internal variability in terms of magnitude, while externally driven in terms of frequency of occurrence. Other external factors that can contribute to the local intensification of heatwaves are

Table 1. Indices proposed in the literature to quantify the magnitude and probability of occurrence of heatwaves.

Author	Index
Nairn and Fawcett (2015) Added an acclimatization index $\mathrm{EHF}_{\mathrm{accl}}$ because living beings may potentially suffer more consequences if the heatwaves determine a sudden rise in temperature	**Excess Heat Factor** $\mathrm{EHF} = \mathrm{EHF}_{\mathrm{sig}} \times \max\left(1, \mathrm{EHF}_{\mathrm{accl}}\right)$ where $\mathrm{EHF}_{\mathrm{sig}} = \frac{\overline{T}_i + \overline{T}_{i+1} + \overline{T}_{i+2}}{3} - \overline{T}_{95}$, $\mathrm{EHF}_{\mathrm{accl}} = \frac{\overline{T}_i + \overline{T}_{i+1} + \overline{T}_{i+2}}{3} - \frac{\overline{T}_{i-1} + \ldots + \overline{T}_{i-30}}{30}$, $\overline{T}_i$ is the mean daily temperature at day i, $\overline{T}_{95}$ is the 95th percentile temperature
Russo *et al* (2014, 2015) Estimated the heatwave magnitude by integrating the exceedance to a percentile threshold for every day of an event	**HeatWave Magnitude Index daily** $\mathrm{HWMId} = \sum_{i=1}^{n} \left(T_{\max,i} - T_{\max,25}\right)\left(T_{\max,75} - T_{\max,25}\right)^{-1}$, where $i = 1, \ldots, n$ are the number of heatwave days, $T_{\max,i}$ is the daily temperature at day i, $T_{\max,25}$ and $T_{\max,75}$ are the 25th and 75th percentiles, respectively
Raei *et al* (2018) Introduced a probabilistic and generalized index to describe heatwaves according to their probability of occurrence In long-term records	**Standardized Heat Index** $\mathrm{SHI}\left(\hat{T}\right) = \Phi^{-1}\left(p\left(\hat{T}\right)\right)$ where $\hat{T} = \frac{\overline{T}_i + \overline{T}_{i-1} + \overline{T}_{i-2}}{3}$ Φ is the standard normal distribution of the Gringorten plotting position $p\left(\hat{T}\right) = \frac{r - 0.44}{n + 0.12}$, r is the rank of $\hat{T}$ on a sample of size n
French *et al* (2019) Adopted a general loss function to define heatwaves according to their intensity, duration, and spatial extent	**HeatWave Functional** $H(Y)\left(s_i, t_k\right) = S_d \circ D_l$ where $Y\left(s_i, t_k\right)$ is a collection of functional curves at position s_i and time t_k, S_d and D_l are the spatial and duration functionals, respectively.
Keellings and Moradkhani (2020) Proposed an integrated index that combines intensity and spatial extent	**Heatwave Coverage Index** $\mathrm{HSCI} = \sum_{i=1}^{n} m_i \times a_i$ where $i = 1, \ldots, n$ are the number of heatwave days, m is the average magnitude exceedance from a temperature threshold in the spatial extent of the heatwave a
Wang and Yan (2021) Proposed a revised version of HWMId in which this index is averaged over the grid boxes affected by the heatwave	**Regional Heatwave Magnitude index daily** $\mathrm{RHWMId} = \sum_{g=1}^{m} \mathrm{HWMId}(g) \times wgt(g)\left(\sum_{i=1}^{M} wgt(i)\right)^{-1}$ where $g = 1, \ldots, m$ are the grid boxes affected by the heatwave, wgt is the area weight of a grid box, $i = 1, \ldots, M$ are the total number of grid boxes
Wanyama *et al* (2023) Proposed a composite index that integrate standardized mean variables concerning heatwave characteristics	**Combined Heatwave Characteristic Index** $\mathrm{CHCI} = \overline{a} \times \overline{m} \times \overline{np} \times \bar{f}$ where $\overline{a}$, $\overline{m}$, $\overline{np}$, $\bar{f}$ are the mean spatial extent, magnitude, number of patches and fragmentation score of heatwave events during the set time scale by pixel

urbanization (Lin *et al* 2018, Ye *et al* 2018) and the subsequent interaction between heatwaves and urban heat islands (Lemonsu *et al* 2015, Ward *et al* 2016).

The literature has proposed a wide range of indices to identify heatwave events and estimate their characteristics (Perkins 2015). Concerning the identification, indices usually require to exceed a temperature threshold and a temporal extent. These indices differ in the adopted weather variables (e.g. daily maximum, mean, or minimum temperatures, wet-bulb globe temperature, universal Thermal Climate Index), the minimum duration to classify as a heatwave (generally between 2 and 6 d), the adoption of absolute or percentile thresholds, and the reference period to evaluate percentile thresholds (e.g. a seasonal or a 15 d window reference period estimated over 30 years). Stefanon *et al* (2012) also added constraints on the spatial extent to avoid spurious local events. Baldwin *et al* (2019) replaced a continuous threshold-exceedance duration criterion with an intermittent one to classify as heatwave events the periods of hot days interspersed by short breaks. Table 1 reports some valuable indices to estimate the heatwave magnitude and probability of occurrence.

The choice of indices affects the comparison between heatwave events (Becker *et al* 2022) and the simulation of future trends (Vogel *et al* 2020). Different indices can highlight distinctive attributes of heatwaves leading to potentially inconsistent conclusions and complicating the assessment of risks (Perkins and Alexander 2013, Ahn 2022). For instance, the selection of minimum, mean, or maximum temperature can affect the detection of different types of heatwaves (i.e. daytime, nighttime, or compound events) that are differently correlated to human morbidity and mortality (e.g. Xu and Tong 2017). Another example is the meta-analysis conducted by (Xu *et al* 2016) which concluded that the excess of mortality ranges between 3% and 16% based on the percentile thresholds and duration selected for identifying heatwaves. Relative risks for heatwave days compared to non-heatwave days range between 1.0 and 1.5 depending on the selected identification index between the 12 ones tested by de Moraes *et al* (2022). Kent *et al* (2014) compared 15 indices by analyzing data concerning preterm births in Alabama (USA). Although the percent changes in heatwave days are usually significantly positive, some indices result in negative associations. Odd ratios range between −9.7% and 11.6% (between −17.9% and 19.5% considering confidential intervals) in the 10 indices that include more than 500 preterm-birth cases. Since the heterogeneity of the adopted indices can affect the comparison of quantitative results, we have decided to not report quantitative information in both this and subsequent sections.

4. Exposure & vulnerability

4.1. Health

Heatwaves can have significant implications on human health and the healthcare system leading to an excess of morbidity and mortality due to multi-organ diseases, direct economic losses (e.g. ambulance transport and medical treatments), economic losses caused by patients' inability to work, and saturation of hospital facilities when heatwaves occur simultaneously to other emergencies. Figure 4 summarizes the exposure and vulnerability components, risks, and possible adaptation and mitigation measures that can reduce these risks in the healthcare sector. The increase in frequency and severity of heatwaves due to global warming is leading to higher heat-mortality rates (Lüthi *et al* 2023). Excess mortality is mainly explained by the heatwave magnitude (Gasparrini and Armstrong 2011), especially of compound heatwaves (e.g. Xu and Tong 2017, Wang *et al* 2021a). The relationship between temperature and human health may change with the heatwave type due to adaptive physiological responses (e.g. cutaneous vasodilatation) that nonlinearly vary according to cumulative excess heat (Liu *et al* 2025). The lower the average summer temperature usually experienced by a population, the lower the threshold temperature above which heat-related deaths might begin to occur (e.g. Gosling *et al* 2007) resulting in a latitudinal dependence (e.g. Curriero *et al* 2002). However, literature suggests that people may acclimatize to high temperatures leading to a larger excess of hospitalization during the first summer event than the subsequent ones (e.g. Liss *et al* 2017, Sun *et al* 2020b). Several studies have attributed a portion of causalities to mortality displacement (e.g. Gosling *et al* 2007), affecting unhealthy people who would have died shortly anyway (Huang *et al* 2018). Furthermore, heatwave duration may also affect mortality although the analyses of its contribution have given uneven results. For instance, Gasparrini and Armstrong (2011) and Rocklöv *et al* (2011) have found an added effect conversely to Zeng *et al* (2014). Dong *et al* (2016) found this added effect only for the elderly.

The adaptive response of our body is cutaneous vasodilation (Lõhmus 2018) which facilitates heat dissipation by bringing metabolic heat to the surface (Morrison and Nakamura 2011) and providing blood plasma, i.e. a precursor for sweat production (Smith and Johnson 2016). Vasodilatation causes a larger cardiac output to compensate for both the decreased blood flow in visceral areas (i.e. vasoconstriction) and the sufficient provision of oxygen to organs. The elderly are particularly susceptible to heat stress due to the lower production of sweat, efficiency of vasodilatation, and the physiological decrease in surface thermoreceptor density that compromises sensory perception (Chang *et al* 2022). Minson *et al* (1998) found that the cardiac output in the elderly is 67% less than in youth when the body is passively heating up to its thermal tolerance. As a consequence, less blood flow is transported to the skin. Smith *et al* (2013) measured responses during passive heating up to a 1 K increase in oral temperature. The skin blood flow was attenuated in the arms and back (56% and 82% of the values observed in youth, respectively) while sweating was reduced more in the arms and abdomen (26% and 29% of youth, respectively). If vasodilatation does not work in dissipating heat, temperature continuously increases until body core temperature exceeds 40 °C and heat stroke occurs. The consequences are organ dysfunctions that may affect the individual's functional status for years in case of survival. Argaud *et al* (2007) reported a 2 year survival rate of 29% of patients after the 2003 heatwave in France. The long-term compromises may include the brain due to both higher blood temperature in input and lower oxygen saturation levels during the heat stroke (Lõhmus 2018).

