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26 **Abstract:**

27 There is now a strong consensus that during the 20th century, and especially during recent
28 decades, the earth has experienced a significant warming trend with projections suggesting
29 additional further warming during the 21st century. Associated with this warming trend are
30 changes in climate that are expected to show substantial spatial variability across the earth's
31 surface. Globally fish production has continued to increase during recent years at a rate
32 exceeding that of human population growth. However the contribution from capture
33 fisheries has remained largely static since the late 1980s with the increase in production
34 being accounted for by dramatic growth in the aquaculture sector. In this study the
35 distribution of vulnerability of aquaculture related livelihoods to climate change was
36 assessed at the global scale based on the concept of vulnerability as a function of sensitivity
37 to climate change, exposure to climate change, and adaptive capacity. Use was made of
38 national level statistics along with gridded climate and population data. Climate change
39 scenarios were supplied using the MAGICC/SCENGEN climate modelling tools. Analysis was
40 conducted for aquaculture in freshwater, brackish, and marine environments with outputs
41 represented as a series of raster images. A number of Asian countries (Vietnam, Bangladesh,
42 Laos, and China) were indicated as most vulnerable to impacts on freshwater production.
43 Vietnam, Thailand, Egypt and Ecuador stood out in terms of brackish water production.
44 Norway and Chile were considered most vulnerable to impacts on marine production while
45 a number of Asian countries (China, Vietnam, and the Philippines) also ranked highly.

46

47 **Key Words:** Climate change, vulnerability, aquaculture, livelihoods, adaptability

48

49

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51

52 **Introduction:**

53 Globally, fish production has increased steadily over the last five decades at a rate exceeding
54 that of human population growth so that in 2012 mean World *per capita* fish consumption
55 was estimated at 19.2kg compared with 9.9kg in the 1960s (FAO, 2014). This increase is
56 generally seen as beneficial from a health perspective with fish consumption providing an
57 important source of high quality protein, essential fatty acids and micronutrients
58 (Kawarazuka, 2010). In many poorer regions where fish represents a significant portion of
59 consumed animal protein, and where diet in general may lack diversity, the contribution of
60 fish to overall nutrition may be especially significant (Belton et al., 2014, Thilsted, 2013).
61 While total global fish production has continued to increase, the proportion supplied by
62 capture fisheries has remained largely static since the late 80's onwards with increased

63 production accounted for by the dramatic growth in the aquaculture sector which was
64 estimated at 42.15% of total fisheries production in 2012 (FAO, 2014). Inland fish
65 production represents an increasingly large proportion of total global fisheries production;
66 33.86% in 2012 compared with 28.43% in 2007 (FAO, 2014). As with total global production
67 the growth of the inland fishery sector is largely accounted for by a rapidly expanding
68 aquaculture sector representing 78.32% of global inland fisheries production in 2012(FAO,
69 2014), with pond culture of warm water fish species playing the largest role (Dugan et al.,
70 2007).

71 As well as providing an important source of food, aquaculture makes significant economic
72 contributions in many regions and provides income and employment for an increasingly
73 large number of people. It is estimated that around 16.5 million people are involved in
74 aquaculture worldwide, with approximately 16 million of these in Asia (FAO, 2012). As well
75 as those directly involved in aquaculture production there will be many more individuals
76 whose livelihoods are at least partially connected to the aquaculture sector via the supply of
77 goods and services such as: transportation, ice making, feed production and marketing.
78 Overall, it is estimated that more than 100 million people depend on aquaculture for a
79 living, either as employees in the production and support sectors or as their dependants
80 (FAO, 2012).

81 There is now a very strong consensus that the earth has experienced a significant warming
82 trend during the 20th century, especially the second half, and continuing to the present
83 time with an average global temperature increase in the region of 0.72°C for the period
84 1951-2012 (IPCC, 2013). There is also strong agreement that this trend is at least partly a
85 result of human driven increases in greenhouse gas concentrations (Cook et al., 2013, IPCC,
86 2013). It is likely that we are committed to at least some further warming as a function of

87 the thermal inertia of the oceans and ice sheets (IPCC, 2013) and, as green house gas
88 concentrations continue to increase steadily, some degree of additional warming seems
89 inevitable. It is important to note that while warming is often discussed as a global average,
90 change is not evenly distributed spatially. In general there is a tendency for greater than
91 average warming over land areas with considerable variability both regionally and
92 seasonally (IPCC, 2013). While there is less agreement among the current generation of
93 climate models over precipitation regimes compared with those for temperature, patterns
94 of precipitation are also projected to change with some areas becoming dryer while others
95 become wetter (IPCC, 2013).

