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Article

Economic evaluations of the health impacts of weather-related extreme events: a scoping review

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Abstract: The frequency and severity of extreme events is expected to increase under climate change. There is a need to understand the economic consequences of human exposure to these extreme events, to underpin decisions on risk reduction. We undertook a scoping review of economic evaluations of the adverse health effects from exposure to weather-related extreme events. We searched Pubmed, Embase and Web of Science databases with no restrictions to the type of evaluations. Twenty studies were included, most of which were recently published. Most studies have been undertaken in the US (9 studies) or Asia (7 studies), whereas we found no studies in Africa, Central and Latin America or the Middle East. Extreme temperatures accounted for more than a third of the pool of studies (7 studies), closely followed by flooding (6 studies). No economic study was found on drought. Whilst studies were heterogeneous in terms of objectives and methodology, they clearly indicate that extreme events will become a pressing public health issue with strong welfare and distributional implications. The current body of evidence, however, provides little information to support decisions on the allocation of scarce resources between risk reduction options. In particular, the review highlights a significant lack of research attention to the potential cost-effectiveness of interventions that exploit the capacity of natural ecosystems to reduce our exposure to, or ameliorate the consequences of, extreme events.

Keywords: climate change, heat waves, floods, hurricanes, economic evaluation, morbidity, mental health, mortality

20 1. Introduction

21 An increase in extreme events, including their frequency, intensity and modifications to their spatial
22 extent and timing, constitutes one of the many expected consequences of climate change [1]. Extreme
23 weather has attracted increasing attention over the last 15 years in the aftermath of a series of
24 highly-devastating events, including the European heat wave in 2003, hurricanes Katrina and Rita in the
25 US in 2005, a series of extensive floods in Japan (2007), Vietnam (2007), Pakistan (2010) and Bangkok
26 (2011) and hurricane Sandy in 2012.

27 The economic consequences of weather-related extreme events are substantial, with estimates of
28 annual costs ranging from \$94 billion to over \$130 billion globally [2]. In addition to causing
29 considerable damages to assets and productive capital, the adverse effects of climatic extremes on human
30 health figure prominently on the political agenda around addressing climate change risks [3]. This can
31 be seen both as a response to public opinion, where adverse health effects have been identified as one of
32 the main public concerns about climate change consequences [4] and an appreciation that health costs,
33 in terms of individual welfare changes but also health care resource use and labour productivity loss, are
34 expected to make a substantial contribution to the overall economic impacts associated with a warmer
35 climate [5,6].

36 Interestingly however, as recently noted by the Intergovernmental Panel on Climate Change (IPCC)
37 [7], studies of the economic impacts of climate change have essentially focused on impacts to
38 infrastructure and tradable assets, as opposed to impacts on the health of humans and ecosystems and,
39 when health effects have been considered (e.g. PESETTA project in Europe [8]), they essentially pertain
40 to a gradual increase in global mean temperatures, e.g. Bambrick *et al.* [9], Kovats *et al.* [10], Bosello
41 *et al.* [11]. Not only do these studies not fully capture the burden of heat waves, due to non-linearity in
42 risk at high temperatures and the cumulative effect of sustained heat load [12], but they ignore the health
43 costs associated with other weather-related extreme events, such as droughts, floods and hurricanes.
44 Furthermore, in a context where the effects of climate change are already being experienced, economic
45 studies are needed not only to assess the size of the current and projected health costs of extreme
46 events but also, to evaluate the cost-effectiveness of risk reduction measures. Whilst the IPCC recently
47 concluded that the evidence base on the economic efficiency of adaptation measures against climatic
48 extremes is limited [7], the most recent review used to support this statement dates back to 2009 [13].

49 To our knowledge, beyond the economic evidence related to climate change in general, which has
50 overwhelmingly focused on heat risk, there has been no review of studies that evaluate the economic
51 costs of the adverse health effects associated with human exposure to extreme events. In addition,
52 it is of particular interest to evaluate the latest state of the economic evidence base on risk reduction
53 measures targeted at reducing population exposure to extreme events. We therefore conducted a scoping
54 review of this important area of research. Scoping reviews are particularly suitable for conveying the
55 extent and breadth of a given field of research that spans across methods and disciplines by using
56 broad search terms and not applying quality filters [14–16]. Scoping reviews also involve an analytical
57 interpretation of study findings [17], which helps underline the policy implications of current evidence

58 as well as directions for future research. In order to try to capture the diversity of studies' objectives and
59 methodologies used, we did not apply any restrictions to the type of economic studies included in our
60 scoping review, provided they incorporated some estimates of costs.

61

62 **2. Method**

63 *2.1. Search terms and databases*

64 We searched Pubmed, Embase and Web of Science databases in December 2015, without date
65 limitations, for papers in English that provide an economic evaluation of the health costs resulting from
66 human exposure to weather-related extreme events. Search keywords were determined in agreement
67 with all three authors after an initial broad search of the literature. They included a broad range of terms
68 relevant to the varied nature of: (i) weather-related extreme events (search terms included: "extreme
69 heat", "extreme cold", "hot temperature", heat wave, heat, hot, flood, drought, smog, ozone, cyclonic
70 storms, hurricane) AND (ii) the health effects associated to them (search terms included: morbidity,
71 mortality, death, hospitalization, illness, exposure, stress, post-traumatic). Since the focus of the review
72 was specifically on economic studies, these two search fields were combined (AND) with the keyword
73 "cost" in title or abstract. Whilst other economic-relevant keywords such as "economic" or "burden"
74 or "losses" were initially added to the search, they were dropped as they were not found to improve
75 the accuracy of the search that was specifically looking for cost estimates, as opposed to a qualitative
76 assessment of the magnitude of the economic burden of extreme events.

77 *2.2. Inclusion/exclusion criteria and identification of the pool of relevant articles*

78 Articles had to meet three inclusion criteria. First, they had to pertain to weather-related extreme
79 events. This means that papers which solely produced projections of health burden and associated
80 economic impacts under various scenarios of a warmer climate were excluded. Whilst air pollution
81 is essentially the by-product of human activity, pollution peaks often result from the conjunction of high
82 levels of pollutant emissions and meteorological conditions (e.g. high pressure systems); consequently,
83 it was decided to include pollution peaks as weather-related extreme-events. Second, articles had to
84 include health effects, i.e. not focus solely on non-health related impacts, such as damage to assets.
85 Third, whilst no restriction was applied to the type of economic evaluation, articles had to provide
86 economic information. To avoid over-restricting the pool of relevant studies, monetized health impacts
87 did not represent an inclusion criterion. However, in order to be included, studies had to include cost
88 estimates alongside health impacts, be it costs of adaptive measures, monetized damages to assets or
89 productivity losses for instance.

90 The document selection process, underpinned by the three above-mentioned inclusion criteria, is
91 summarized in Figure 1. After removing duplicates, the search led to the identification of 2325 distinct
92 articles, 2207 of which were excluded by one reviewer (LS) based on title and/or abstract. These
93 excluded articles were either on natural or mechanistic systems (n=869) or their content was irrelevant to

94 weather-related extreme events (n= 1338). Irrelevant articles pertained to five main categories: diseases
95 non related to extreme events; medical therapies; burns; occupational heat exposure and ambient air
96 pollution, since only peaks in exposure or alternatively, on pollution levels during heat waves were
97 deemed relevant to the research question.

98 This led to the identification of a pool of 108 articles selected for full review, all of which could
99 be retrieved. From this pool of articles, 98 articles were excluded after full review by LS and
100 cross-validation with the other two authors (PW and HG). More specifically, articles suggested for
101 exclusion by LS were classified according to four main categories of reasons for exclusion from each
102 of which PW and HG independently took random samples of minimum five articles, in order to check
103 for the validity of the exclusion decision. This cross-validation process was also performed for articles
104 suggested for inclusion. For articles for which there was inconsistency between the three authors (n=4),
105 further discussions were held to reach consensus on inclusion or exclusion.