Psychiatric patients are more exposed to heatwaves because some neurotransmitters are involved in both thermoregulation and mental diseases (Bark 1998). Their susceptibility may be exacerbated by both mobility and cognitive problems (Linares *et al* 2016). In addition, some drugs can promote the onset of heat strokes by increasing metabolic heat production and reducing sweating and cutaneous vasodilatation (Lõhmus 2018). Although both alcohol and opioids increase cutaneous vasodilation,

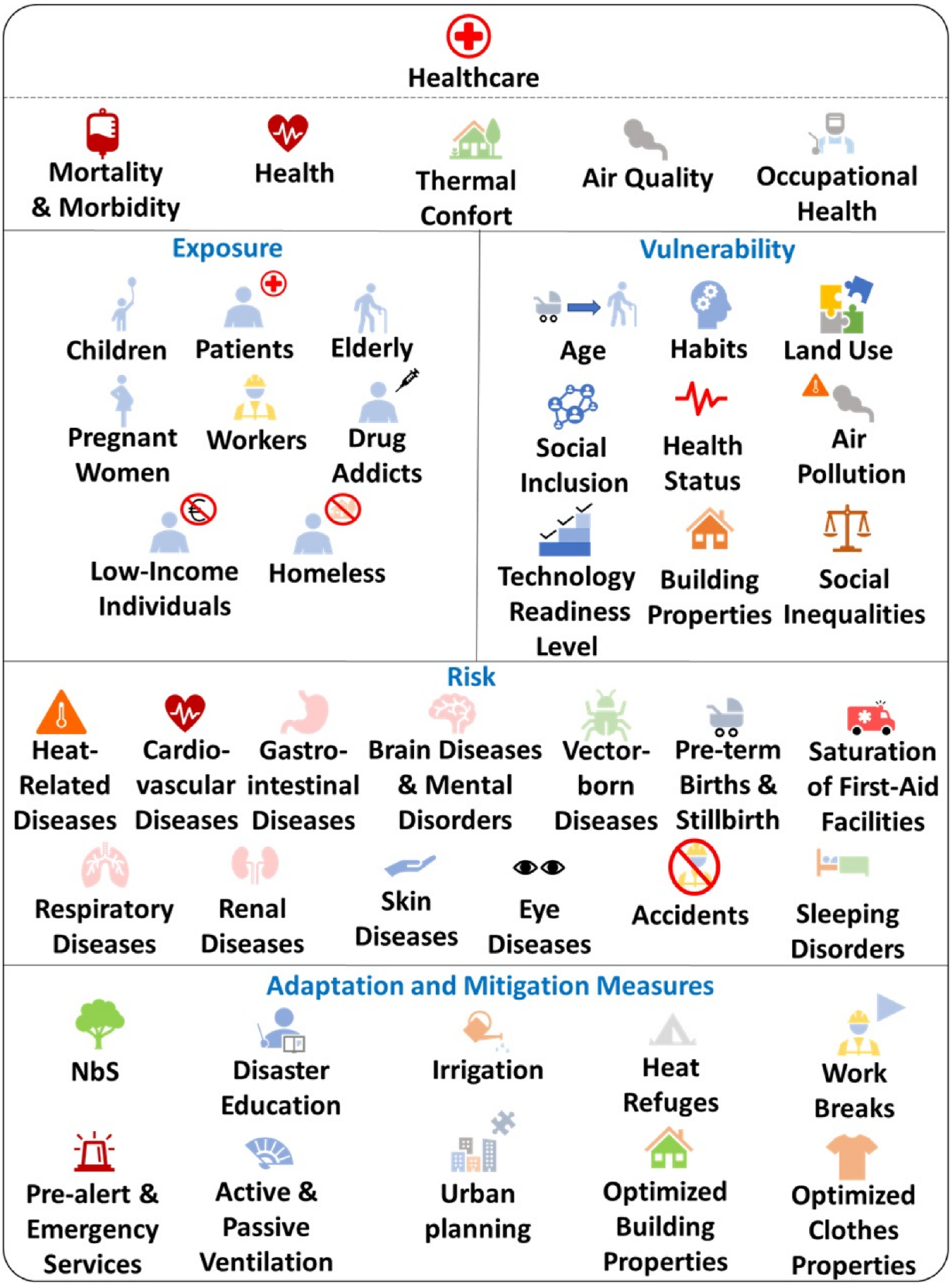

Figure 4. Info-graphic that summarizes the sub-categories of the healthcare (*HC*) research field affected by heatwaves (i.e. the hazard), the exposure and vulnerability components, the possible risks, and adaptation and mitigation measures that can be adopted to reduce these risks.

these substances can cause dehydration (Cusack *et al* 2011). The loss of only 2% of total body water content can result in significant impairment in both physical and cognitive performances (Grandjean and Grandjean 2007). The elderly are more susceptible to dehydration, electrolyte abnormalities, and renal diseases. This susceptibility is caused by age-related physiological changes, collateral diuretic effects of drugs, and lower water uptake due to both physical disability or embarrassment associated with incontinence (El-Sharkawy *et al* 2014).

The concurrency of heatwaves and outbreaks of infectious diseases can lead to the saturation of hospital facilities. High temperatures can contribute to infectious diseases (Damonti *et al* 2023) by promoting pathogen proliferation (Hackbusch *et al* 2020), affecting the food chain (D'Souza et al 2004, Milazzo et al 2016), and altering the hygiene behavior of population (Xu et al 2014). Cheng et al (2020) found a correlation between the occurrence of heatwaves and dengue outbreaks, with longer delayed effects (around 14 weeks) on large outbreaks possibly caused by an over-compensatory mechanism of mosquito-population persistence (Chaves et al 2014, Cheng et al 2021, Damtew et al 2023). Despite the high temperatures can inhibit viral activity (Dabisch et al 2021), excess body heat in conjunction with air pollution can worsen respiratory symptoms by increasing systemic and pulmonary inflammation and compromising breathing patterns (Anenberg et al 2020). A portion of heat-related deaths is attributable to the positive relationship between ambient temperature and the production rate of pollutants (e.g. $PM2.5$ and tropospheric ozone O_3; Fischer et al 2004, Filleul et al 2006, Tong et al 2010, Chen et al 2017). High temperatures enhance the emissions of biogenic volatile organic compounds (VOC) from urban greenery leading to an increase in O_3 concentrations produced by photochemical reactions between VOC and urban anthropogenic pollutants such as nitrogen oxides (NO_x). Biogenic emissions are associated with at least 20% of summer O_3 concentrations in the USA with peaks of 40% (Tao et al 2003). However, this positive relationship is modified by the concentration of other chemical compounds, weather, and urban morphology. For instance, carbon dioxide (CO_2) inhibits the natural emission of some VOC (Doherty et al 2017), and winds and turbulence can diffuse pollutants (Pu et al 2017, Barbano et al 2021, Kajino et al 2022).

Air pollution can further increase the risk of preterm births (Sun et al 2020a, Wang et al 2020a, Kwag et al 2021) which is already exacerbated by heat stress (Wang et al 2013, Smith and Hardeman 2020, Huang et al 2021). A higher risk of preterm birth was found when the mother experiences heatwaves during the first 5 weeks and 20–26 weeks after conception (Hough et al 2023), and the last week of gestation (Ilango et al 2020, Cushing et al 2022). High temperatures are also associated with both reduced birth weight, stillbirths (Wang et al 2019, Chersich et al 2020), multiple congenital heart defects (Agay-Shay et al 2013), and severe maternal morbidity Jiao et al (2023). Children under one year of age are particularly susceptible to heatwaves (Xu et al 2012), especially during the perinatal period (i.e. the first week of life; Basagaña et al 2011). This susceptibility depends on both physiological and cognitive faculties. For instance, newborns and young children cannot be able to communicate their symptoms clearly (Zivin and Shrader 2016).

Workers are exposed to occupational injuries during heatwaves, especially if they have low heat adaptation, aerobic fitness, and body mass (Foster et al 2020). Young workers are susceptible to occupational injuries due to their propensity to perform more arduous physical activities, respect less the preventive measures, have less experience, and receive less safety training to recognize heat-related risks (Binazzi et al 2019). On the other hand, older workers may perceive comfortable conditions even under extreme heat strain (Kim and Yoo 2023) for their compromised thermoreceptors. Xiang et al (2014) reported a significant increase during heatwaves of burns, wounds, lacerations, and amputations, due to environmental factors, the usage of moving objects, or contact with chemicals. Outdoor laborers and tradespersons were found to be the most exposed to injuries and illnesses, especially those employed in agriculture, forestry, and fishing activities or electricity, gas, and water production. In addition to direct exposure to the sunlight, physiological stress can be increased by the presence of hot machinery or the wearing of poorly-breathable protective clothing for safety reasons (Morris et al 2020). Morabito et al (2006) reported a higher amount of work-related hospital admissions in the early summer days hypothesizing a behavioral change when heat stress increases. Occupational injuries are projected to increase in future climate scenarios (Fatima et al 2023).

Few studies have estimated the cost of heat-related hospitalizations finding relevant economic losses (e.g. Wondmagegn et al 2021). Adélaïde et al (2022) found the economic losses of heat-related mortality in the French healthcare system are billions of euros and at least an order of magnitude greater than losses due to both morbidity and minor restricted activity days. Stewart et al (2017) reported the cost of mortality outweighed the one of additional electricity demand during heatwaves in Vancouver (Canada).

In the context of climate justice, Campbell et al (2018) highlighted that scientific research up to May 2017 was spatially heterogeneous. Only 20% of papers analyzed the exposure of the healthcare system to heatwaves in tropical and high-latitude regions. Demographic projections show that the population is aging worldwide (e.g. Oven et al 2012) and will be more exposed to heatwaves during the coming decades, especially in Africa, South and East Asia, the Middle East, Northern Australia, and Central and South America (Liu et al 2017, Freychet et al 2022, Yin et al 2022). Hanberry (2022) hypothesized that most land regions could reach a tipping point incompatible with high urban-population densities by 2081–2100. Population in megacities may experience a high degree of thermal inequality associated with residential segregation (Mitchell and Chakraborty 2018). Fünfgeld (2010) identified key barriers to effective adaptation in cities including the lack of governance frameworks for climate risk management that integrate the socio-economic processes with scientific knowledge about hazards and risks. Limited resources and a lack of responsibility identification often coexist in vulnerable low-income and multi-ethnic neighborhoods where short-term responses based on subjective opinions and risk perceptions may lead to potential long-term maladjustment (Zografos *et al* 2016). Although the population in urban areas is usually more exposed to high temperatures, rural ones may be more vulnerable due to insufficient hospital resources, lower disposable income, and a larger number of elderly that live alone (Chen *et al* 2015, Kim *et al* 2017). Strengthening people's inclusion in the community can support individual and collective adaptive initiatives as well as the detrimental elderly's perception of independence and reluctance to ask for help (Wolf *et al* 2010).

The homeless are particularly at risk (Schwarz *et al* 2022) and can find comfort in public heat refuges which need to be evenly distributed across each city (Voelkel *et al* 2018). Short visits to refuges temporarily reduce core temperature and cardiovascular strain (McCormick *et al* 2023, Meade *et al* 2023). Sy *et al* (2022) highlighted the importance of having access to safe drinking water at home. Low-cost and informally constructed homes can experience indoor-temperature variations even larger than the daily ambient-temperature ones (Naicker *et al* 2017). In several states in which the energy demand is dominated by the need for heating during wintertime, regulations focus attention on thermal insulation overlooking effective adaptation plans for heatwaves (Baniassadi *et al* 2018, Arriazu-Ramos *et al* 2023). Attia *et al* (2023) assessed the energy performance of buildings directive for the European Union countries and proposed recommendations to align current criteria with climate-sensitive metrics. Mavrogianni *et al* (2012) analyzed dwelling types and characteristics in London (UK) finding that orientation, surrounding buildings, and insulation levels are the most relevant factors in determining the heat response. Under the current climate, roof insulation and window upgrades reduce daytime indoor temperature up to 1 °C during warm days. Since the dwellings are physical objects that interact with the surroundings, urban planning can affect indoor thermal performance (Lee and Kim 2022). For instance, the spatial disposal of terraced houses limits natural ventilation and negatively affects indoor temperature (Ozarisoy and Elsharkawy 2019, Wright and Venskunas 2022).