96 Although aquaculture systems are to varied extents managed and controlled, with the
97 possible exception of indoor recirculating systems they are dependent on local
98 environmental and climate conditions (Kapetsky, 2000). Climate related drivers of change
99 for aquaculture systems can largely be considered as: changes in temperature of inland
100 water or sea surface waters(Hanson and Peterson, 2014, Ficke et al., 2007), changes in
101 oceanographic variables such as currents and waves, changing sea levels and associated
102 inland salination (Nguyen et al., 2014), changes in solar radiation, changes in the availability
103 of fresh water(Hanson and Peterson, 2014), and changes in the frequency and / or intensity
104 of extreme events (Handisyde et al., 2006, De Silva and Soto, 2009). These changes can have
105 physiological impacts via changes in growth, development, reproduction and disease,
106 ecological impacts through changes to organic and inorganic cycles, predation, ecosystem
107 services, and operation impacts such as species selection, site selection, sea cage technology
108 etc. (Handisyde et al., 2006). Potential relationships between changing climate and
109 aquaculture are summarised in Table1.

110

111 Given the uncertainties about future development and data limitations, broad-scale
112 assessments of vulnerability to climate change often aim to rank areas by showing relative
113 differences between them in terms of vulnerability rather than trying to quantify results. As
114 well as providing useful tools for decision makers in their own right, broad assessments of
115 vulnerability may also provide useful starting points for guiding further and more detailed
116 research in specific areas. While such assessments for aquaculture are surprisingly
117 uncommon, Doubleday et al. (2013) provides an example of a regional vulnerability
118 assessment that is focused specifically on the aquaculture industry and used a two stage
119 assessment process in conjunction with a consensus of expert opinion to rank 7 aquaculture
120 species in terms of climate change-related risk for south-eastern Australia.

121 To date, there have been very few attempts to investigate the spatial component of fisheries
122 related vulnerability to climate change at the global scale. Handisyde et al. (2006) used a
123 geographic information system (GIS) to conduct an assessment for aquaculture dependant
124 livelihoods whilst also incorporating climate data at the sub-national level. Allison et al.
125 (2005) and Allison et al. (2009) used a range of indicators to rank the vulnerability of
126 national economies to climate change related impacts on capture fisheries. The current
127 assessment aims to produce an up-to-date and significantly improved spatial representation
128 of global vulnerability of aquaculture-related livelihoods using a number of focused
129 indicators in association with a GIS.

130 **Materials and methods:**

131 Vulnerability (V) of aquaculture and associated livelihoods in relation to climate change are
132 considered in the current assessment as a function of exposure to climate change (E),
133 sensitivity to climate change (S) and adaptive capacity (AC):

$$134 \quad V = f(E, S, AC)$$

135 This working method of assessing vulnerability in relation to climate change was
136 implemented in the Intergovernmental Panel on Climate Change third assessment report
137 (McCarty et al., 2001) with similar approaches being applied in a range of vulnerability
138 studies (e.g. Allison et al., 2005, Allison et al., 2009, Cooley et al., 2012, Metzger et al., 2005,
139 O'Brien et al., 2004, Schröter et al., 2005).

140 Rather than representing data at the national level using only a simple numerical index the
141 current assessment makes use of a GIS to represent and combine data spatially using a
142 series of raster grids. Along with allowing for easy visual interpretation of results and
143 intermediate stages of the vulnerability assessment, the use of gridded data within a GIS
144 also enables the combination of data that are available at varied resolutions while
145 maintaining as much detail as possible.

146 Data in the current assessment represent local conditions and are best viewed as an
147 indicator of vulnerability to direct impacts on aquaculture as a result of climate change.
148 Ways by which climate change will indirectly impact aquaculture may be subtle, complex and hard to
149 identify or quantify, operating at a range of scales from local to global. It is likely that in many cases
150 community level studies will probably be needed to unpick the pathways involved (Handisyde et
151 al., 2006). That said, given that analysis is strongly dependent on metrics of sensitivity (*per capita*
152 aquaculture production quantities and value) and adaptive capacity (with these components also
153 represented in isolation in the current study it could be suggested that the indication of nations
154 where aquaculture production is especially significant and where adaptive capacity is low may also
155 provide some indication of countries where indirect impacts may be significant and further
156 investigation may be warranted.