106 One category of articles excluded after full review was constituted of papers that only quantified
107 the functional relationship between extreme events exposure and health effects and/or the burden of
108 ill-health associated with extreme events, without encompassing any economic information (36 articles).
109 A second category comprised general reviews as well as studies of the burden of climate change that
110 solely provided an evaluation of effects under projections of changes in mean global temperatures,
111 as opposed to effects associated with specific extreme events (37 articles in total; 2 of which [18,19]
112 evaluated reduced GDP loss from reduced work capacity due to projected increases in thermal stress).
113 A third category comprised articles that solely focused on damage to assets, property or crops and did
114 not cover health effects (17 articles, mainly on flooding). A fourth category was constituted of articles
115 pertaining to the health effects of indoor or ambient air pollution (8 articles excluded after full review,
116 since most of these had been previously excluded based on abstract screening).

117 A total of 20 articles, corresponding to 20 distinct studies, were identified as relevant. Whilst no
118 quality appraisal filters were applied, all but two articles were published in peer-reviewed journals.
119 One paper [20] was a statistical bulletin and another [21], a publication from conference proceedings.
120 Relevant articles came from all three databases searches, though a greater proportion came from Web of
121 Science. Each relevant peer-reviewed article was published in a different journal and the main expertise
122 areas they came from were: (i) Disaster and Preventive Medicine; (ii) Public Health; (ii) Environmental
123 Management.

124 2.3. Data extraction

125 Each publication (i.e. study) was reviewed with respect to five key features: (i) general descriptive
126 information, e.g. publication date, environmental hazard and geographical region of focus; (ii) type of
127 research output, e.g. burden evaluation, economic appraisal, descriptive analysis; (iii) method used to
128 measure and to monetize health effects; (iv) consideration of distributional effects and (v) consideration
129 of ecosystem services to help alleviate risk and damages. A complete set of the information extracted
130 for each study can be found in Table 2 in section 3.8. Data extraction was conducted by one reviewer
131 (LS) and checked by the other two authors (PW, HG).

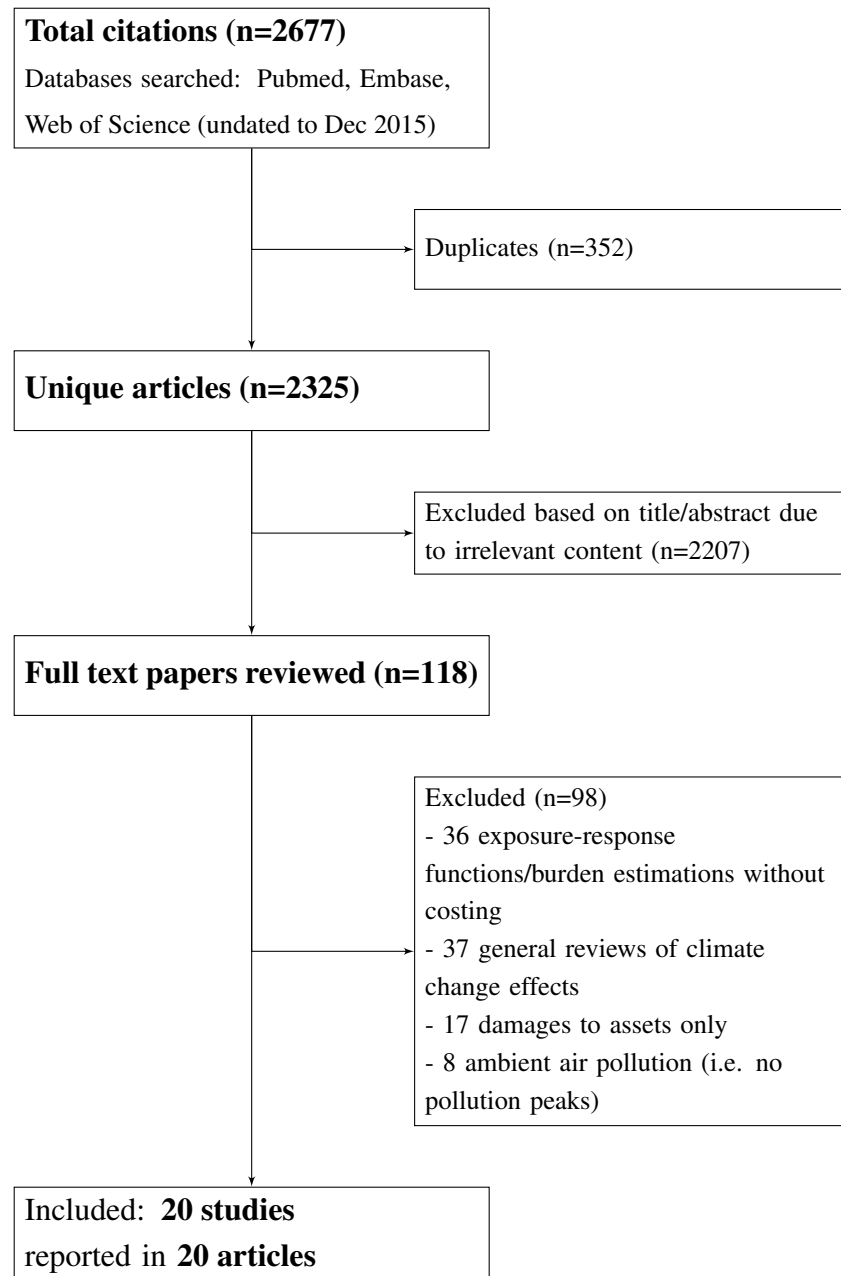


Figure 1. Flow chart of document selection.

133 3. Results

134 3.1. Publication date, environmental hazard and geographical region of focus

135 Despite the absence of date limitations in the search, the earliest relevant study was published in
 136 1999 and two-thirds (13 out of 20) of the articles were published over the last five years (2011-2015).
 137 As Figure 2 indicates, the total number of relevant publications has increased seven-fold over the last
 138 decade. The implied growth rate is higher than the background increase in the global number of scientific
 139 publications (estimated at 5.6% per year over 1997-2006 for scientific publications in Pubmed Medline
 140 for instance [22]) and suggests that the economic evaluation of the health consequences of extreme
 141 weather events represents a very recent, but now rapidly-growing, field of research.

142

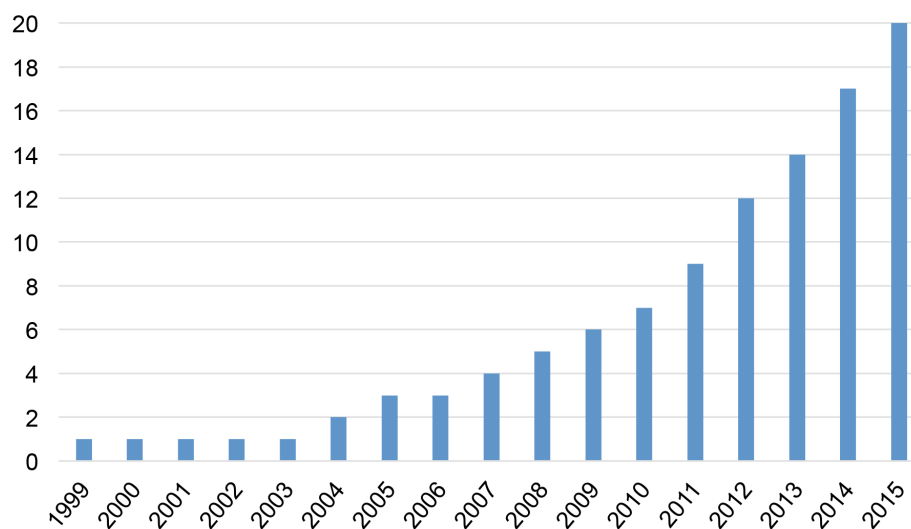


Figure 2. Cumulative number of studies providing an economic evaluation of the health impact of extreme events.