People's actions can significantly reduce overheating in indoor environments by opening windows for natural ventilation when the external temperature is lower than the internal one, and providing internal shading during the daytime through reflective materials (Porritt *et al* 2012, Baborska-Narozny *et al* 2017, Rempel *et al* 2022). From an economic and climate perspective, Morris *et al* (2020) suggested that occupational heat strain can be mitigated by the adoption of improved physiological acclimatization, planned breaks, shading, and optimized clothing properties. However, coupling passive and active measures can be the optimal solution for improving energy efficiency and thermal comfort (e.g. Sun *et al* 2020c). Scientific literature has produced mixed results concerning the effectiveness of electric fans (Gupta *et al* 2012, Ravanelli *et al* 2017, Cramer *et al* 2020) because air velocity increases the latent heat flux between the skin and the environment. The body can gain heat from the environment If air temperature exceeds the skin temperature, especially in the elderly who have reduced sweating capacities. An experiment conducted by Gagnon *et al* (2017) showed that the use of fans at 42 °C and humidity between 30% and 70% increases resting heart rate (+5 beats per minute), core temperature (+0.2 °C) and skin temperature (+0.5 °C) in elderly. Another active solution consists of air-conditioning systems. The adoption of these systems can significantly enhance indoor thermal comfort decreasing heat-related deaths over time (Davis *et al* 2003, Barnett 2007, Trigo *et al* 2009, Nunes *et al* 2011). However, air conditioning promotes social inequalities because low-income people may limit its use for preventing economic losses (Hansen *et al* 2011, Flores-Larsen and Filippín 2021). In addition, air conditioning can overload the electricity network (Stone Jr *et al* 2021a) and release a significant amount of CO_2 emissions and heat affecting the outdoor temperature. The overuse of air conditioning can be reduced in single-story structures by installing cool roofs that decrease the building-interior temperatures up to 4 °C during the daytime (Stone Jr *et al* 2021b). By lowering peak temperatures, cool roofs can offset a fraction of heat-related mortality (Macintyre and Heaviside 2019).

Other adaptation measures include the shading of buildings with trees and the implementation of green roofs and facades (Flores-Larsen and Filippín 2021). Although both green and cool roofs are effective in reducing indoor and outdoor temperatures, mixed results were produced in the literature concerning the comparison between these types of roofs. For instance, Xing and Jones (2021) compared measurements between a green and a cool roof reporting that the green one is 2.5 °C more efficient in reducing the ceiling maximum temperature. On the other hand, the modeling study of Imran *et al* (2018) reported that the introduction of cool roofs in Melbourne (Australia) would reduce the roof-surface temperature up to 1.4 °C more than green roofs.

Greening cities can also reduce heat-related mortality (Zhang *et al* 2021b, Chaston *et al* 2022). Wang *et al* (2020b) analyzed several biomes in the USA finding a positive linear relationship between tree cover and surface temperature. However, the effect of trees on temperature, ventilation, and air quality depends on both surface types (Winbourne *et al* 2020) and tree morphological features such as canopy size, shape, structure, number, and distribution (McPherson *et al* 2018, Barbano *et al* 2020, Rahman *et al* 2020). High leaf density can trap long-wave radiation under the canopy causing an increase in nighttime surface temperature (Ziter *et al* 2019), and pollutants close to the

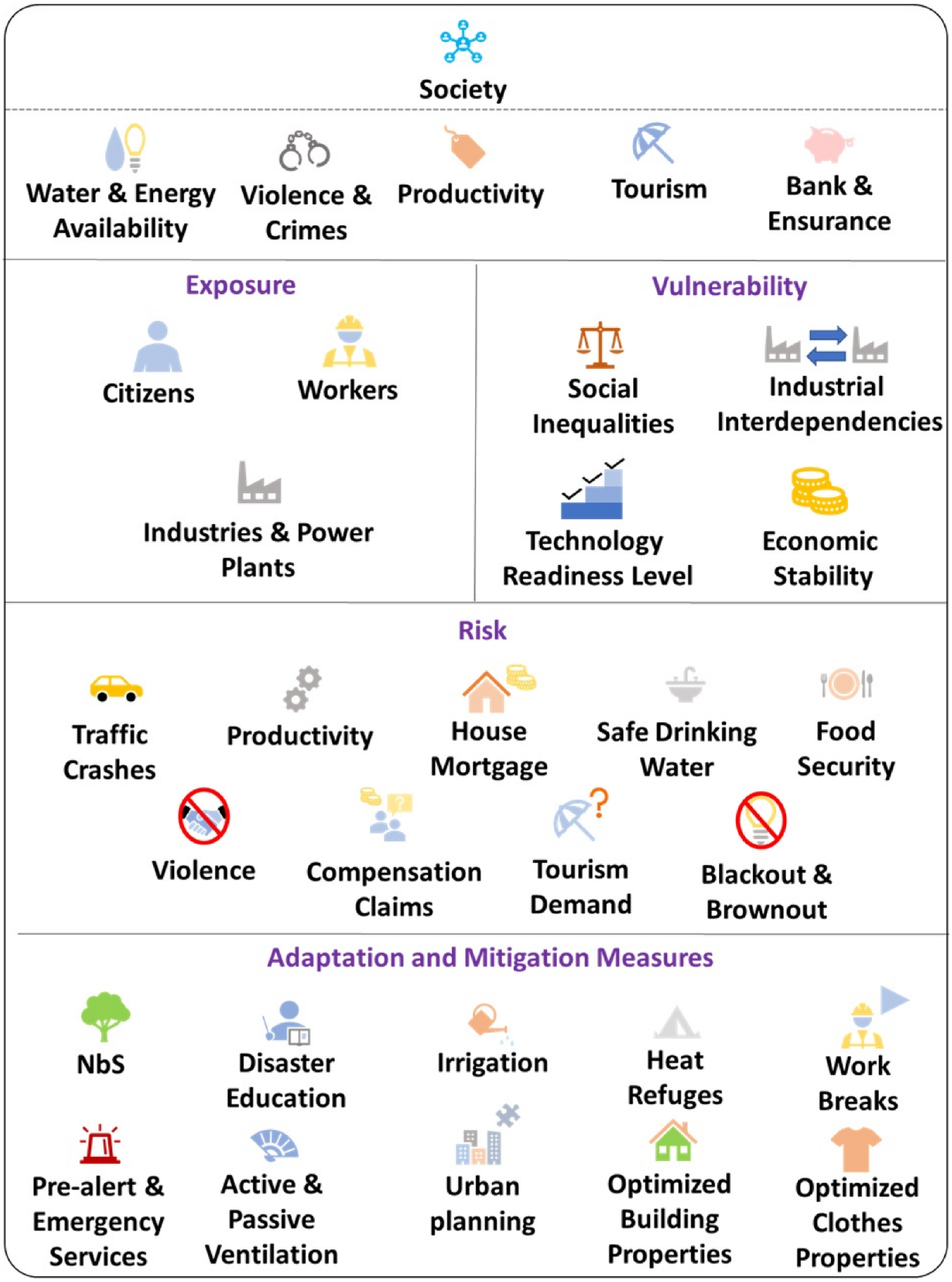

Figure 5. Info-graphic that summarizes the sub-categories of the society (*S*) research field affected by heatwaves (i.e. the hazard), the exposure and vulnerability components, the possible risks, and adaptation and mitigation measures that can be adopted to reduce these risks.

surfaces (Jung and Yoon 2022). A key factor in the response of street trees can be the availability of water (Winbourne *et al* 2020). If water uptake from the soil is not sufficient, trees may close stomata to preserve water during heatwaves. Stomatal closure leads to the decline (or even stop) of transpiration affecting temperature due to the lower latent heat fluxes, and decreasing O_3 uptake with detrimental effects on human health (Emberson *et al* 2013, Doherty *et al* 2017). A strategy to prevent stomatal closure can be urban irrigation (e.g. Hendel *et al* 2020). However, irrigation increases water consumption and provides both a positive effect on thermal comfort by enhancing surface latent fluxes and a negative one by increasing air humidity. Broadbent *et al* (2018) found the positive effect outweighs the negative one proportionally to the fraction of pervious urban areas. Although no papers have investigated the mitigation role of the measures included in this section, it is worth noting that street trees and other NbS can act as a sink of CO_2, while optimized building properties can reduce emissions.

4.2. Society

Heatwaves can threaten our society undermining our safety, leisure, work activities, and availability of basic needs. Figure 5 summarizes the exposed elements in the societal sectors, their vulnerabilities, risks, and proposed adaptation and mitigation measures identified in the current review. However, more research is necessary to verify and better understand the effects of heatwaves in this research field. It is unclear which is the relation between traffic accidents and heatwaves. Lower driving performance due to heat stress was significantly associated with fatal crashes in the United States (Wu *et al* 2018b; increment of 3.4% during heatwave days) and traffic crashes in Catalonia (Spain, Basagaña *et al* 2015; 2.9%), while Wu *et al* (2018b) found a non-significant decrease in both fatal and traffic crashes in Alabama (United States; −4.7% and −1.4%, respectively). All the cited papers classified heatwaves as events in which the mean or maximum temperatures are above the 95th percentile for at least two days.

High temperatures have been associated with violent behaviors (Schinasi and Hamra 2017, Hu *et al* 2020) such as assaults and robberies (Michel *et al* 2016, Lemon *et al* 2017), and intimate partner violence that may culminate with femicides (Sanz-Barbero *et al* 2018). Page *et al* (2007) reported a positive association between temperature and suicides despite they found mixed results during heatwaves. Mixed results were also found for conflicts (Theisen *et al* 2013). For instance, Slettebak (2012) did not report a correlation between heatwaves and civil conflicts, while Nel and Righarts (2008) found that multiple hydro-meteorological hazards including heatwaves can significantly increase the risks in the short and medium term, especially in low- and middle-income countries with mixed regimes and high levels of inequality.