157

158 *Study extent and data selection*

159 The study area was global in extent with spatial data represented on a latitude-longitude
160 grid at 10 arcminute resolution (approximately 18.6km at the equator). The first priority
161 when selecting data was its availability and consistency across all areas. In practical terms
162 this limited selection to those data sets that are already available with global coverage. Such
163 data are often available at limited spatial resolution which in many cases means at the
164 national level. A second priority for data selection and the modelling process was that it
165 should be as focused as possible with a moderate number of relevant indicators. Global
166 indices of vulnerability have received criticism for lacking such focus (Füssel, 2010, Gall,
167 2007) and while use of a large number of broad ranging indicators may seem attractive in
168 terms of inclusivity and give the impression of a more 'sophisticated' modelling process, it is
169 worth considering that as the number and scope of indicators is increased their individual
170 power and focus is typically reduced. The third priority when selecting indicators of exposure
171 to climate change for the current assessment was choosing those likely to be generally
172 applicable across a broad range of aquaculture practices. In view of this indicators relating
173 to temperature, water availability and the potential impacts of extreme events were
174 considered most appropriate. While climate related changes in salinity are likely to be
175 minimal in the context of offshore mariculture, for inland culture in coastal and estuarine
176 areas changes in salinity may be important. Unfortunately, good quality data relating to
177 salinity in coastal areas is lacking at the local level let alone at the global scale and thus is
178 omitted from the current study. Changes in pH in response to increasing levels were also
179 excluded from the current study, again due to data limitations but also as it was viewed as
180 an issue for certain subsections of marine aquaculture, notably bivalve production (Gazeau

181 et al., 2007, Narita et al., 2012)), and thus more applicable to studies focusing on this sector
182 and specific locations.

183

184 Details of all data sets used in the current assessment are provided in Table 2. Countries
185 included in the current assessment were those where data were present for all indicators. In
186 practice this was dictated by the indication of any amount of production for the given
187 culture environment in the FishStat database (FishStatJ, 2013). The total number of
188 countries included for each culture environment were; 167 (freshwater), 69 (brackish), and
189 73 (marine).

190

191 Apart from projected changes for surface air temperature and precipitation, data
192 representing current conditions were used meaning that current aquaculture-related
193 vulnerabilities were assessed in relation to potential future climate changes. For more
194 specific and localised assessments of vulnerability with access to a greater range of high
195 quality data it may be possible to produce future projections for a wider range of indicators.
196 In the case of the current assessment, and notably in relation to aquaculture trends and to a
197 large extent adaptive capacity, the view was taken that attempting to extrapolate future
198 scenarios over a time period relevant to climate change is likely to introduce considerable
199 inaccuracies into the modelling process and that the use of current indicators in association
200 with future climate scenarios provides the best proxy when comparing vulnerability at a
201 broad scale (Adger and Kelly, 1999, Vincent, 2004, Allison et al., 2009).

202

203

204 *Overview of model structure*

205 The model followed a hierarchical structure where a range of indicators were combined to
206 represent the sensitivity, exposure and adaptive capacity components (described elsewhere
207 in this document as sub-models) which were then combined to indicate vulnerability (Fig 1).
208 It should be noted that not all inputs are necessarily used at any one time with the choice of
209 inputs and weightings (level of influence within the model) varying depending on the culture
210 environment being evaluated, e.g. fresh, brackish or marine. Full details of layer
211 combinations and weightings are provided in Tables 3 (freshwater aquaculture), 4 (brackish
212 water aquaculture), and 5 (marine aquaculture).

213

214 *Data standardisation*

215 In order for indicators to be combined they must be transformed to a common scoring
216 system. For the current assessment the majority of the input data sets were in the form of a
217 continuous numeric series, for example increase in temperature in degrees centigrade. All
218 data were standardised to a continuous scale from 0-1 with higher numbers representing
219 greater vulnerability, lower adaptive capacity, greater exposure, or greater sensitivity. In
220 terms of the modelling process and interpretation of results this effectively represents a
221 continuous series as opposed to a number of distinct classes. Details of how data were
222 standardised for all variables used are provided in Table 6.

223

224 *Sub-model construction*

225 *Sensitivity*

226 Sensitivity in the context of the current assessment aims to indicate the significance of
227 aquaculture to people within a country and thus how sensitive their livelihoods may be to

228 impacts on the aquaculture sector. Aquaculture production is considered on a *per capita*
229 basis so total population size of countries does not influence the analysis.