143 An analysis of the distribution of the pool of identified studies according to their primary
 144 environmental hazard and geographical region of focus (Table 1) shows that some parts of the world
 145 are clearly under-represented. Most studies have been undertaken in the US (9 studies out of 20) or
 146 Asia (7 studies out of 20), whereas no study has covered Central and Latin America, the Middle East
 147 or Africa. This imbalance also explains that most studies (13 studies out of 20) pertained to high or
 148 middle-income countries; however, only one study was based in Europe (Spain).

149 Extreme temperatures (heat waves mainly) accounted for more than a third of the pool of studies (7
 150 studies out of 20), closely followed by flooding (6 studies out of 20). No economic study was found on
 151 drought. Whilst extreme temperatures have been considered in all but one region covered by the pool
 152 of identified articles (namely North America, Asia, Europe and Australia), flooding has been the main
 153 focus of studies in Asian countries and Turkey. All studies on hurricanes or tropical storms are from the
 154 US whereas the two studies on pollution peaks are based on case studies in Asia (China and Malaysia
 155 respectively).

156

Table 1. Distribution of studies according to their primary environmental hazard and geographical region of focus.

	Extreme temperatures	Floods	Hurricanes	Pollution peaks	Multiple events ³	Total by region
Asia	1	4		2		7
Australia	1					1
Europe	1					1
Turkey ¹		2				2
North America ²	4		3		2	9
Total	7	6	3	2	2	20

¹ As Turkey is both in Europe and Asia it was considered a region of its own.

² All studies in North America were from the US.

³ When two or more different types of extreme events were considered in a study.

157

158

159 3.2. *Typology of evaluation*

160 Studies were heterogeneous in terms of objectives and methodology and were classified into six
161 categories - labelled A to E - as represented in Figure 3.

162 Half of the studies (n=10) were classified as burden evaluation studies (Group A). They exhibited great
163 variation in methods and could be further subdivided into four sub-groups (see Figure 3). Two studies
164 [20,23] analysed hospital admission records for extreme temperatures exposure, in order to provide an
165 estimate of the health care cost burden associated with extreme heat and extreme cold. They also aimed
166 to identify disparities in vulnerability to excessive temperature exposure between population subgroups
167 stratified by age, gender and socio-economic status. Six studies performed an empirical estimation of the
168 functional relationship between health effects and extreme event exposure using time-series data specific
169 to their case studies, with view to estimating the associated health and economic burden. Three of these
170 six studies focused on extreme heat [24–26], two on hurricanes [27,28] and one on smoke haze [29].
171 Among the three burden studies that focused on extreme heat as health-risk, two included projections of
172 health and economic burden under IPCC climate scenarios [24,25]. The remaining two studies of Group
173 A provided respectively: (i) a comparison of the burden associated with six types of climate-change
174 related events (three of which were weather-related extreme events) that occurred in the US over the
175 period 2000-2009 [30]; and (ii) an estimation of the health and economic burden associated with the
176 severe haze event of January 2013 in Beijing using secondary epidemiological data [31].

177 The three studies classified in group B [32–34] provided descriptive statistics for trend analysis. They
178 exploited records of extreme events fatalities and/or health care data and asset losses and aimed to assess
179 whether trends in damages and loss of life were correlated with trends in the frequency and intensity
180 of extreme events. Two of these studies ([33,34]) also investigated whether a change in meteorological
181 conditions as a result of climate change could have influenced the frequency or intensity of extreme

182 events and could explain the current upwards trend in fatalities and damages whereas the third one ([32])
 183 aimed at identifying seasonal trends in flood frequency as well as and the geographical areas that are the
 184 most prone to flooding in Turkey.

185 The three studies in group C [21,35,36] estimated the willingness to pay (WTP) to avoid the adverse
 186 health impacts associated with extreme events using the contingent valuation method (see section 3.5
 187 for further explanations). Two of these WTP studies pertained to mental health effects and well-being
 188 reduction from flooding whereas the third [36] focused on the excess risk of cardio-vascular death from
 189 heat-stress and also estimated the functional relationship between these two outcomes using data for
 190 Taiwan. Two WTP studies were undertaken in high-income countries (Taiwan and Japan) and one in a
 191 low-income country (Vietnam).

192 Group D comprises two population-based surveys [37,38] that aimed to estimate the health and
 193 economic burden to households associated with flooding. Both surveys were undertaken in low-income
 194 countries (Pakistan and Bangladesh).

195 The study in Group E [39] is an economic appraisal of a risk reduction measure, namely a heat
 196 warning system in Philadelphia. The authors investigated the statistical relationship between excess
 197 deaths and heat wave warnings, in order to estimate the number of lives saved by the warning system,
 198 and compared the obtained benefits with the cost of running the system.

199 Finally, one study [28] - classified as "other" (Group F) - draws from behavioural economics. This
 200 study tested for a potential relationship between (i) hurricane and tornadoes casualties and (ii) work
 201 routine and the embedded economic incentives in driving the adoption of risk protection measures at the
 202 individual level in the US.

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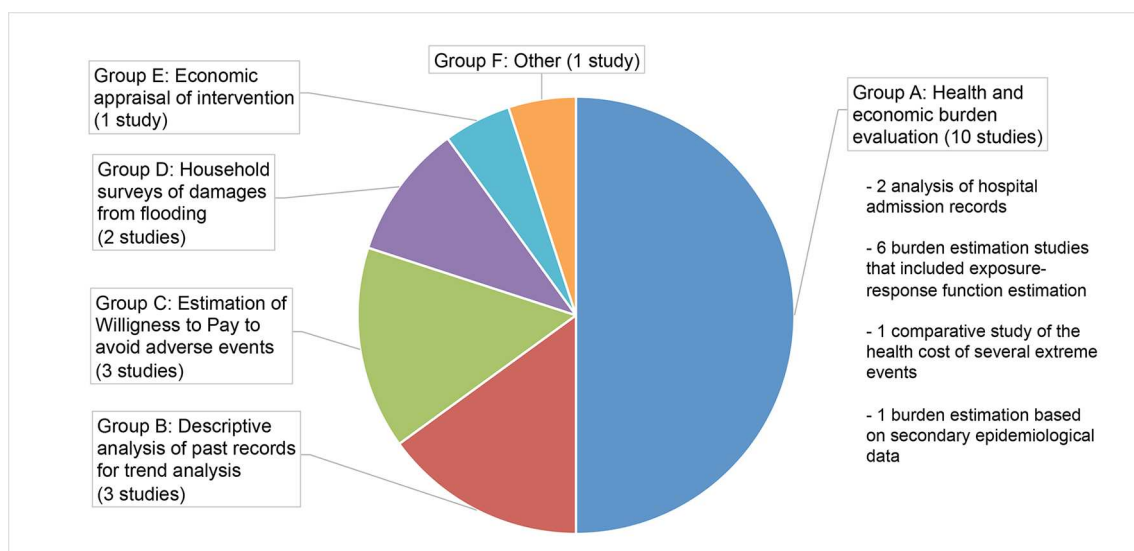


Figure 3. Typology of evaluation undertaken by the identified studies

205 3.3. Reliability of study-specific results

206 Whilst scoping reviews do not apply quality filters to the body of the scientific evidence searched,
207 because the studies were identified through a search of databases of peer-reviewed papers, a *de facto*
208 quality filter was imposed.