Inequality can be exacerbated by poor work conditions and productivity losses (Ullah *et al* 2022). Xia *et al* (2018) found several billion euros in economic losses per year in Nanjing (China) due to the lower productivity of workers exposed to heatwaves. These losses are caused by substantial industrial interdependencies in the manufacturing sector, and direct losses in both the agricultural and mining sectors. Stalhandske *et al* (2021) confirmed the huge amount of losses corresponding to hundreds of million euros per year in Switzerland. The losses in productivity may triple by the end of the century in high-emission pathways. Heat-related occupational diseases affect the insurance sector leading to more requests for compensation claims (Xiang *et al* 2015). Larsson (2023) proposed a framework to structure different types of insurance contracts. Hot extremes may also have detrimental effects on residential mortgage lending due to the sensitivity of non-bank lenders to climate change (Baranyai and Banai 2022). Working and leisure time are compromised by electric interruptions too (Shivakumar *et al* 2017). Energy consumption for cooling requirements can double during heatwave events compared to typical summer days (Morakinyo *et al* 2019) resulting in blackouts (i.e. the complete failure of electricity distribution) or brownouts (i.e. voltage reductions) when demand exceeds supply. Prolonged interruptions of electricity can enhance bacteria proliferation on refrigerated food and affect domestic water supply systems in multi-story buildings (Zeuli *et al* 2018). This issue may leave the population without safe drinking water when abrupt increases in urban water demand usually occur (Adamowski *et al* 2013, Hatvani-Kovacs *et al* 2016). Quilty *et al* (2019) developed an ensemble forecasting framework for probabilistic water-resource forecasts able to integrate the increased water demand during heatwaves.

Some indices were developed in the literature to estimate the detrimental contribution of weather to tourism such as the Tourism Climate Index (Mieczkowski 1985) and the Holiday Climate Index (Scott *et al* 2016). However, a few studies have analyzed the effects of heatwaves on the length and quality of tourism seasons. Gómez-Martín *et al* (2014) explored demand in Spain concluding that the internal national market is not significantly affected by heatwaves because young people do not perceive high temperatures as negative for vacation. Although young people do not tend to change or postpone their initial holiday plans, the provision of diversified recreational practices is essential to minimize losses in the tourist sectors.

4.3. Ecosystem

Heatwave events can cause a broad range of detrimental effects on ecosystems (figure 6) because the atmospheric temperature affects the optimal conditions of living beings, the energy available in physical processes, and the concurrent or consecutive occurrence of other hazards. Hazards interact across multiple spatial and temporal scales amplifying the susceptibility of the exposed elements in the involved ecosystems (Zscheischler *et al* 2018). For instance, heatwaves can amplify the Urban Heat Island (UHI) phenomenon. Although the area affected by UHI may remain unchanged during heatwaves (Tomlinson *et al* 2012), the UHI magnitude can be amplified (e.g. Ward *et al* 2016). This amplification in Beijing (China) is caused by the increased contrast in surface evapotranspiration between urban and

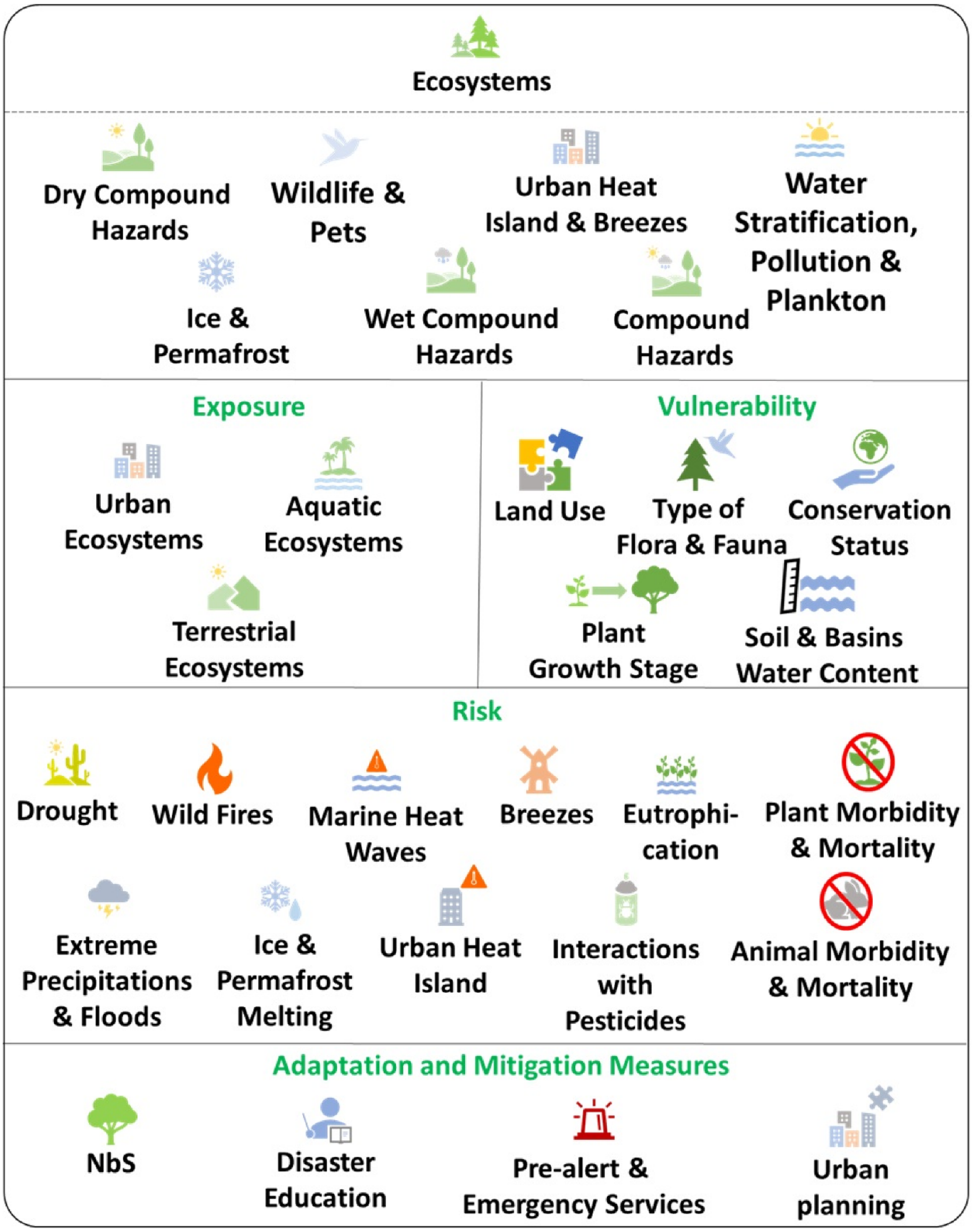

Figure 6. Info-graphic that summarizes the sub-categories of the ecosystem (*EC*) research field affected by heatwaves (i.e. the hazard), the exposure and vulnerability components, the possible risks, and adaptation and mitigation measures that can be adopted to reduce these risks.

rural areas during daytime and, both anthropogenic heat and warm advection during nighttime (He *et al* 2020). However, this interaction is not trivial and has given uneven results. Possega *et al* (2022) found a positive contribution of heatwaves only during nighttime in several European cities, except Copenaghen (Denmark). Urbanization patterns and city street orientation may modulate this interaction (Ramamurthy and Bou-Zeid 2017). Although city densification is a key parameter (Lemonsu *et al* 2015, Wei *et al* 2022), the local hydroclimate controls the urbanization contribution to heatwaves (Liao *et al* 2018). Ward *et al* (2016) reported that the extra heat load by heatwaves is larger in cities with cooler climates, more water bodies that release heat slowly at night, and more urban green areas that experience a reduction in evapotranspiration and changes in albedo. The interaction may be even more complex when involves sea breezes (Shen *et al* 2019) and lake breezes (Keeler and Kristovich 2012, Qin *et al* 2023) by modifying the thermal contrasts between water bodies and city.

Concerning consecutive hazards, some papers have reported that the sequential occurrence of heatwaves and extreme precipitations are becoming more likely (e.g. Chen *et al* 2021). Although internal climate variability (e.g. ENSO) can cyclically affect weather patterns, this increase in frequency was associated with global warming and urbanization. The occurrence of hotter heatwaves results in larger sensible heat fluxes contributing to atmospheric convection and possible heavy rainfalls (You and Wang 2021, Chen *et al* 2022). This process can be combined with moisture convergences that provide more precipitable water. Wu *et al* (2021) reported that another key factor is urbanization which promotes the release of sensible heat fluxes due to human activities and changes in land use. Zhou *et al* (2023c) found that these compound events can be further exacerbated in this century, especially in tropical regions and the Tibetan Plateau. Although more studies are needed to understand the driving mechanisms in future climates, their occurrence may amplify losses. For instance, people may be more exposed to heatwaves after a flood event that destroyed the electricity network and houses limiting access to air-conditioning systems.

Climate variability can induce the occurrence of dry compound events (e.g. Feng and Hao 2021, Li *et al* 2021c). However, Alizadeh *et al* (2020) reported that the climate warming trend is the dominant driver of dry and hot extremes which are substantially increasing in frequency over the United States in the last decades. Tripathy *et al* (2023) found that the Southern Hemisphere will experience a larger increase in frequency during the current century, while the Northern Hemisphere will be affected by a larger severity. The occurrence of heatwaves is one of the factors that can contribute to the exacerbation of the magnitude and duration of drought events (Manning *et al* 2019, Kyatengerwa *et al* 2020), and the trigger of wildfires (Parente *et al* 2018, Libonati *et al* 2022). Drought and heatwaves enhance each other through the positive feedback between atmospheric heating and further drying of the soil due to large sensible heat fluxes at the interface between the land surface and the atmosphere (Perkins 2015). Flash droughts consecutive to heatwaves are more likely to occur in dense-vegetation areas that experience moisture depletion by evapotranspiration (Mo and Lettenmaier 2015). The water loss into the soil results in dry vegetation which can provide fuel for wildfires enhancing their magnitude, spread rate, average size, and likelihood of occurrence (Cardil *et al* 2014, Sharples *et al* 2021). A possible transition towards a more water-limited regime at the continental scale is hypothesized for both Europe (Bastos *et al* 2020) and Asia (Zhang *et al* 2020) leading to a progressive decay of productivity in ecosystems. Tree die-off events are likely to occur when extreme droughts coincide with heatwaves (Mitchell *et al* 2014, Gazol and Camarero 2022). For instance, broadleaf and coniferous forests in France were severely affected by the 2003 heatwave that caused leaf loss (i.e. crown dieback) and 1% increase in mortality in the subsequent years (Zaitchik *et al* 2006, Bréda and Badeau 2008). O'sullivan *et al* (2017) found a meridional gradient for both the critical temperatures at which the photosynthesis stops and the leaf respiration rapidly declines. Mid-latitude plants are most likely to exceed thermal tolerance margins in both the current and future climate scenarios. The usual adaptation measure to preserve water is stomatal closure. However, stressed plants can choose to open stomata and prevent leaves from overheating (Marchin *et al* 2022). Factors that increase plant susceptibility include high leaf size, high osmotic potential, low leaf mass per area, and low transpirational capacities, as well as low soil thickness (McGrath *et al* 2023). The most sensitive growth stages include reproduction, seed dormancy, and germination (Ooi 2012, Jagadish *et al* 2021) which are affected by a decline of seed viability due to higher soil temperatures in sparsely vegetated habitats, the occurrence of wildfires, and a reduction of seed longevity as a result of the temperatures experienced by the parent plants.