230 Two metrics are included in the sensitivity sub-model: aquaculture production quantity
231 (kilograms *per capita* excluding aquatic plants) and aquaculture production as a percentage
232 of GDP (again excluding aquatic plants). Quantity of aquaculture products *per capita* aims to
233 represent the physical size of the aquaculture sector within a country. While the type, scale,
234 and intensity of aquaculture operations will be significant it is assumed that, in general,
235 nations with a high per capita production of aquaculture products are likely to have a
236 greater percentage of their population whose livelihoods' are either directly linked to
237 aquaculture production, or indirectly linked through the supply of goods and services to the
238 industry. Viewing aquaculture production as a percentage of GDP gives an indication of
239 aquaculture's importance to the economy. Aquaculture's contribution to the economy will
240 not only be dependent on the scale of aquaculture production within a country in terms of
241 physical quantity but also on the relative value of aquaculture products being produced and
242 the overall size of the national economy. In richer countries it is likely that not only will
243 aquaculture make a smaller contribution to overall wealth, but people are more likely to
244 have economic alternatives and thus be more able to adapt to potential impacts and
245 change. This issue is further addressed within the adaptive capacity sub-model in the
246 current assessment in terms of per capita GDP.

247 National level statistics for aquatic animal production quantities (tonnes) and values (US
248 dollars) were obtained from Fisheries Department of the Food and Agriculture Organization
249 of the United Nations via the FishStat database (FishStatJ, 2013). Data were also sorted by
250 culture environment which are defined by the FAO as: freshwater, brackish or marine. For
251 both quantity and value statistics, data for the three most recent years available (2008 to

252 2010) were averaged with the aim of reducing the effect of the inter-annual fluctuation that
253 is seen, especially in countries with lower levels of production. Figures for GDP for the same
254 2008 to 2010 period were obtained from the World Bank (World_Bank, 2013) while
255 population data for the same period were obtained via the United Nations population
256 division (UN_Population, 2013).

257

258 Exposure

259 Exposure to climate change in the context of the current assessment can be viewed as the
260 relative extent of change between locations rather than an attempt to quantify actual
261 changes. Future changes in annual mean surface air temperature and precipitation are
262 considered while water balance (precipitation minus actual evaporation) is used as a proxy
263 for current water availability. Population density is also included in the exposure sub-model
264 based on the assumption that in areas with higher population densities the potential
265 impacts of climate change may be increased through mechanisms such as increased
266 requirements for resources such as water(Murray et al., 2012), and greater environmental
267 pressure e.g. through increased pollution.

268 As a proxy for future risk from such events the frequency of past climate extremes in the
269 form of cyclones, drought and flood events is used in the exposure sub-model based on the
270 assumption that any increases in the intensity or frequency of these extremes is likely to be
271 significant in areas where they are already common (Handisyde et al., 2006, Islam and Sado,
272 2000).

273 Data from an increasingly large number of climate models are now available and when
274 operating at the global scale the combined results from an ensemble of climate models
275 typically show greater skill in reproducing the spatial details of climate when compared to a

276 single model(Fordham et al., 2011, IPCC, 2007, Pierce et al., 2009, Reichler and Kim, 2008).
277 For the current assessment gridded global data for projected changes in annual mean
278 surface air temperature and precipitation levels were obtained at 2.5 degree resolution
279 using MAGICC/SCENGEN (version 5.3.v2) (Wigley, 2008). MAGICC is a software package that
280 integrates a number of coupled gas-cycle, climate and ice-melt models. It allows for the
281 exploration of projections for: average global surface air temperature, greenhouse gas
282 concentrations and average global sea level change under a wide range of green house gas
283 emission scenarios. The global average warming scenarios generated by MAGICC are fed
284 into SCENGEN where libraries of observed climate data are used along with the CMIP3
285 (Meehl et al., 2007) data base of climate model outputs generated for the IPCCs fourth
286 assessment report (IPCC, 2007) to generate spatially explicit change scenarios. The key
287 advantage of using the MAGICC/SCENGEN package in the current study is that it removes the
288 influence that differences in sensitivity between Atmosphere-Ocean General Circulation
289 Models (AOGCM) would have when constructing patterns of change.