209 The significance and reliability of results from the identified studies will greatly depend on the specific
210 strengths and limitations of the method and datasets used. For instance, the reliability of burden estimates
211 (Group A) from studies that relied on an empirical estimation of the functional relationship between
212 exposure and effect using time-series data specific to their case studies is expected to be higher than
213 estimates based on secondary epidemiological evidence (all else being equal), since extreme events
214 are very context-specific and existing epidemiological data may not be easily transferable to different
215 contexts and populations.

216 The significance of descriptive studies results (Group B), which only exploited correlation between
217 selected variables of interest, will greatly depend on the temporal and spatial scale of the data and on
218 the accuracy of the records (e.g. missing values). The three descriptive studies of group B used data for
219 extensive time-periods (≥ 25 years), in order to evaluate time trends in impacts at country (Turkey, US)
220 or regional level (Eastern Black sea basin).

221 The main limitation of WTP studies based on stated preference methods (Group C) is that they
222 rely on hypothetical scenarios which may lead to several biases. Nevertheless, the presently included
223 WTP studies implemented innovative approaches in an effort to address the validity issues deemed most
224 relevant to their specific case study. Matsushima *et al.* [21] valued WTP to avoid mental damages from
225 flooding using an option value approach, in order to address potential strategic bias that would lead
226 to an over-valuation of WTP. Navrud *et al.* [35]'s WTP study in Vietnam estimated the willingness to
227 contribute in labour, in order to circumvent the fact that most individuals would not be able to afford any
228 financial payment.

229 Population-based surveys results (Group D) may suffer from recall and/or strategic bias, where
230 interviewees may exaggerate the severity of their losses if they believe this might help them to obtain
231 further assistance.

232 The only economic appraisal study (Group E, [39]) identified is a very simple comparison of costs
233 and benefit cumulated over three years without applying any discounting. It is worth noting that in this
234 study, the association between heat wave warning and excess mortality was not statistically significant at
235 5% level but given the low cost of running the heat wave system, the large uncertainty around expected
236 health benefit was deemed acceptable.

237 Finally, the statistical study constituting Group F [28] provides a innovative analysis of US records
238 of hurricanes and tornadoes and their associated losses and casualties but may suffer from a lack of
239 household-based variables to provide a deeper understanding of the drivers of evacuation and sheltering
240 behaviours.

241 3.4. Health outcomes and metrics used

242 The health impacts of extreme events can be categorised into direct effects, including injuries, deaths
243 and mental health difficulties and indirect effects that result from the primary damage [2]. This includes
244 for instance, water-borne or food-borne diseases as a result of respectively flooding or heat waves.

245 Most studies focused on direct impacts. The four main types of health metrics used were: (i)
246 deaths; (ii) hospital admissions and outpatients visits; (iii) cases of acute morbidity or injuries; and (iv)
247 depressive disorders or reduction in well-being. Death was used to measure the health burden associated
248 with all four categories of extreme events represented by the selected studies, i.e. hurricanes, flooding,
249 heat waves and air pollution peaks. By contrast, mental health problems were solely considered with
250 regards to flooding (two studies; [21,35]), and to a lesser extent, hurricanes (one study; [28]). In addition,
251 hospital admissions were extensively used to measure the impact of extreme temperatures and peaks in
252 air pollution.

253 Only one study [27] specifically evaluated indirect effects by investigating the effect of a
254 heavily-damaged health infrastructure in the aftermath of hurricane Katrina on the long-term health
255 outcomes of diabetic patients in Louisiana. This was also the only study that used a summary measure
256 of population health (quality-adjusted life expectancy impacts) as a health outcome, whereas all the other
257 studies reported various health impacts separately, i.e. un-aggregated.

258 3.5. Approach to monetization of health impacts

259 The total welfare effect associated with adverse health end-points typically encompasses three
260 elements: (i) health care resource use; (ii) productivity loss; and (iii) dis-utility from suffering or
261 life-shortening, where the latter component commonly drives the welfare loss associated with premature
262 death in older people [12]. The money value of dis-utility associated with an adverse health outcome
263 is typically informed by wealth-health trade-offs that individuals either reveal in surrogate markets
264 (such as risk premiums in the job market) or state in hypothetical markets, as is done via contingent
265 valuation or multiple choice experiments. The result is referred to as the willingness to pay (WTP) to
266 avert outcomes or, when considering mortality risk, the value of a statistical life that is derived from
267 individuals' aggregated WTP for a small change in survival probabilities [40].

268 Out of the 10 studies that used death to quantify health impacts, only four applied a monetary value to
269 this outcome by multiplying it with a value of statistical life. This is not surprising given that monetizing
270 death is less useful for descriptive studies investigating trends in effects or for studies reporting results
271 from population-based surveys (which represent five studies in our review).

272 With the exception of the studies that specifically aimed to estimate the WTP for morbidity risk
273 reduction [21,35], the monetization of morbidity impacts was found to depend on the perspective of
274 analysis chosen, though the latter was often not clearly stated. When burden analysis was undertaken
275 from the perspective of the health care system [20,23,24,26,27], morbidity impacts were monetized using
276 health care costs. In this case, mortality effects, if evaluated, were not monetized. Alternatively, when
277 a broader societal perspective of analysis was chosen, [25,29–31], the cost of morbidity included lost
278 productivity alongside health care costs. Whilst such an approach is commonplace in cost-of illness

279 studies, it is worth underlining that it implicitly assumes that the loss of quality of life (or the dis-utility)
280 from morbidity is nil and thus places a lower-bound to the total welfare effect of morbidity.

281 *3.6. Distributional assessment*

282 Nine studies [20,23–25,27,28,35,37,41], paid particular attention to the distribution of impacts based
283 on demographic and socio-economic factors such as age, gender, race/ethnicity and income and/or
284 focused on specific population subgroups expected to be most vulnerable to extreme events. Vulnerable
285 population subgroups considered - which may overlap - were: (i) older individuals (aged 65 and above)
286 and disabled people (i.e. Medicare population in the US); (ii) single parent; (iii) patients with a chronic
287 condition (diabetes); and (iv) low-income communities. The large majority of the studies that examined
288 the distribution of effects within population subgroups were undertaken in the US (6 out of 9 studies),
289 two were carried out in Asia [35,37] (focusing on low income communities only) and one in Australia
290 [24] (focusing on age-related differential susceptibility to heat effect).

291 *3.7. Consideration of ecosystem services to help alleviate risk and damages*

292 There is a substantial literature on the protective benefits of natural ecosystems such as coastal
293 wetlands, riparian forests and reefs against the devastating effects of flooding and hurricanes [42–44]. In
294 addition, urban trees have been shown to help alleviate air pollution in cities by absorbing atmospheric
295 pollutants [45] and reduce city heat island effects by lowering temperatures [46]. Despite this evidence
296 and whilst a number of the included studies recommended the adoption of risk reduction measures, only
297 one study on flooding [33] briefly suggested investing in natural ecosystems (watershed management) as
298 part of a portfolio of adaptive measures.

299 *3.8. Data extracted from each study*

300 Table 2 provides a summary of the information extracted from each relevant study.

Table 2. Information extracted from the pool of relevant studies.