Li *et al* (2020) do not find significant effects of heatwaves on soil respiration. However, heat and water stress can affect CO_2 fluxes in terrestrial ecosystems due to changes in stomatal conductance (Marchin *et al* 2020, 2022) and above-ground biomass reduction (Li *et al* 2021a). High temperatures in early spring can extend the growing season and stimulate CO_2 sequestration, while negative effects are expected during summer leading to earlier leaf senescence in the autumn and a lower leaf area in the following year (Walker *et al* 2015, Xie *et al* 2018, Xu *et al* 2020, Kwon *et al* 2021). Wooded areas with low tree canopy cover are less resilient (Van Gorsel *et al* 2016). These areas can be subjected to a decrease in latent heat fluxes and CO_2 sequestration, and may switch into a CO_2 source on a daily average.

Additional research is needed to confirm and deepen the effects of heatwaves on arctic regions, oceans, rivers, and lakes. Heatwaves can contribute to snowmelt in arctic regions resulting in anomalous earlier vegetation greening followed by deficits in soil water content (Gloege *et al* 2022), the abrupt releases of ice algae, and the triggering of under-ice phytoplankton blooms (Fortier *et al* 2002). The releases of algae may provide food for benthic communities and act as a significant sink for atmospheric CO_2. However, the melting of arctic permafrost can lead to methane emissions in the atmosphere (Froitzheim *et al* 2021). Heatwaves can also increase sea surface temperature (Guinaldo *et al* 2023) and trigger marine heatwaves when the warming occurs in combination with storms that enhance vertical mixing and homogenize the temperature in the water column (Dzwonkowski *et al* 2020). Surface temperature and thermal stability can be affected in temperate lakes leading to a higher risk of deep-water anoxia (Jankowski *et al* 2006) and eutrophication due to the increase of phytoplankton (Joehnk *et al* 2008) if their upper thermal tolerance is not overcome. Rivers can be also affected, especially in dry periods in which the river flow is low (Huguet *et al* 2008). Although heatwaves are usually correlated to significant negative anomalies of both river discharge (Zampieri *et al* 2016) and groundwater recharge (Vanham *et al* 2009, Han *et al* 2019), runoff in alpine glacierized basins can temporarily increase due to the meltwater contribution (Zappa and Kan 2007, Keiler *et al* 2010). The thermal erosion of permafrost increases the active layer thickness leading to lower stability of high-altitude rock walls and a higher risk of rockfalls (Blanchet and Davison 2012, Ravanel *et al* 2017), debris flows (Marcer *et al* 2020) and lake drainage events (Sakai *et al* 2016).

The health status of wildlife is usually strongly connected with the habitats in which animals live. For instance, alpine wetlands that are not recharged by snowfields are likely to dry out resulting in mass die-offs of aquatic fauna (Carlson *et al* 2020). Heatwaves may threaten the macrobenthic community (Mouthon *et al* 2010, Pitacco *et al* 2018) and enhance both the transmission pressure and success of lethal parasites (Studer and Poulin 2013, Kunze *et al* 2022). Birds may die if temperatures overwhelm their thermoregulation capacities (Cunningham *et al* 2013, Albright *et al* 2017, Sharpe *et al* 2019). Ground-nesting species and permanent resident species are the most exposed to heatwaves (Albright *et al* 2011). Limited studies have investigated the susceptibility of mammals (except humans). Few tests on mice have confirmed that heat stress can cause oxidative stress in the brain and organs (Jacobs *et al* 2020) and alteration in the cardiac function (Wang *et al* 2014a, Zhang *et al* 2015) leading to negative consequences on cognition, reproduction and life expectancy. Bruchim *et al* (2017) reported mortality rates of 50% for dogs affected by heat stroke. Mixed results were observed concerning insect reproduction, and the life span and size of offspring (e.g. Sales *et al* 2018, Stahlschmidt *et al* 2022). Heatwaves can synergistically interact with pesticides and affect the immune function, growth rate, total fat content, and metabolic rate of damselflies (Arambourou and Stoks 2015, Dinh *et al* 2016, Sniegula *et al* 2017), mosquitoes (Delnat *et al* 2019), and honey bees (Kim *et al* 2022b).

At least to our knowledge, no studies have quantitatively analyzed solutions to enhance thermal comfort in ecosystems, except for the urban one as already reported in section 4.1. However, NbS includes by definition the protection, restoration, or enhancement of ecosystems. Vegetation cover is positively correlated to the survival of amphibians in wetlands (Beranek *et al* 2022) and may reduce mass die-offs in bats (Pruvot *et al* 2019). Furthermore, vegetation provides shelter (Gols *et al* 2021) and helps maintain habitat connectivity, decreasing habitat fragmentation of insect populations during heatwaves (Piessens *et al* 2009).

4.4. Agriculture

Heatwaves have several implications on agriculture resulting in a lower production of food. Vulnerabilities and risks are summarized in figure 7 along with measures to reduce them. Heat stress adversely affects germination, photosynthesis, respiration, water relations, and membrane stability, leading to consequences during the entire life cycle of crops although the magnitude changes at the different stages (Wahid *et al* 2007). The literature has mainly focused on cereal growth. High temperatures speed up plant development, reduce the grain-filling period (Rosenzweig *et al* 1998), and accelerate senescence (Rezaei *et al* 2015). The damages are amplified by the occurrence of dry compound events during the growing season as experienced by most of the land regions in the last 40 years (Arnell *et al* 2019, He *et al* 2022b). The occurrence of these events explains more than 40% of the inter-annual production variability of wheat in several agro-climatic regions (Zampieri *et al* 2017). Production losses due to extreme weather (Brás *et al* 2021) may have repercussions on market exports and prices reducing caloric intake in poor countries, and contribute to geopolitical instabilities as occurred during the Arab Spring (d'Amour *et al* 2016, Arreyndip 2021).

Vegetables are less studied at least to our knowledge. Although further analyses are required to examine the effects of heatwaves on vegetables, the literature confirms that heatwaves affect their production. Vulnerable crops include hop (Potopová *et al* 2021), nutmeg (Anripa *et al* 2023), tomatoes, cucumbers, and root vegetables (Potopová *et al* 2017). Luo (2011) reviewed temperature thresholds for a broad range of crops, including legumes. Heatwaves can also affect several phenological stages in grapes with consequences on the quality and quantity of the wine sector (De Rességuier *et al* 2023). As an adaptation measure, De Rességuier *et al* (2023) has suggested increasing the trunk height over tilled soil to reduce heat exchanges between grapes and soil. de León and Bailey (2022) have developed a 3D model to simulate berry temperatures by varying the vineyard architecture, e.g. row spacing, row orientation, slope grade and aspect, and shade cloth density.

Different solutions were proposed in the literature to improve the heat tolerance of crops. Wahid *et al* (2007) suggested genetic approaches and the stimulation of plants with preconditioning and exogenous applications. Srinivasarao *et al* (2016) tested NbS in Indian villages concluding that yields are enhanced by the introduction of short-duration

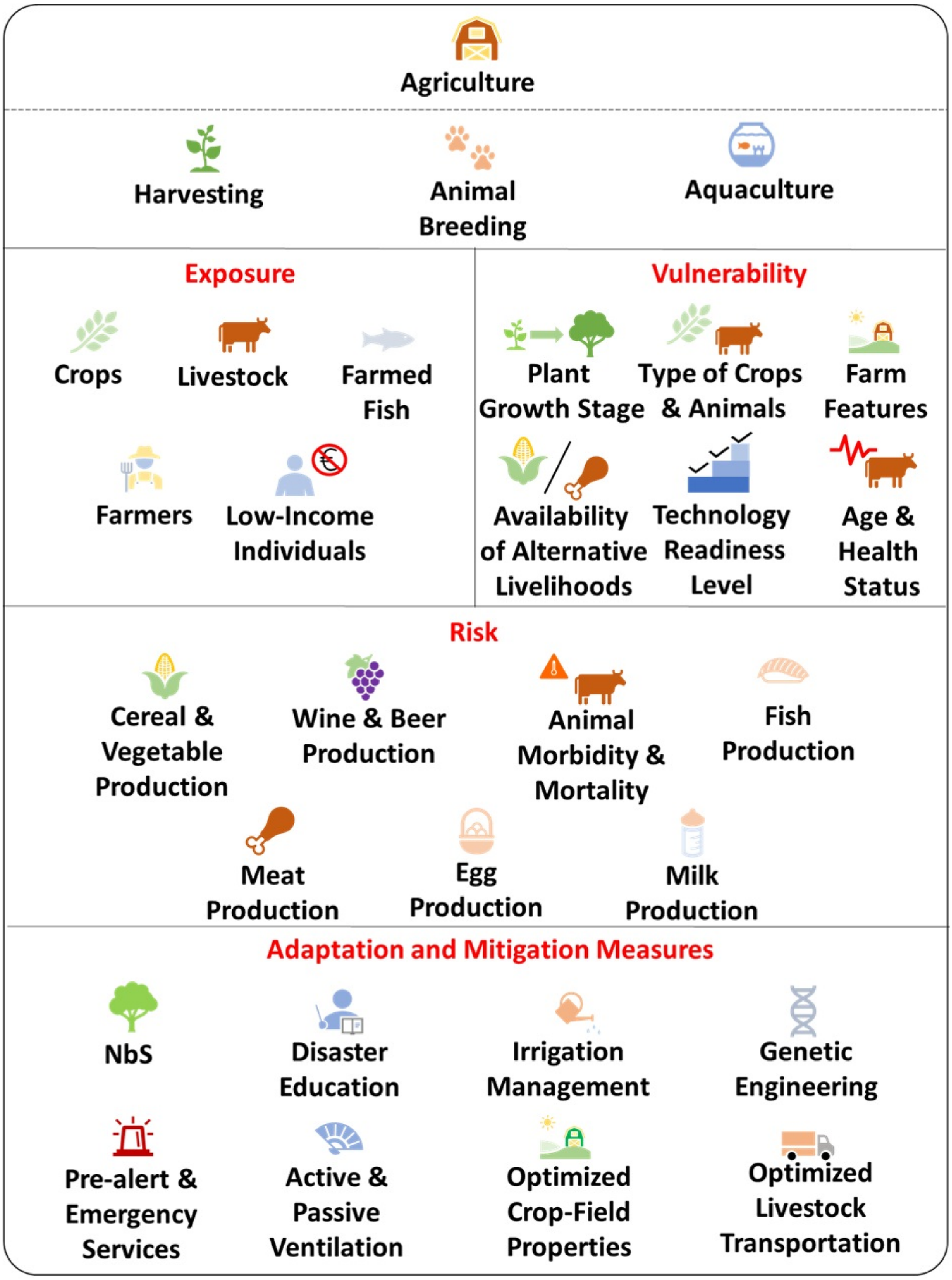

Figure 7. Info-graphic that summarizes the sub-categories of the agriculture (*A*) research field affected by heatwaves (i.e. the hazard), the exposure and vulnerability components, the possible risks, and adaptation and mitigation measures that can be adopted to reduce these risks.

tolerant varieties to climate extremes, the adoption of moisture conservation practices, and the collection of rainwater that is then distributed through water-saving irrigation methods. Irrigation modifies moisture and sensible heat fluxes affecting both the occurrence of precipitations and local heatwave characteristics (Valmassoi *et al* 2020a, 2020b). Kala *et al* (2022) suggested the adoption of crop albedo enhancement (e.g. the selection of more reflective crops) as a solution able to reduce the frequency of heatwaves in current and future climate scenarios.