290 While the CMIP3 ensemble of AOGCM results contains outputs from 24 models only 20 of
291 these are available for selection in SCENGEN due to the availability of necessary variables.
292 For the current assessment all 20 AOGCMS were selected in SCENGEN for the pattern
293 scaling process. The global mean warming used to drive SCENGEN was 2°C based on a year
294 1990 base point. Multiple warming scenarios were not considered relevant to the current
295 assessment as the aim is to show relative differences between global areas, rather than
296 quantify vulnerability in relation to a given amount of warming, and the spatial distribution
297 of results from SCENGEN change in a largely linear way in relation to overall mean surface
298 air temperature change.

299

300 Adaptive capacity

301 Adaptive capacity in the current assessment was based on the United Nations Human
302 Development Index (HDI) (Malik, 2013). The HDI represents a globally complete and
303 consistent data set that is based on the combination of health (life expectancy at birth),
304 education (combination of mean years of schooling and expected years of schooling) and
305 living standards (gross national income per capita). All components within the HDI are
306 transformed to a 0-1 scale before being combined by calculating the geometric mean of the
307 three components. Füssel (2010) cites Gall, (2007) who undertook an evaluation of global
308 indices in relation to social vulnerability. While generally critical of many of the indices, Gall
309 (2007) concluded that the HDI outperforms the other indices examined despite containing
310 fewer variables.

311

312 *Vulnerability assessment: model component combination and weightings*

313 Handisyde et al. (2006) conducted an evaluation of global aquaculture vulnerability to
314 climate change that incorporated spatial data and was also based on the concept that
315 vulnerability is a function of sensitivity, exposure, and adaptive capacity. The authors used
316 weighted arithmetic means to combine data and the resulting sensitivity, exposure, and
317 adaptive capacity sub-models. A similar approach was taken by Allison et al. (2009) for
318 capture fisheries although in that case all variables had equal weightings. One potential
319 drawback of averaging a large number of variables is that the power of each individual
320 variable is reduced. In terms of assessing aquaculture vulnerability using mostly national
321 level statistics, a key issue is the distinction between areas producing very little and large
322 amounts of aquaculture products on a per-capita basis. In the case of Handisyde et al.
323 (2006) some areas with little aquaculture production were indicated as vulnerable due to

324 scoring highly in terms of exposure and adaptive capacity indicators. If the aim is to evaluate
325 where any aquaculture-related livelihoods may be at risk then this is not an issue but if the
326 aim is to highlight areas where greatest overall impact on livelihoods is likely when they are
327 viewed as a whole then there are limitations.

328 In order to address the above issues in the current assessment considerable emphasis was
329 placed on the sensitivity component based on kg *per capita* production of aquatic species
330 and contribution to GDP. In practice this means that countries where aquaculture
331 production is very low are indicated as being significantly less vulnerable and in these cases
332 the sensitivity component of the model becomes much less relevant. In these cases studying
333 the outputs of the adaptive capacity and exposure sub-models in isolation can provide
334 useful insights into potential vulnerability that are not affected by overall scale of
335 aquaculture production. A further potential improvement in the current assessment when
336 compared with Handisyde et al. (2006) is the use of a continuous scale (0 to 1), rather than 5
337 discreet classes, allowing for greater differentiation between areas in terms of vulnerability
338 and its contributing components.

339 All weightings were assigned by the authors after consultation with a focus group consisting
340 of a range of experts within the Institute of Aquaculture, Stirling. Details of weightings used
341 for the freshwater, brackish water, and marine assessment are given in Tables 3 to 5. The
342 use of a geometric mean for the final combination results in very low values exerting a
343 greater influence on the final output. In practice this means that countries where
344 aquaculture production is very low are indicated as being significantly less vulnerable. This
345 approach was considered appropriate based on the assumption that higher levels of
346 aquaculture production within a region are likely to be at least partially associated with a

347 greater number of livelihoods being either directly or indirectly linked to the sector and/or
348 greater levels of dependence for both food and income.

349 Vulnerability results were aggregated in order to produce national averages and allow
350 ranking nations using the following procedures; for freshwater gridded vulnerability values
351 were averaged over the entire land area of each country. For brackish water vulnerability
352 values were a averaged over land area within 50km of the coast. For mariculture
353 vulnerability values were average over each countries coastal waters for an area extending
354 50km offshore.

355

356

357 **Results:**

358 Vulnerability assessment results for each culture environment are presented as a set of
359 raster images (Figures 2 to 4). The colour range indicates vulnerability relative to other areas
360 within the same culture environment and is not intended to be a quantitative means of
361 comparing vulnerability between culture environments. The greatest variability is seen
362 between countries due to the more strongly weighted sensitivity and adaptive capacity
363 components where data is available at the national level. Variability seen within countries
364 results from the exposure component and provides a useful indication of where the effects
365 of changing climate may be most extreme.