Authors (Date)	Event type	Country	Time-period/ case study	Pop	Study objective & method	Typology	Health metrics	Health impacts monetization	Ecosystem services mentioned?	Distributional Analysis	Key results
[20] (2008)	Extreme temperatures	US	2005	All	Descriptive analysis of statistics on hospital stays resulting from excessive heat or cold exposure due to extreme weather conditions.	Burden evaluation (Group A)	Hospitalization admissions	Health care costs	No	Yes	Excessive temperatures costed US hospitals \$ 120m in 2005. The average cost of a heat-related stay amounted to \$ 6,200 vs. \$ 12,500 for cold-related stay. Patients admitted were older than the average hospital patient (6 to 7.6 /100,000 people aged \geq 65 yrs old). Hospitalizations were found to be about 2 to 2.5 times more common in the poorest communities than in the wealthiest ones and slightly more common in rural regions.
[21] (2007)	Flooding	Japan	2004 Toyooka flood	All	Estimation of WTP (contingent valuation) to avoid of mental damage caused by flood disaster (indirect approach using option value).	WTP study (Group C)	Mental damage	WTP estimated in the study	No	No	Individuals expressed a significant WTP to avoid mental damage: Mean WTP 44,769 yen.
[23] (2012)	Extreme temperatures	US	2004-2005	US medicare pop. (\geq 65 yrs old or disabled)	Descriptive study to assess the health care burden of hypo- and hyperthermia due to extreme weather conditions.	Burden evaluation (Group A)	Inpatient & outpatient visits	Health care costs	No	Yes	Hyperthermia-related visits were more frequent than hypothermia but less costly (\$ 36m vs. \$ 98m for hypothermia in 2004-05). Black and Native americans had a significantly higher relative risk of health care visits than their White counterparts.
[24] (2015)	Extreme temperatures	Australia	2000-2010 for current burden; 2030 and 2060 for projections	All	Estimation of the current and projected burden of heat-related emergency department visits in Brisbane under a range of two IPCC climate scenarios	Burden estimation (Group A)	Emergency Department (ED) visits	Health care costs (normalised to AU\$ 2013)	No	Yes	Higher relative risks of ED visits for adults aged 65+ than for their younger counterparts (RR for all ED visits=1.09 vs 1.06) on hot days (>35 degrees). ED visits are projected to increase considerably on hot days in the future under population growth and climate change scenarios. The excess number of visits by older patients is estimated to grow twice as much as the younger group. The excess demand is estimated to add an extra cost of around AU\$ 78,000-260,000 in 2030 and AU\$ 215,000-1,985,000 in 2060 (2013 prices).
[25] (2012)	Extreme temperatures	US	1991-2004 for current burden; 2046-2065 and 2080-2099 for projections	All	Estimation of current and projected heat-related public health burden in New York State under a range of three IPCC climate scenarios.	Burden estimation (Group A)	Respiratory admissions	Health care costs and productivity loss due to days hospitalized. Adjustment for inflation and 3% discounting used. Costs normalised to \$ 2004.	No	Yes	Hospital costs associated with heat-related respiratory admissions in NYS are currently estimated at \$ 0.64m p.a. and projected to increase to \$ 5.5-7.5m in 2046-2065 and to \$ 26-76m in 2080-2099. The public health burden is projected to be greater among females and in low-income groups.
[26] (2015)	Extreme temperatures	Spain	2002-2006	All	Estimation of: (i) the impact of excessive heat on mortality; (ii) the temperature threshold to mortality increase; (iii) the hospital cost of heat-attributable deaths.	Burden estimation (Group A)	Deaths	Health care costs	No	No	A statistically significant increase in mortality was observed when daily max temperature reached 38 C degrees. Over 2002-2006, excessive heat was found to be responsible for 107 (95%CI: 42-173) premature deaths, associated with a health care cost of €426,000 (€167,000 - 689,000).

Table 2. *continued*

Authors (Date)	Event type	Country	Time-period/ case study	Pop	Study objective & method	Typology	Health metrics	Health impacts monetization	Ecosystem services mentioned?	Distributional Analysis	Key results
[27] (2009)	Hurricanes	US	Hurricane Katrina in 2005	Patients with diabetes	Observational before/after study of the impact of Katrina on health care management of patients with diabetes in 3 different health care systems and projected health and health care costs consequences of treatment disruption over patients remaining lifetime.	Burden estimation (Group A)	Life expectancy (LE); quality-adjusted life expectancy (QALE)	Health care costs from treatment disruption over patients' remaining lifetime	No	Yes	Treatment disruption in patients with diabetes following Katrina was projected to result in substantial health care costs (\$ 504m for the affected pop.) due to co-morbidities/disease complications in the long run. The impact reflects the high prevalence of the disease (about 9% of US pop.) and the large size of the population affected. The disaster exacerbated inequalities in access to health care and resulting health disparities between socio-economic subgroups.
[28] (2011)	Hurricanes	US	Hurricanes Katrina and Rita in 2005	Single mothers	Estimation of the impact of exposure to hurricanes on the mental health resilience of single mothers versus the general population and computation of the related economic cost from lost productivity.	Burden estimation (Group A)	Days of poor mental health (reported in the last 30 days after event)	Direct private costs from absenteeism due to mental health disturbance	No	Yes	Following exposure to hurricanes Katrina and Rita, days of poor mental health was found to increase by 72% in single mothers vs. 18% in the total population. As a result, single mothers were expected to be absent from work 18.4 more days (vs 3.6 more days of absence for the average person), leading to an income loss of \$ 4,200/person (vs \$ 817 for the average person), thus exacerbating their economic vulnerability. Differential effects were found to persist one year after the events.
[29] (2014)	Pollution peak	Malaysia	2004-2009	All	Estimation of the change in hospital admissions for a change in pollution concentrations (dose-response function) and evaluation of the associated economic burden.	Burden estimation (Group A)	Respiratory and cardio-vascular hospital admissions	Health care costs and productivity loss	No	No	On average, over 2004-2008 for Kuala Lumpur and some areas in Selangor state (equivalent to 25% of the Malaysian population), smoke haze occurrences were found to be associated with an increase in inpatients visits by 2.4/10,000 people per year, representing a 31% increase from normal days. The associated economic loss amounted to \$ 91,000 per year. Under no change in haze recurrence, over 20 years, this would represent a cost of \$ 1.7m, discounting at 5% p.a.
[31] (2015)	Pollution peak	China	Severe haze event in January 2013	All	Modelling of $PM_{2.5}$ concentrations during the haze episode and estimation of the associated acute mortality and morbidity impacts and associated health care costs.	Burden estimation (Group A)	Deaths, cases of acute bronchitis and asthma, hospital admissions	VSL for mortality (\$ 274k); WTP or Health care costs and productivity loss for morbid endpoints	No	No	The total economic cost of the haze-related health impacts was estimated, under conservative assumptions, at \$ 253m, i.e. about 0.8% of the annual GDP of Beijing.
[32] (2005)	Flooding	Turkey	1970-1996 (624 floods recorded)	All	Descriptive analysis of seasonal and regional trends in the mortality and economic impacts of flooding based on registered flood reports	Descriptive analysis (Group B)	Deaths	N.A. (see sections 2.2; 3.5)	No	No	Seasonal and regional trends in terms of human deaths and economic impacts were determined. Most floods and deaths happened in the summer season. Most of the floods and deaths occurred in the Black Sea region.