Livestock is also vulnerable to heatwaves (Nardone *et al* 2006, Lallo *et al* 2018). Despite the fact that heat stress can lead to a positive reduction of cattle emissions depending on both intake of food and digestibility (Yadav *et al* 2016), the other results provided by the literature are adverse. Heat stress reduces the rate of weight gain in cattle (Hubbard *et al* 1999), milk yield (West 2003), reproduction (Jordan 2003), and the quality of meat and milk (Pragna *et al* 2017, Summer *et al* 2019). The literature has confirmed an excess of cattle mortality albeit with contrasting results concerning vulnerability factors. For instance, Vitali *et al* (2009, 2015) found that dairy cattle older than 28 months are exposed to higher risks during prolonged heatwaves that occur at the beginning of summer. In contrast, Morignat *et al* (2014) did not report significant differences among sub-populations by age and type of production. Measures to reduce detrimental effects include the adoption of an early warning system to alert farmers and veterinarians, a transportation ban during the hottest hours, indoor cooling systems, and the provision of shade in pastures (Bishop-Williams *et al* 2015). Although less studied by the contributions included in the current review, the analyzed papers confirm that heatwaves can also affect goats and sheep (weight gain, milk production, and reproduction; Lu 1989, Marai *et al* 2008, Salama *et al* 2014, Lallo *et al* 2017), pigs (reproduction; Brito *et al* 2022), layer chickens (egg quality and production; Mashaly *et al* 2004, Ajakaiye *et al* 2011), and broiler chickens (meat production; Abu-Dieyeh 2006, Lin *et al* 2006).

More studies are needed to understand the susceptibility of fish species suitable for freshwater aquaculture. However, these studies agree that fish outside their optimal water-temperature ranges experience a higher risk of morbidity and mortality, stress, and a reduction in immune functions, appetite, growth, and reproduction (Pankhurst and King 2010). Quinn *et al* (2011) reported that ribosomal proteins are gene targets for enhancing the development of broodstock and monitoring both stress and recovery in cold-water salmonids. McArley *et al* (2022) suggested that hyperoxia conditions (i.e. the supersaturation of oxygen) can enhance cardiorespiratory performances and heat tolerance in trout.

4.5. Infrastructure

Heatwaves can affect infrastructure by triggering industrial accidents, damaging energy production and distribution, degrading materials used in the transport sector, and affecting the stability of buildings. Figure 8 shows the info-graphic that summarizes vulnerabilities, risks, and possible measures reported in the few contributions on infrastructure included in this review. Additional studies are necessary to confirm the following findings.

Heatwaves affect the content of water in both the soil and basins. The deficit in soil water content can cause clay soil subsidence reducing the stability of buildings if they do not have deep foundations (Salagnac 2007). The lower and hotter water in basins can affect the cooling efficiency of thermal and nuclear power plants slowing down energy production (Rutten *et al* 2008, Linnerud *et al* 2011, Rübbelke and Vögele 2011). Water and energy are also interdependent in desalinization plants (Salomons *et al* 2023). Heatwaves can trigger technological accidents (e.g. Na-Tech) in plants and industries (Ricci *et al* 2023) due to the increase of internal pressure over the security limits and fires, self-decomposition and self-ignition of hydrocarbons, waste storage, and processing systems. The electricity sector is particularly exposed even during the energy-distribution phase. Overheating of electric cables can over-expand the cables and cause the shutting down of transformers in electricity towers (Oloruntoba 2013) leading to blackouts. Several adaptation measures have been proposed in the literature such as the burial of the distribution network (Feng *et al* 2022), the adoption of smart meters and intelligent switches that provide limited local electric power services (Baik *et al* 2018), and public safety power shutoffs (Wong-Parodi 2022). Liang *et al* (2016) suggested an integrated modeling tool to plan a rationing regime of electricity in selected sectors.

Heatwaves can also affect transport services due to deformations of roadways (McEvoy *et al* 2012, Kottayi *et al* 2019) and the buckling of railway lines (Oloruntoba 2013). However, at least to our knowledge, few studies have investigated weather and structural conditions in which these processes occur. Matini *et al* (2022) found a lower resilience of road pavements with sand subgrades. Nguyen *et al* (2012) used Monte-Carlo simulations to estimate the number of track segments that experience buckling in a railway network during a heatwave. Despite this number being small (i.e. the 2×10^{-3}% of segments during a heatwave event that exceeds 43 °C for 3 consecutive days), even one large buckle may not allow to stop a running train and avoid the derailment (Yang and Bradford 2018). Ferranti *et al* (2018) reported a significant amount of delay minutes in the UK network due to both the direct effect of hot temperatures and speed restrictions to prevent buckling. Ferranti *et al* (2018) suggested the adoption of measures such as monitoring low-cost sensors and green NbS for shading the railway network.

4.6. Heritage

Heatwaves can affect both natural and cultural heritage as shown by the summary info-graphic in figure 9. To the best of our knowledge, there are no papers on Web of Science or in other scientific databases that have quantified the damages of heatwaves to natural heritage, effects on local and traditional ecological knowledge, or economic losses to cultural heritage sites or works of arts. Marginal to this topic, a limited number of studies have delved into the thermal degradation of marble which is a widely used material for works of art and monuments.

Marble is a carbonate rock primarily composed of calcite (i.e. calcium carbonate) that shows

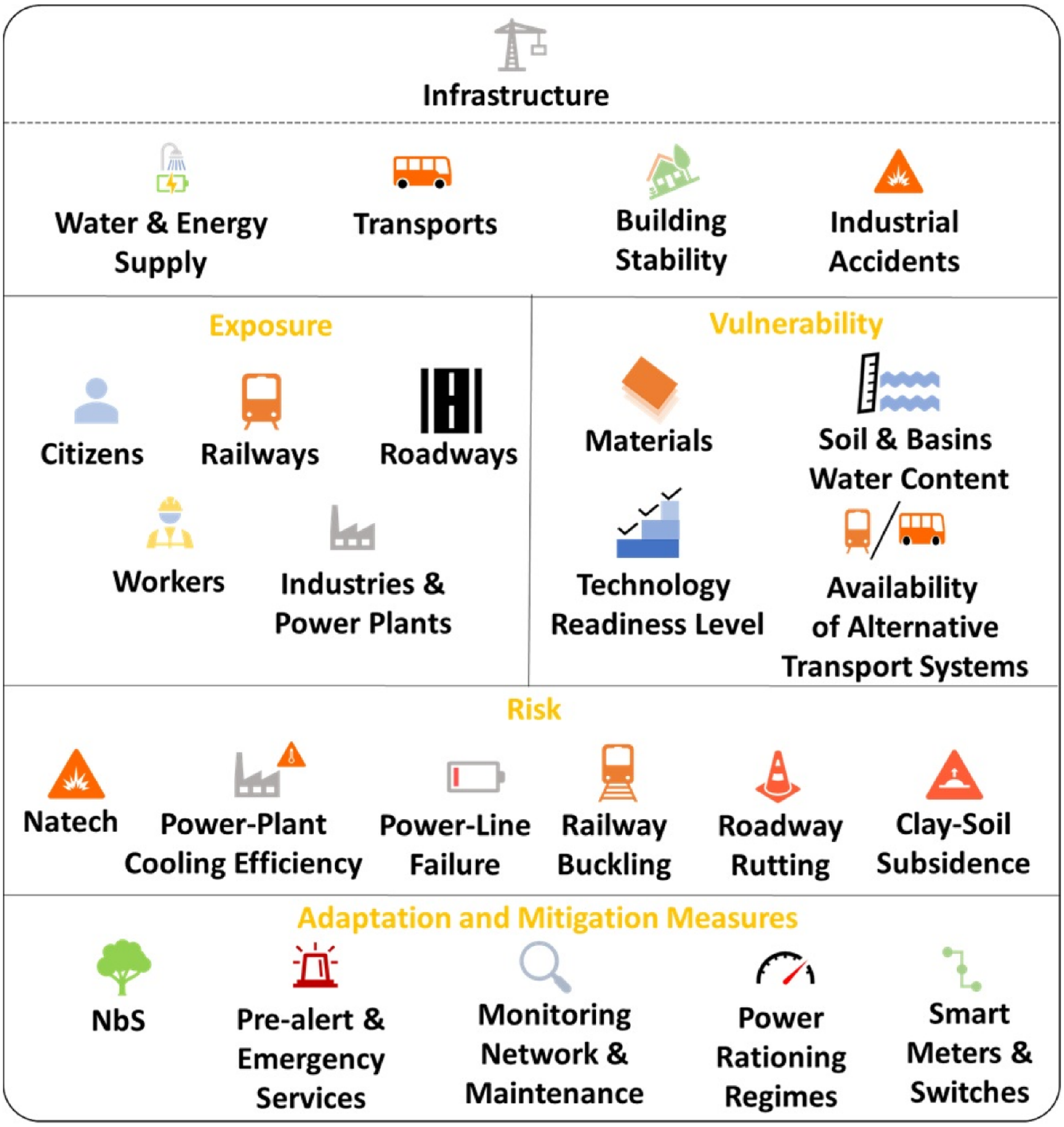

Figure 8. Info-graphic that summarizes the sub-categories of the infrastructure (*I*) research field affected by heatwaves (i.e. the hazard), the exposure and vulnerability components, the possible risks, and adaptation and mitigation measures that can be adopted to reduce these risks.

a thermoelastic behavior when exposed to heatwaves. Each calcite crystal tends to expand along a crystallographic axis and contract perpendicular to this axis. However, the compact microstructure of marble limits these anisotropic deformations leading to cracks. These cracks result in the bowing of slabs (i.e. the deformation or curvature of stone slabs, Siegesmund *et al* 2008, Shushakova *et al* 2013), and sugaring (i.e. granular disintegration of marble as a sugar-like powder, Sassoni and Franzoni 2014). The thermal response depends on the type of marble and some fabric parameters such as texture (Shushakova *et al* 2013). This response is not linear. For instance, (Siegesmund *et al* 2021) found that larger deformations occur at the first heating than other subsequent equal stresses in dry conditions. However, wet conditions can reactivate the process. Sassoni *et al* (2018) and Naidu *et al* (2016) verified that some inorganic coatings are effective conservation treatments that do not cause excessive pore occlusion and stiffening. To protect marble sculptures and other works of art, adaptation measures are essential in modern insulated buildings that host museum collections for reducing overheating and high relative humidity (Huijbregts *et al* 2012).