366

367 Additional images showing results for individual sub-models are also provided. Figures 5 to 7
368 show results of the sensitivity sub-model for the freshwater, brackish and marine
369 environments respectively and provide an indication of where aquaculture production, at any
370 scale, is recorded in FAO production statistics (FishStatJ, 2013). Figures 8 to 10 show the

371 results of the exposure sub-model for the freshwater, brackish and marine environments
372 respectively. Figure 11 shows adaptive capacity where the same values are used across all
373 three environments. Viewing the exposure and adaptive capacity components in isolation is
374 useful when considering all countries involved in aquaculture regardless of current extent.
375 This is potentially valuable when considering nations where aquaculture production is
376 currently low as a national average but where an indication of vulnerability is needed for
377 those who are involved in the sector. It may also be possible that countries where
378 aquaculture is less significant will be less able, or prepared, to invest in adapting to impacts
379 on production.

380 In terms of vulnerability related to freshwater aquaculture, Asia with its large aquaculture
381 sector features strongly with Vietnam indicated as the most vulnerable country followed by
382 Bangladesh, Laos, and China. Within the Americas Belize, Honduras, Costa Rica and Ecuador
383 appear most vulnerable. Uganda is indicated as the most vulnerable country in Africa
384 followed by Nigeria and Egypt (Fig 2). It is worth noting that while African countries are
385 ranked quite low in the overall vulnerability assessment due to relatively low levels of
386 aquaculture production many are indicated as having very low levels of adaptive capacity
387 (Fig 11).

388 For brackish water production Vietnam again has high vulnerability scores as does Ecuador.
389 Egypt with its aquaculture production within the Nile delta and Thailand with its significant
390 brackish water production of crustaceans also feature strongly (Fig. 3). When considering
391 adaptive capacity alone (Fig 11) in relation to countries currently engaged in brackish water
392 aquaculture at any level then Senegal, Ivory Coast, Tanzania and Madagascar score highly in
393 Africa as do India, Bangladesh, Cambodia and Papua New within Asia.

394

395 Norway and Chile are indicated most strongly in terms of vulnerability in relation to marine
396 aquaculture (Fig. 4). It is worth noting that in terms of *per capita* aquaculture production
397 and contribution to GDP the Faroe Islands are significantly above Norway and Chile and
398 must be considered strongly dependent on the aquaculture sector although the Faroe
399 Islands were not included in the current assessment as not all of the required data were
400 available. Within Asia, China is indicated as most vulnerable in terms of mariculture
401 production followed by Vietnam and the Philippines. Madagascar is the African country
402 indicated as most vulnerable while in the Americas Peru emerges most strongly after Chile.
403 Mozambique, Madagascar, Senegal, and Papua New Guinea stand out as countries involved
404 in mariculture that also have low levels of adaptive capacity (Fig11).

405

406 Table 7 provides a summary of averaged vulnerability scores for the top 20 most vulnerable
407 countries for each culture environment. While direct comparison of values between
408 different culture environments is not warranted due to varied data and combination
409 methods, the appearance of countries for more than one environment can be considered
410 significant. In this respect Vietnam stands out by being ranked most vulnerable in relation to
411 freshwater culture, second most vulnerable in relation to brackish water culture and fifth
412 most vulnerable for mariculture. A number of other Asian countries (China, Thailand, and
413 the Philippines) also appear in the top 20 for the three culture environments.

414

415 **Discussion:**

416 Allison et al. (2005) and Allison et al. (2009) conducted a valuable global assessment of
417 livelihood vulnerability to climate change impacts on capture fisheries using a range of
418 indicators available at the national scale that represented total fisheries production from all

419 environments i.e. inland and marine. The authors acknowledge that these different
420 environments are likely to be affected in different ways by changing climate. For example
421 changes in precipitation are likely to be relevant for inland situations while sea surface
422 temperature may be more significant for the marine environment. Allison et al. (2009) go on
423 to suggest that future studies should consider separating inland and marine fisheries.