Table 2. *continued*

Authors (Date)	Event type	Country	Time-period/ case study	Pop	Study objective & method	Typology	Health metrics	Health impacts monetization	Ecosystem services mentioned?	Distributional Analysis	Key results
[33] (2013)	Flooding	Turkey	Large floods between 1955-2005 in the Eastern Black Sea Basin (EBSB)	All	Descriptive analysis of flood occurrence and meteorological conditions and identification of trends in damages and human lives loss.	Descriptive analysis (Group B)	Deaths	N.A. (see sections 2.2; 3.5)	Yes	No	Between 1995-2005, 51 floods occurred in EBSB causing 258 deaths and \$ 500m of damages to assets. Most floods occurred during summer months when snow melt is combined with heavy rainfall in mountainous valleys. Despite the absence of an increasing trend in extreme rain values and flood frequency, an upward trend in terms of both death and damages was found. The latter was attributed to human factors such as illegal land use, urbanization in flood-prone areas, road construction in stream beds, deforestation and insufficient drainage structures. Alongside structural measures, watershed management and reduced deforestation were suggested to reduce vulnerability to flood.
[34] (1999)	Multiple Events	US	1968-1995	All	Descriptive analysis of trends in the frequency of extreme events and their associated fatalities and economic losses.	Descriptive analysis (Group B)	Deaths	N.A. (see sections 2.2; 3.5)	No	No	The upward trends in human fatalities and economic losses from extreme events was found to be essentially related to an increased vulnerability stemming from a growing population in coastal areas and lifestyle and demographic (population ageing) changes.
[35] (2012)	Flooding	Vietnam	2007 floods	All	Estimation via contingent valuation of the welfare loss from flood-related illnesses and well-being reduction following flood disaster in a developing country. Willingness to contribute in kind was used to estimate WTP to avoid this welfare loss.	WTP study (Group C)	Flood-related illnesses; well-being reduction	WTC in-kind estimated in the study multiplied by an estimate of the opportunity cost of labour time	No	Yes	Flood damage was estimated on average to represent about 20% of households' annual income. However, it was not possible to disentangle the welfare loss from morbidity and well-being reduction from the welfare loss due to damages to assets. Poor households were found to be more vulnerable to floods as the associated damage made up a significantly larger portion of their annual income. Households heavily dependent on agricultural activities were also found to be more vulnerable.
[36] (2010)	Extreme temperatures	Taiwan	1971-2006	All	Estimation of (i) the impact of climatic conditions on cardiovascular deaths in Taiwan over 1971-2006 and (ii) WTP (contingent valuation method) to avoid the increase in cardiovascular deaths projected under climate change	WTP study (Group C)	Cardiovascular deaths	WTP estimated in the study.	No	No	Cardiovascular deaths are projected to increase by 1.2% to 4.1% in Taiwan under alternative IPCC climate scenarios and each individual would be willing to pay annually \$ 51 to \$ 97 to avoid such an increase in mortality risk.
[37] (2015)	Flooding	Thailand	2011 floods	All	Survey of flood victims in three severely affected provinces of Thailand to capture health related and non-health related costs of damage.	Population-based survey (Group D)	Flood-related diseases	Health care costs from flood-related diseases	No	Yes	Health-related costs were negligible in contrast to losses to tangible assets (property, valuable etc). Few households experienced health-related losses (11% of sample). Evacuation rates varied between poor and non-poor households: 65% of poor households had some members evacuate vs. 77% for non-poor households.

Table 2. *continued*

Authors (Date)	Event type	Country	Time-period/ case study	Pop	Study objective & method	Typology	Health metrics	Health impacts monetization	Ecosystem services mentioned?	Distributional Analysis	Key results
[38] (2014)	Flooding	Pakistan	Pakistan floods in 2010	All	Comparison of the economic impacts and time-to-recovery after floods in Pakistan versus after an earthquake in Haiti using Cross-sectional cluster surveys.	Population-based survey (Group D)	Death and injuries	N.A. (see sections 2.2; 3.5)	No	No	Injuries and deaths were much greater in Haiti. Whilst a decline in income was widespread in both countries, relative household income loss was greater in Pakistan because of damages to the agricultural economy. Housing recovery was however quicker in Pakistan and food insecurity was smaller than in Haiti due to greater receipt of food aid.
[39] (2004)	Extreme temp.	US	1995-1998	≥ 65 yrs old	Retrospective statistical analysis of the effectiveness of Philadelphia's heat warning system (PWWS) in terms of reduced excess mortality	Economic Appraisal (Group E)	Deaths	VSL (\$ 4m)	No	No	117 lives are expected to have been "saved" (with substantial uncertainty around this estimate) over the 3 year period thanks to PWWS. This is equivalent to a gross benefit of \$ 468m that is much higher than the cost of running the system (\$ 210k).
[30] (2011)	Multiple events	US	2000-2009	All	Estimation and comparison of the health costs associated with 6 climate change-related events : (i) California heatwave 2006; (ii) ozone air pollution (for daily levels above national standards- impacts computed for the years 2000-2002); (iii) Florida hurricane season 2004 (4 hurricanes in one month); (iv) West Nile virus outbreak (vector-borne disease) in Louisiana; (v) red river flooding in North Dakota in 2009 (vi) Southern California Wildfires in 2003	Burden study (Group A)	Deaths, hospitalizations, emergency department visits and outpatient health care use	VSL for mortality (\$ 7.8m in \$2008); health care costs and loss-work productivity for morbid endpoints	No	No	Events associated with the greatest number of premature deaths were associated with the highest costs. The costliest weather-related extreme event in terms of health impacts was California's 2006 heat wave (\$ 5.3bn), followed by Florida hurricane season (\$ 1.4bn), California wildfires (\$ 600m), West Nile infectious disease outbreak (\$ 207m) and red river flooding (\$ 20m). When normalised to 1,000 people, the cost of river flooding was however, nearly as high as the cost of heatwave (\$ 150k/1,000 person).
[41] (2013)	Hurricanes & tornadoes	US	1989-2005	All	Testing for a potential relationship between hurricane and tornadoes-related casualties and work routine.	"Other" (Group F)	Deaths and injuries	N.A. (see sections 2.2; 3.5)	No	Yes	Daily variation in casualties from hurricanes and tornadoes is affected by the work routine. All things being equal, hurricanes, which provide at-risk population with some lead time, lead to greater casualties during week-days since the opportunity cost (namely income loss) of adopting protection measures (e.g. evacuating) is much larger than during week-ends. On the opposite, tornadoes, which provide little lead-time, lead to larger casualties during weekends as the acquisition of risk information is harder on week-ends and workplaces and schools are safer than private homes. Casualty risk from tornadoes was found to reduce by 6-8% for every \$ 1000/per capita income added at county-level.

301 4. Discussion

302 4.1. Key findings

303 4.1.1. Health impacts represent an substantial economic burden that is likely to rise steeply

304 All studies indicate that the economic cost associated with the adverse impacts of extreme events on
305 human health is substantial. Whilst it is not the aim of this review to report all quantitative estimates
306 here, key economic findings reported by each study can be found in Table 2.

307 The comparative study by Knowlton *et al.* [30] of the health costs associated with a range of six
308 climate-change related events that happened in the US between 2000 and 2009, ranked heat waves as
309 the most costly weather-related extreme event (\$ 5.3bn for California's 2-week long heat wave in 2006).
310 Heat waves indeed claim substantial death tolls and a large number of emergency department visits due
311 to a large exposed population. The interpretation of this ranking, however, requires caution. First, it was
312 based on a selection of a single case study for each type of extreme event, which may explain why, in
313 contrast to Knowlton *et al.* [30], other authors have ranked flooding as the weather-related extreme event
314 with the greatest health impacts [47]. Second, only direct health impacts were accounted for in this study.
315 Accounting for indirect health effects over a longer time horizon, such as reduced health care provision
316 following damage to infrastructures (see section 4.1.2), may provide a slightly different picture. Third,
317 this ranking may be different in low-income countries, where the number of deaths from flooding and
318 hurricanes is greater than in high-income countries.