5. Risk assessment in the literature

Few publications have estimated the heatwave risks (*R*) resulting from hazard, exposure, and vulnerability. 42 *R* publications (93.3% of the total) investigated the role of heatwaves (implicitly or explicitly combined with UHI) on human health to identify the most vulnerable cities and neighborhoods (e.g. Tomlinson *et al* 2011, Morlot *et al* 2023) and provide an estimate of the mortality risk due

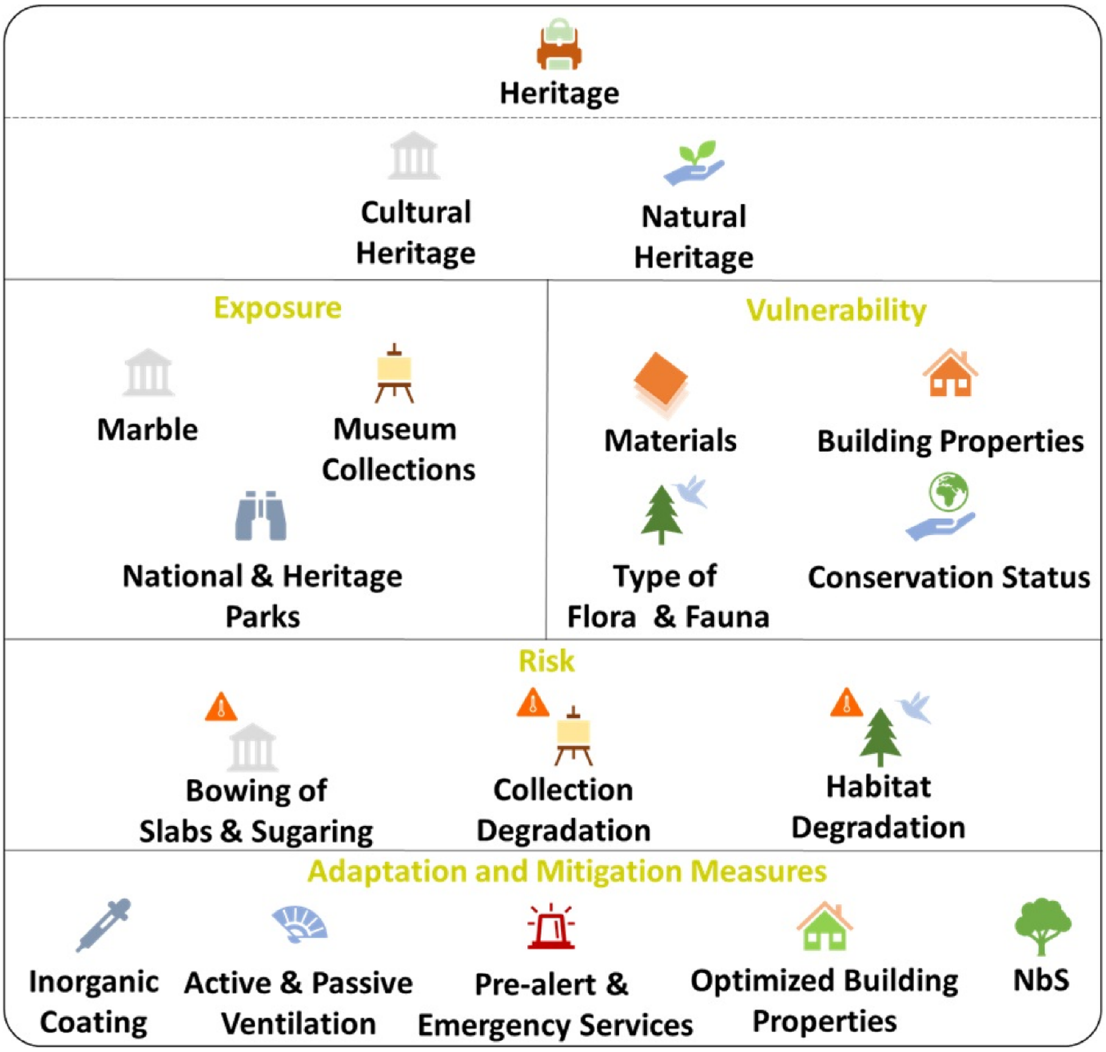

Figure 9. Info-graphic that summarizes the sub-categories of the heritage (*HR*) research field affected by heatwaves (i.e. the hazard), the exposure and vulnerability components, the possible risks, and adaptation and mitigation measures that can be adopted to reduce these risks.

to heat stress (e.g. Zeng *et al* 2014, Abadie *et al* 2019, Zemtsov *et al* 2020). The hazard component is estimated from both land surface temperature and humidity retrieved by in-situ instrumentation and satellites, or simulated in several climate scenarios. Keramitsoglou *et al* (2013) used an artificial intelligence fuzzy logic model to classify heatwave events according to their duration, intensity, and time of occurrence. Holec *et al* (2021) included the cooling effect of urban trees in the hazard component by correcting a modeled air-temperature layer with a tree-cover density mitigation layer. Then, each study combined the hazard with both land-use and socio-economical data (e.g. current or projected demography) for estimating the exposure component. The vulnerability component is estimated by the aggregation of several indicators which are normalized to compare values with different dimensions and metrics. Data include individual factors related to health (e.g. elderly, death rates), economic conditions (e.g. population below poverty level), education (e.g. educational attainment), social susceptibility (e.g. single-person households, distance to medical assistance facilities), and building characteristics (e.g. high rise living, old buildings). Some studies (e.g. Zaidi and Pelling 2015, Hatvani-Kovacs *et al* 2016, Dai *et al* 2021) also included adaptive-capacity data such as urban design (e.g. green and blue areas), people behaviors (e.g. drink more water, use air-conditioning), and adaptive governance. Different approaches are used to combine vulnerability data, such as the unweighted quantitative aggregation (e.g. Johnson *et al* 2016), the multivariate statistical techniques (e.g. Apreda *et al* 2019, He *et al* 2019), and the subjective weights based on expert judgment (e.g. Räsänen *et al* 2019, Dai *et al* 2021).

Twenty *R* papers (44.4%) provided heatwave risk maps in urban areas which are typically normalized by the maximum risk or the population unit (e.g. Aubrecht and Özceylan 2013) and presented in classes of risk (e.g. very low, low, medium, high, very high). These classes are selected according to equal intervals of normalized risks (e.g. Buscail *et al* 2012), risk matrix approach (e.g. Papathoma-Koehle *et al* 2016), or statistical natural breaks analysis (Aubrecht and Özceylan 2013). Maps show a higher risk in the downtown areas in 16 papers due to high temperatures exacerbated by UHI, population density, and the fraction of people that live in high-rise flats. However, hot spots can be also located in high-populated outskirts, especially if characterized by low medical services, socio-economical conditions, and thermal insulation of building envelope. Li and Sun (2023) found that the most at-risk areas are the ones in which the cooling supply of vegetation and demand by people are mismatched as the main urban area of Beijing (China). Based on the risk map, Dong *et al* (2020) analyzed the effectiveness of local governance measures in improving human thermal comfort with both green and blue NbS. Buchin *et al* (2016) concluded that passive cooling and air-conditioning are the most effective measures for reducing the risk of mortality followed by cool roofs and facade greening. Stone Jr *et al* (2014) simulated the coupling effects between changes in vegetative cover and surface albedo in several US metropolitan areas finding a reduction of the excess heat-related mortality that is expected to rise in 2050 if no strategies will be adopted (Wu *et al* 2014).

Eleven studies (24.4%) expanded the risk assessment to higher spatial scales up to the national scale (e.g. Dubey *et al* 2021, Kc *et al* 2021) and the continental scale (e.g. Yin *et al* 2020). Díaz *et al* (2019) estimated the economic losses attributable to mortality in Spain, finding that the implementation of adaptation strategies can reduce losses of an order of magnitude in the 2051–2100 time horizon. However, low-development countries are the most at risk as reported by Russo *et al* (2019) which assessed the heatwave risk worldwide focusing on health for different climate scenarios and societal-development pathways. This risk assessment was obtained by the product of the probability of occurrence of extreme heatwaves, population density, and the Human Development Index (a socioeconomic composite indicator that includes income, health, and education). Low-development countries at a 1.5 °C warming level are expected to be more exposed than very high-development countries at a 2.0 °C warming level. Busby *et al* (2014) assessed risks for African countries by summing indices of physical exposure to climate-related hazards, population density, household and community resilience, and governance and political violence.

At least to our knowledge, the heatwave risk was poorly analyzed in the other research fields (4 papers, 8.9%) before Brogno *et al* (2024). Lee *et al* (2020) proposed a multi-risk Bayesian network for the assessment of energy consumption and mortality. Mechler *et al* (2010) studied agricultural economic losses through the Catastrophe Simulation model framework. The framework used the risk concept to estimate the direct asset losses. Then, these losses are used as input to assess fiscal consequences due to natural disasters as well as the costs and benefits of adaptation measures. Economic consequences related to the heatwave risk have been also studied by Borg *et al* (2023) which analyzed the increasing trend of claims data arising from occupational injuries in Australia in both current and projected climate.

6. Conclusions

This paper analyzes the relationship between heatwaves and risks from a multidisciplinary perspective. A systematic literature review was conducted using the keywords ‘heatwave’ and ‘risk’ in Web of Science, supplemented by snowballing citations and previously known contributions. After the screening of titles and abstracts, the final database consists of 1459 papers, reviews, and book chapters. Following the IPCC’s definition of risk (Pörtner *et al* 2022), these publications were classified according to the risk component they addressed, namely (1) hazard (H), (2) exposure-vulnerability (EV), (3) mixed (M) for publications that combined elements of both H and EV, and (4) Risk (R) if the combined H and EV elements lead to a risk estimate or discussion. Then, EV, M, and R publications were further classified according to the topic in six fields of research, i.e. healthcare (HC), society (S), ecosystem (EC), agriculture (A), infrastructure (I), and heritage (HR).