424 Taking the above recommendation into consideration data for these environments were
425 extracted from the FAO FishStat database (FishStatJ, 2013). However, distinctions between
426 these categories are not always clear and decisions taken by those reporting on production
427 will have an influence, especially in the case of fresh and brackish water where there is a
428 continuum between the two environments. It is worth noting that the bulk of production
429 listed as taking place in brackish water is of crustaceans while for fresh water it is of
430 cyprinids suggesting that the environmental distinctions are likely giving a reasonable
431 indication of the type of aquaculture taking place in many cases. While there will be
432 situations where both inland and coastal ponds could be affected by changes in
433 temperature and precipitation leading to water quality and availability issues, the effects of
434 cyclones and associated storm surges are most likely to affect coastal regions and pose a
435 threat to brackish and marine aquaculture.

436 It is also worth noting that the accuracy of reporting of aquaculture production is likely to
437 vary between countries with both over and under reporting being a possible issue. For
438 potential future vulnerability assessments being conducted at the national, or particularly
439 sub-national level, it may be practical to pursue other data sources although errors in
440 reporting at the farm level would be difficult to address in anything other than extremely
441 detailed and localised investigations. For a global assessment, such as the current one, the

442 view is taken that aquaculture production data available via FAO FishStat (FishStatJ, 2013)
443 provides the most complete and consistent source, and can be viewed as a useful indicator.
444 Allison et al. (2009) used a single metric to assess exposure to climate change when ranking
445 vulnerability of capture fisheries based livelihoods, in the form of mean surface air
446 temperature change projected by the UK Hadley Centre climate model (HadCM3). The
447 authors accepted the limitations of this approach stating “Choosing an indicator of exposure
448 to climate change for a global analysis is fraught with constraints and assumptions” but
449 suggest that temperature change is also the most readily available and best understood
450 indicator. Handisyde et al. (2006) used a greater number of metrics to represent exposure to
451 climate change by including projected precipitation change as well as historic data for
452 extreme events in the form of floods, drought and cyclones. By representing data for
453 climate variables as a global grid rather than national averages the authors also reduced the
454 potential loss of information that is likely to occur, especially in the case of large countries.
455 The present assessment also uses multiple indicators for exposure but includes the use of
456 gridded actual evapotranspiration data as well as a larger database of recorded storms in
457 order to represent cyclone risk. Another significant improvement in the current assessment
458 compared to Handisyde et al. (2006) is the use of an ensemble of AOGCMs via the
459 MAGICC/SCENGEN application rather than from a single climate model which results in a
460 better representation of future change. This said, there is still much room for improvement
461 in terms of climate modelling especially in relation to patterns of precipitation change
462 where agreement between models tends to be less strong than seen for surface air
463 temperatures. With this in mind updating of the database and model is necessary as new
464 and improved climate projections become available.

465 The application of higher resolution gridded indicators of exposure in combination with
466 national level indicators of sensitivity and adaptive capacity raises the issue of how to
467 combine data at differing resolutions. One approach would be to represent climate change
468 data as national averages effectively removing the spatial element of the current
469 assessment beyond that of ranking at the national level. Such an approach is defensible in
470 terms of methodology and has been used in previous vulnerability assessments including
471 those investigating the vulnerability of fisheries-related livelihoods to climate change
472 (Allison et al., 2005, Allison et al., 2009). A key drawback of working at the lowest resolution
473 is that valuable information contained within the higher resolution data may be lost. This
474 can be illustrated using a hypothetical example of a large country with projected decreases
475 in precipitation over half the country while an increase is projected over the other half.
476 While these changes may be significant in terms of factors such as water availability, floods
477 and droughts, when considered as an average over the entire country they may largely
478 cancel each other out resulting in very little or no indicated change. This said, combining
479 spatial data at different resolutions is not without potential issues which have been
480 reviewed by Gotway & Young, (2002). In the context of the current study the smoothing
481 effect that accompanies the low resolution, national level data used to indicate sensitivity
482 and adaptive capacity removes the heterogeneity that will exist within countries. This
483 results in the higher resolution exposure component being combined with sensitivity and
484 adaptive capacity values that are limited to representing a national average rather than the
485 spatially variability that will exist.

486

487 Issues of multi-resolution data combination can perhaps be considered of most concern
488 when results are represented as spatially detailed maps without adequate explanation of

489 how they were derived and in which context they should be applied. In the case of the
490 current study the sensitivity and adaptive capacity components are weighted more strongly
491 than the exposure component. The result is a global indication of vulnerability where the
492 biggest differences are seen between countries with sub-national variability being relatively
493 small. While keeping the points outlined above regarding the combination of multiple
494 resolution data in mind and accepting the limitations of national level data, it is suggested
495 that the outputs from the current assessment are best viewed as a valuable global overview
496 of potential aquaculture vulnerability that primarily operates at the national scale but where
497 the inclusion of the higher resolution exposure data provides additional useful information
498 at the sub-national scale as to where physical effects of a changing climate may be felt most
499 strongly.