319 More importantly, the two studies that included burden projections under various climate scenarios
320 [24,25] show that - whilst unavoidably highly uncertain - the health and economic burden of extreme
321 events is set to rise steeply under projected increases in mean temperatures globally. For instance, Lin
322 *et al.* [25] estimated that the annual health care costs from heat-related respiratory admissions in New
323 York city currently amounts to \$ 0.64m but is projected to surge to \$ 5.5-7.5m p.a. in 2046-2065 and to
324 \$ 26-76m p.a. in 2080-2099.

325 4.1.2. Health consequences may be incurred long after event occurrence

326 Whilst extreme events are typically brief, their consequences for public health may last over long
327 time-horizons. For instance, Fonseca *et al.* [27] estimated that the disruptive impact of hurricane Katrina
328 on the health care management of patients with diabetes would lead to a \$ 504m health care bill over the
329 patients' remaining lifetimes (discounting at 3% p.a.). This finding was based on the expected increase
330 in incidence of co-morbidities and health complications in patients with diabetes, following medication
331 deprivation during the shut-down period of local medical facilities. Furthermore, Zahran *et al.* [28] found
332 that, in the aftermath of hurricanes Katrina and Rita in 2005, not only did single mothers experience a
333 very high mental strain but, unlike the general population, they did not return to their pre-disaster mental
334 health levels more than a year after event.

335 Although the indirect long-term consequences of extreme events are potentially large and, in some
336 cases, expected to substantially contribute to the total economic impact of these events, they appear to be

337 rarely examined (two studies out of the pool of relevant studies). The reason is that, since these impacts
338 are temporally separated from event onset, it is much more resource-intensive to capture them, requiring
339 for instance follow-up surveys or modelling expertise to extrapolate health consequences later in life.

340 4.1.3. An increased vulnerability to events exacerbated by human factors

341 Kunkel *et al.* [34] and Yüksek *et al.* [33]’s analyses suggest that the upwards trend in adverse health
342 impacts and asset damages from extreme events witnessed over the last decades essentially results
343 from increased vulnerability, as opposed to changes in atmospheric conditions. Whilst the factors that
344 exacerbate vulnerability to extreme events will vary geographically, they typically include a growing
345 population in coastal areas, land-use modification (deforestation) due to rapid urbanization and an ageing
346 population in developed countries.

347 Economic factors were also found to play a major role in shaping people’s attitudes towards the risk
348 of extreme events. For instance, Yüksek *et al.* [33] suggest that the rise in land and property prices in the
349 Eastern Black Sea Basin in Turkey has pushed people to settle on riverbanks, despite known flood risk.
350 In addition, the results of Zahran *et al.* [41] support the hypothesis that the cost of adopting protection
351 measures, such as income loss, influences individuals’ evacuation behaviour when informed of hurricane
352 risk.

353 4.1.4. Disparities in vulnerability between population subgroups is expected to exacerbate health 354 inequalities between income-groups

355 A number of population subgroups such as older people, single mothers, patients with a chronic
356 condition and socio-economically disadvantaged communities were found to bear a disproportionate
357 health burden associated with extreme events. Whilst the review does not represent the overall body of
358 evidence on vulnerability factors, it is worth noting that its findings are in line with the literature on the
359 distributional effects of extreme events, heat-stress in particular [12,48].

360 All four studies that investigated the interactional effect of age and extreme temperatures found an
361 increased vulnerability to heat-stress associated with age [20,23–25], with a significantly higher rate
362 of hospital admissions in older age-groups. By contrast, evidence of gender-related susceptibility to
363 extreme temperatures is more mixed. Males were found to be at greater risk of hospitalization for
364 both hypo- and hyperthermia [20,23], whereas females were found to bear a disproportionate burden of
365 respiratory admissions due to excess heat [25].

366 Low income was also found to be a factor associated with vulnerability. Merrill *et al.* [20] reported
367 that hospitalization rates in US hospitals due to extreme temperatures were 2 to 2.5 times higher in the
368 poorest communities than in the wealthiest ones. This was corroborated by findings from Lin *et al.*
369 [25] who found a significant increase in the risk of respiratory admission under extreme heat among
370 neighbourhoods with a high proportion of individuals on low income. Importantly, the effect of income
371 on vulnerability is not limited to extreme temperatures. Zahran *et al.* [41] for instance, found that, at
372 county level, the casualty risk from tornadoes decreased by 6 to 8% for every additional \$ 1000 per
373 capita income.

374 People on low income are expected not only to be more vulnerable to direct short-term effects but also
375 to suffer a disproportionate burden of indirect consequences of events in the long run. In the US, Zahran
376 *et al.* [28] showed that after hurricanes Katrina and Rita struck the US Gulf coast in 2005, single mothers
377 experienced a significantly higher numbers of days of poor mental health than the general population.
378 When translated into productivity loss due to absenteeism, this additional mental strain represented
379 an expected private income loss of \$ 4,200 per single mother, as opposed to \$ 817 for the average
380 person. Fonseca *et al.* [27] demonstrated that the health of patients with diabetes who were treated in a
381 state-funded system were more severely affected by hurricane Katrina than the health of patients treated
382 in private or veterans-only health care systems, reflecting longer health care service disruption. As a
383 result, the long-term health care cost impact of the hurricane is expected to be significantly higher for
384 patients treated in state-run systems than in private systems. Given the tighter resources constraints that
385 state-systems face, the hurricane is expected to have long-lasting implications for SES-related health
386 inequality.

387 In developing countries, poorer households and households with livelihoods dependent on the
388 exploitation of natural resources are expected to be more vulnerable to extreme events such as floods,
389 as the associated damage makes up a significantly larger portion of their annual income [35]. With
390 regards to the distribution of health impacts, based on the 2011 Greater Bangkok floods case study,
391 Nabangchang *et al.* [37] did not find a difference in flood-related injuries and illnesses between income
392 groups. However, they found that evacuation rates did vary by income, with 77% of non-poor households
393 having some members evacuate compared to 65% of poor households, which may suggest a greater
394 adaptive capacity in non-poor households. In addition, whilst the authors did not provide the distribution
395 of health-related costs (i.e. medicines, doctors' visits and foregone income of patients and caretakers)
396 by income strata, they reported a great variation in health costs incurred by households. Such a
397 skewed distribution of health care costs impacts may further exacerbate wealth inequalities within the
398 community.

399

400 4.2. Relevance of currently identified evidence for policy-making

401 It is worth restating that the review exclusively focused on economic evaluations of adverse health
402 effects resulting from human exposure to extreme events. It therefore did not aim to review the overall
403 evidence on the functional relationships between exposure to the various types of extreme events and
404 health effects. Similarly, owing to its focus on extreme events, the review did not encompass the growing
405 number of studies that provide projections of the health and economic burden associated with a future
406 global rise in temperatures. It is nevertheless of interest to note that this excluded literature, namely
407 exposure-response functions or health burden projections under climate change scenarios, has so far
408 overwhelmingly focused on heat stress as risk factor [49].

409 Whilst the databases searched are the ones widely used in the health and environment fields, by
410 holding information on published peer-reviewed research, they are likely to be biased toward studies
411 in high-income countries, thus leading to an under-representation of the body of "grey" research in
412 low-income countries. In contrast, we do not consider the exclusion of non-English language papers will

413 have introduced a publication bias into our review. While we did not collect information on the number of
414 non-English papers, a recent systematic review of extreme water-related weather events and waterborne
415 disease that searched standard databases and included English and non-English language papers found
416 that only 5% of the papers were not in English - and this small group were in other European languages
417 [50].

418 Collectively, the studies in our review, which cover a diverse set of case studies, represent a valuable
419 body of evidence on the size of the economic burden associated with the adverse health effects caused
420 by exposure to weather-related extreme events. Alongside the literature on the health effects of climate
421 change, the identified studies also provide policy-makers with an indication of how much this burden
422 may grow by the end of the century, especially with regards to extreme temperatures.