The literature was screened to assess the approaches adopted for each risk component and research field in the context of the heatwave risk. Specifically, for the ‘hazard’ component, section 3 reported the actual trends in the frequency of occurrence and magnitude for the heatwave events, the projected changes, the natural and anthropogenic drivers, and the indices proposed for the identification and classification of events. Then, the exposed elements, their vulnerabilities, and the proposal of adaptation and mitigation measures are discussed for a broad range of risks related to each research field. For the research field ‘healthcare’, section 4.1 shown the linkage between the heatwave characteristics and human health, the mechanisms of thermoregulation, the main causes of morbidity and mortality, the occupational heat stress, the contribution of air quality, and several proposed measures (e.g. optimized building properties, active and passive ventilation, NBS). For the research field ‘society’, section 4.2 reported how heatwaves can affect the occurrence of traffic crashes and crimes, work productivity, the insurance sector, the availability of electricity and water, and tourism. For the research field ‘ecosystem’, section 4.3 discussed the occurrence of compound hazards, and the effects of heatwaves on aquatic and terrestrial ecosystems, plants, and wildlife. For the research field 'agriculture', section 4.4 reported the connection between heatwaves and the health of crops and livestock, production losses, and damage to aquaculture. For the research field 'infrastructure', section 4.5 shown damages related to heatwaves that can affect industrial security, the supply of water and electricity, and transport networks. For the research field 'heritage', section 4.6 briefly reported marble degradation. Lastly, section 5 is dedicated to discussing the approaches adopted by the papers that integrate all three components in a risk assessment. Overall, the results highlight that all six fields of research examined one or more individual risks, but there were disparities in terms of either available literature or the number of studies specifically developed for this purpose. While it is true that such disparities might have been caused by the specific methodological approach adopted in the present review, this does not undermine the following discussed general conclusions and recommendations.

- The literature agrees on the definition of heatwaves as anomalous hot weather events that persist for several days. However, depending on the specific study under consideration, significantly different indices are adopted in the same research field for the identification and classification of heatwave events. This choice affects the results (e.g. Kent *et al* 2014) leading to inconsistent conclusions between papers. As a consequence, the derivation of quantitative estimates of risks from the intercomparison of results is challenging and hampers our understanding of the potential effects of heatwaves. Our recommendation to the scientific community is to converge on the adoption of common indices in each field to make comparable case studies on the same topic. For example, it is true that the perceived heat stress of living beings is affected by acclimatization factors. However, the adoption of percentiles rather than absolute thresholds is recommended to compare results from different geographical areas.
- The indices adopted for the identification of heatwave events effectively consider their main characteristics as duration and magnitude. However, these characteristics are often neglected in the results. The majority of papers show results obtained by the integration of several events without the possibility of distinguishing each single event. This choice limits the understanding of how risks change according to the heatwave characteristics. Since future projections show more long-lasting and intense events, this could have strong repercussions on policies that try to anticipate the future consequences of climate change. Our recommendation is the provision of risks as functions of heatwave characteristics (e.g. Zeng *et al* 2014).
- Current research remains largely focused on the healthcare and ecosystem fields, often overlooking the effects of heatwaves on our society, agricultural production, the availability of infrastructure, and the preservation of heritage. These disparities may hinder the identification of relevant exposed elements in a given territory, directly impacting policy decisions. Our recommendation is to promote more interdisciplinary studies (e.g. Stone Jr *et al* 2021a). These studies allow the understanding of the interdependencies between fields with repercussions even in the most analyzed fields. For instance, the health of humans and ecosystems depends on several factors such as socio-economic conditions, land use, and food security.
- Only a limited number of papers proposed risk frameworks developed for heatwaves or tested them on this hazard. Furthermore, the application of these frameworks is still restricted to urban thermal comfort and mortality providing a narrow and human-centric perspective of the heatwave risk. Our recommendation is the development and application of quantitative frameworks that integrate and compare more research fields such as Brogno *et al* (2024). This framework covers several climate and economic contributions allowing both an in-depth analysis of a specific field and a comprehensive assessment of heatwave events. The total risk is quantified as a cost per day to help policymakers during the decision-making process.

In summary, the present review wishes to inspire a more coherent and comprehensive scientific literature able to support the development and application of quantitative frameworks that take into account the fields so far overlooked.

Data availability statement

No new data were created or analyzed in this study.

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Appendix

The current appendix provides further references concerning heatwave risk and components for each research field.

Table A1. Additional worthwhile references classified according to the risk component (hazard *H*, exposure & vulnerability *EV*, and risk *R*), the research field (healthcare *HC*, society *S*, ecosystem *EC*, agriculture *A*, infrastructure *I*, and heritage *HR*), and the topic to which they respond.

Classification	Sub-Category	Topic	References
H		High-latitude heatwaves	Lian *et al* (2020), Song *et al* (2021), Collow *et al* (2022), González-Herrero *et al* (2022)
		Attribution	Dole *et al* (2011), Hauser *et al* (2016), Kim *et al* (2018), Rogers *et al* (2022)
$EV - HC$	Mortality & Morbidity	Heat Stroke	Gaudio and Grissom (2016), Hifumi *et al* (2018), Leyk *et al* (2019)
		Drug Contribution to Heat Stroke	Martinez *et al* (2002), Kwok and Chan (2005), Bohnert *et al* (2010), Hayes *et al* (2013)
		Cardiovascular diseases	Kenney *et al* (2014), Liu *et al* (2015, 2023), Cottle *et al* (2023)
		Brain diseases	Sharma and Hoopes (2003), Gaither *et al* (2015), Cho *et al* (2018), Zhang *et al* (2023)
		Mental disorders	Li *et al* (2023), Thompson *et al* (2023)
		Vector-born diseases	Viel *et al* (2011)
		Gastro-intestinal diseases	Manser *et al* (2013), Milazzo *et al* (2017), Ford *et al* (2020), Hackbusch *et al* (2020), Fleischmann *et al* (2022)
		COVID-19	Bose-O'Reilly *et al* (2021), Shi *et al* (2021), Lian *et al* (2023)
		Renal & urinary diseases	Chapman *et al* (2023), Huang *et al* (2023), Young *et al* (2023)
		Skin diseases	Rendell *et al* (2020)
		Sleep disturbances	Royé *et al* (2021), Huang *et al* (2022), Buguet *et al* (2023)
		Eye diseases	Echevarría-Lucas *et al* (2021)
		Diabetic people	Moon (2021)
		Obese people	Gildner and Levy (2021)
		Health of elderly	Fukagawa *et al* (1995)
		Health of children	Hashimoto *et al* (2004), Kintu and Brightwell (2014), Wang *et al* (2014b), Romanello *et al* (2021), Tao *et al* (2022)
		Economic value of live	Viscusi and Aldy (2003), Chiabai *et al* (2018)
	Health	Exposure in megacities	Wang *et al* (2023)
		Policy & Governance	O'Neill *et al* (2009), Pascal *et al* (2012), Kotharkar and Ghosh (2022)
		Perception	Esplin *et al* (2019), Erens *et al* (2021)
		Disaster education	Mishra and Suar (2012), Lefevre *et al* (2015), Das (2016), Li *et al* (2021b), Elrick-Barr and Smith (2022)
	Air quality	Contribution to diseases	Shaposhnikov *et al* (2014), Cosselman *et al* (2015), Fu *et al* (2023), Zhou *et al* (2023a)
		Pollutant concentration	Hu *et al* (2009), Lelieveld *et al* (2014), Liu *et al* (2023)
		Fire contribution	Hodnebrog *et al* (2012), Ditto *et al* (2021)
		Pollen	d'Amato *et al* (2011), Weichenthal *et al* (2016), Gilles *et al* (2020)
		Indoor air quality	Terry *et al* (2014)
	Occupational Health	Contribution to diseases	Riley *et al* (2018), Gariazzo *et al* (2023)
		Prevention	Parsons (2009), Rowlinson *et al* (2014), Wang *et al* (2021b), Baek and Wee (2023)
	Thermal Comfort	Indoor temperature	Quinn *et al* (2014), Loughnan *et al* (2015), Serdar *et al* (2022)
		Improved building properties	Kuczyński and Staszczuk (2020), Sun *et al* (2020c, 2021), Kumar *et al* (2021), Staszczuk and Kuczyński (2021)
		Air-conditioning systems	Tremeac *et al* (2012), Amaripadath *et al* (2023)
		Per-cooling systems	Douzi *et al* (2020)
		Green areas	Wu *et al* (2018a), Ossola *et al* (2021)
		Irrigation	Lam *et al* (2020)

(Continued.)

Table A1. (Continued.)

EV − S	Violence & Crimes	Non-domestic urban crimes	Hou *et al* (2023)
	Water & Energy Availability	Energy peak loads	Villa (2021), Kim *et al* (2022a)
EV − EC	Dry Compound Event	Spatio-temporal patterns	Sutanto *et al* (2020)
		Thermal tolerance of plants and trees	Bauweraerts *et al* (2014), Kitudom *et al* (2022)
		Tree responses	Zaitchik *et al* (2006), Bréda and Badeau (2008), Sergent *et al* (2014), Teskey *et al* (2015), Billon *et al* (2020), Gong and Hao (2023)
		Hemiparasitic plants	Griebel *et al* (2022)
		Forest management	Xu *et al* (2020), Petit-Cailleux *et al* (2021)
		Shrubland primary productivity	Peñuelas *et al* (2007)
	Water Stratification, Pollution & Plankton	Heavy-metal concentration	Pili *et al* (2013), Iordache *et al* (2022)
		UV-filter concentration	Thallinger *et al* (2023)
		Plankton composition	Yvon-Durocher *et al* (2011), Koussoroplis *et al* (2023)
		Interactions with Herbicides	Roth *et al* (2022)
		CO_2 fluxes in peatlands	Artz *et al* (2022)
	Ice & Permafrost Melting	Glacier meltwater	Chen *et al* (2023a)
	Wildlife & Pets	Fish	Westley (2020), Gustine *et al* (2023)
		Freshwater animals	Polazzo *et al* (2022)
		Mollusk	Carreira *et al* (2020), Zhang *et al* (2021a), Zhou *et al* (2023b)
		Birds	Jiguet *et al* (2006)
		Lizards	Sinervo *et al* (2010), Abayarathna and Webb (2022)
		Turtles	Laloë *et al* (2017), Lu *et al* (2021)
		Insects	Shama *et al* (2011), Rodríguez-Trelles *et al* (2013), Ma *et al* (2018), Iltis *et al* (2021)
		Prey-predator dynamics	Janssens *et al* (2018), Tscholl *et al* (2023)
		Dogs	Tripovich *et al* (2023)
EV − A	Harvesting	Cereal growth	Nakamoto and Hiyama (1999), Wollenweber *et al* (2003), Fontana *et al* (2015), Zenda *et al* (2022)
		Wheat yield	Semenov and Shewry (2011)
		Rice yield	Barrios-Perez *et al* (2021), Guo *et al* (2023)
		Rapeseed yield	Dikšaityte *et al* (2019)
		Legume yield	Potopová *et al* (2017)
		Grape quality	Kriedemann and Smart (1971), Spayd *et al* (2002), De Orduna (2010), Van Leeuwen *et al* (2020)
		Drip-irrigation cooling	Schaap *et al* (2013)
	Animal breeding	Pasture growth	Harrison *et al* (2017)
		Leishmaniosis	Risueño *et al* (2017)
		Equine asthma	Bullone *et al* (2016)
EV − I	Water & Energy Supply	Energy management	Nik and Hosseini (2023)
	Transports	Bridge deformations	Hagedorn *et al* (2019)

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