423 In line with the wider literature on natural disasters [2], our review indicates that the recent upwards
424 trend in adverse health impacts and asset damages from extreme events can be related in broad terms
425 to demographic and lifestyle factors (e.g. population ageing, growing population in coastal areas)
426 and approaches to natural resources management (e.g. land use modification), as opposed to climate
427 change-related physical forcing. As changes in meteorological conditions become more pronounced
428 under climate change, lifestyle and resource management factors are therefore expected to further
429 exacerbate our vulnerability to extreme events. This review suggests that the modification of these
430 factors should be at the centre of strategies aiming at reducing human exposure to extreme events.

431 Two studies identified in this review [27,28] have highlighted that extreme events can have long-term
432 repercussions, especially on the health of vulnerable population subgroups. This is of particular
433 interest as it can help identify the appropriate time-horizon for the economic evaluations of adaptive
434 interventions, such as the implementation of protective measures.

435 Whilst most of the research on the health and associated economic effects of extreme events has
436 focused on physiological impacts (e.g. deaths, hospitalizations), the recent attempts at valuing well-being
437 and mental health effects will help provide a more comprehensive picture of the range of economic
438 impacts. Efforts to estimate individuals' welfare loss from mental health effects associated with exposure
439 to climatic extremes should be particularly encouraged in light of growing evidence that these effects may
440 be substantial [7] and the fact that, as mentioned in section 3.5, valuing morbidity impacts solely based
441 on health care resource use and/or productivity loss, implicitly assumes that the quality of life loss from
442 morbidity is nil.

443 Finally, the studies contribute to the larger body of evidence on the factors driving the distribution of
444 adverse impacts and to the identification of vulnerable population subgroups stratified by demographics
445 (e.g. age gender, socio-economic status) and health condition. These findings are key to the design
446 and implementation of adaptation measures and, more generally, to inform the development of "Healthy
447 Public Policy", which calls for an explicit consideration of health and equity matters in all policy areas
448 [51].

449

450 4.3. Future research directions

451 The recent increasing research focus on the economic implications of the health impacts from extreme
452 events (see Figure 2) coincides with an increase in the occurrence of weather-related disasters [52,53],
453 linked to growing densities of population and assets in at-risk areas. Although this demonstrates a
454 growing awareness of the need to document the economic burden associated with human exposure to
455 extreme events, the body of evidence remains very thin and has so far largely focused on Asia and North
456 America.

457 In particular, despite wide search terms and a long review period (undated to Dec 2015), we found no
458 relevant study in Africa, Latin and Central America and the Middle East and only one study in Europe.
459 This is an important gap, given that some of these areas are likely to experience severe impacts from
460 climate change-related extreme events [7,54,55] and would highly benefit from a greater appreciation
461 of the associated economic costs and their distributional implications. Whilst we acknowledge that
462 the focus on published peer-reviewed research inherent to the databases searched may have led to an
463 under-representation of research in low-income countries, this is unlikely to explain the paucity of study
464 in Europe. In addition, the lack of relevant economic studies in Africa is consistent with IPCC's recent
465 conclusion that information on the observed frequency of extreme events in Africa still remains limited
466 [7].

467 Although decision-makers require evidence on the economic consequences of the public health
468 burden associated with extreme events, the greatest evidence gap is in economic evaluations of
469 possible interventions to reduce this burden, in order to allocate constrained resources towards the most
470 cost-effective ones. One striking finding of this review, is that despite WHO's 2009 call for further
471 research on interventions to control climate-sensitive health risks and the fact that the large majority of
472 the pool of included studies were published in the last five years, only one out of the 20 economic studies
473 identified was an economic appraisal of a risk reduction measure. This economic evaluation pertained
474 to a heat warning system [39] and was a rather crude comparison of costs and benefits cumulated over a
475 three-year period.

476 This finding is corroborated by results from a recent systematic review by Bouzid *et al.* [56], which
477 highlighted a paucity of evidence on the effectiveness of public health interventions aimed at reducing
478 the health risks related to a changing climate. The authors identified droughts and floods among the
479 climate risks for which there was no review of evidence on the effectiveness of potential interventions to
480 reduce the associated public health burden. Although the authors found two reviews of evidence related
481 to the management of heat stress, one did not pertain to heat waves while the other included studies
482 of very disparate quality. The expected increase in the intensity and the frequency of weather-related
483 extreme events [1] adds urgency to the need to fill the evidence gap pertaining to the economic appraisal
484 of adaptive measures.

485 Our review also indicates that very little research attention has been given to the public health
486 dimensions of natural resource management and, more specifically, to the exploitation of the capacity
487 of natural ecosystems to reduce human exposure to extreme events. This is a highly significant gap
488 in the evidence base, in light of evidence that poor land management has been identified as a key
489 factor exacerbating our vulnerability to extreme events (see section 4.1.3). There is an urgent need
490 to consider the restoration of various natural ecosystems - while taking into account non-linearity and

491 scale-dependence in ecosystem services provision [43,57] - within the scope of potentially cost-effective
492 risk reduction options.

493 Finally, the building of a body of economic evidence to support resource allocation between
494 competing strategies to adapt against a given type of extreme event would require a common
495 methodological framework with regards to the range and duration of health impacts included and the
496 approach to monetization. The choice of the range and duration of impacts are related, whereby indirect
497 impacts typically occur in the long run. The identification of the appropriate analysis time horizon
498 should therefore assess whether indirect effects, such as treatment disruption following damages to
499 infrastructure following a hurricane or delay in care provision due to peaks in health care demand
500 during a heat-wave, are likely to be influential to the analysis. Finally, the evaluation of competitive
501 interventions should ideally be undertaken from the same perspective: e.g. health care system or society,
502 as the chosen perspective of analysis will drive the approach to monetizing health effects (see section
503 3.5).

504

505 **5. Conclusion**

506 Our scoping review has shown that, although the last five years have seen increasing research interest
507 in the economic consequences of the health effects associated with human exposure to extreme events,
508 the evidence base remains thin with limited geographical coverage. We found no studies in Africa, Latin
509 and Central America and the Middle East, a critical gap given the projected distribution of climate-related
510 extreme events for the future.

511 The economic studies identified were heterogeneous in terms of objectives and methodology and
512 provided a mix of descriptive analyses, WTP estimation for health risk reduction, burden estimation
513 and economic appraisal. However, when considered altogether, they clearly indicate that extreme
514 events will increasingly become a pressing public health issue with strong welfare and distributional
515 implications. Health impacts and associated consequences on health care budgets, productivity and
516 individuals' well-being may be incurred long after event occurrence and are expected to exacerbate
517 health inequalities between income subgroups.

518 Whilst the evidence based identified by our review underlines the importance of addressing the health
519 impacts of extreme events, it provides policy-makers with little economic information on which to base
520 decisions about the allocation of scarce resources between potential risk reduction options. In particular,
521 our review highlighted a significant lack of research attention to the potential cost-effectiveness of
522 interventions that exploits the capacity of natural ecosystems to reduce our exposure to extreme events,
523 despite evidence that poor land management contributes to exacerbating our vulnerability to them.

524

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530 **Author Contributions**

531 Hilary M. Graham and Piran C. L. White conceived the research idea. Hilary M. Graham, Piran C. L.
532 White and Laetitia H. M. Schmitt designed the search strategy. Laetitia H. M. Schmitt extracted the data
533 and wrote the draft paper. Hilary M. Graham and Piran C. L. White edited the paper.

534 **Conflicts of Interest**

535 The authors declare no conflict of interest. The funding sponsors had no role in the design of the
536 research; in the collection, analysis, or interpretation of data; in the writing of the manuscript, and in the
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