500 For tropical areas of central and south-east Asia where much aquaculture takes place
501 projected warming over land is in line with or only slightly above the global average with
502 greater increases projected as one extends further north into China.

503 Vietnam stands out as scoring highly for vulnerability across all three culture environments
504 as well as scoring highest in terms of freshwater aquaculture where the production of
505 catfish (*Pangasianodon hypophthalmus*, Pangasiidae) in the Mekong delta area has seen
506 substantial growth in recent years. Nguyen et al. (2014) modelled the impact of sea level
507 rise related salinity change and flood events on in the Mekong delta and suggest that some
508 areas currently involved in the production of *Pangasianodon hypophthalmus* may be
509 negatively impacted. Many of the countries indicated as vulnerable in relation to fresh and
510 brackish water production are located within the tropics where much aquaculture
511 production is derived from relatively shallow ponds, and where potential changes in
512 temperature regimes and water availability may pose risks. Higher average temperatures

513 will result in an increasing number of very hot days or heat waves when compared to
514 current conditions. This in turn may result in direct thermal stress of cultured animals
515 especially where they are near the limits of their range. While average higher temperatures
516 may not be fatal for species nearing the upper limits of their ideal temperature range they
517 may reduce profits though changes in feeding behaviour and feed intake (Hevrøy et al.,
518 2012) or bioenergetic performance and feed conversion ratios (Handisyde et al., 2006, De
519 Silva and Soto, 2009). Increased risk of disease for aquaculture species may also be an issue
520 associated with increasing temperatures in some areas (e.g. Callaway et al., 2012, De Silva
521 and Soto, 2009, Handisyde et al., 2006).

522 While the current model associates vulnerability with increasing temperatures, an approach
523 that has been adopted in previous studies (Allison et al., 2009, Handisyde et al., 2006), there
524 will also be situations where increasing temperatures enhance production of certain species
525 through mechanisms such as: improved growth rates, longer growing seasons, and
526 increased primary productivity (Bell et al., 2013, Lorentzen, 2008). In the present model
527 where the aim is to investigate non-specific climate-related vulnerability of all aquaculture,
528 it is suggested that relating temperature increase to vulnerability is still the best use of the
529 data. However for future studies with a narrower focus in geographic range and culture
530 species, there may be the opportunity to consider both positive and negative impacts on
531 aquaculture performance. This point can be further illustrated by looking at Norway, the
532 country indicated most vulnerable in the current model in terms of mariculture production
533 despite having a high level of adaptive capacity. Norway's high vulnerability score is a
534 consequence of very high per-capita production and above average increases in projected
535 ocean surface air temperature. However it has been suggested that increasing sea
536 temperature within the region may enhance growth performance and thus production,

537 especially in more northern areas (Lorentzen, 2008) although it is worth noting that the
538 analysis is based on temperature dependent growth models and does not consider other
539 potential impacts such as disease (Callaway et al., 2012).

540 The AOGCM ensemble incorporated within the MAGICC/SCENGEN package suggests a
541 general trend for increased precipitation over central Asia and China while very little change
542 or slight increases are projected for south East Asia. East Africa is expected to see increased
543 precipitation while a decrease is projected for the Mediterranean, North Africa and
544 Southern Europe. Decreases in precipitation are also projected for Central America and
545 Eastern Brazil. Decreasing water availability has the potential to negatively affect
546 aquaculture through mechanisms such as: reduced water quality leading to increased levels
547 of stress in culture organisms and potentially disease, greater competition for water use
548 from other sectors, and changes in salinity (Handisyde et al., 2006, Ross et al., 2009).

549 A general trend for reduced water availability may potentially enhance the effect of short
550 term weather extremes such as heat waves which in themselves are likely to be more
551 extreme in a climate with a higher average temperature. Both diurnal temperature
552 variability of surface water and temperature stratification in aquaculture ponds can be
553 substantial while diurnal variability is notably reduced at relatively modest depths of 80 to
554 100cm (Culberson and Piedrahita, 1996, Losordo and Piedrahita, 1991). During a series of
555 informal interviews conducted by the authors with fish and shrimp pond farmers in
556 Bangladesh (2008) it became clear that high temperature and drought were viewed as a
557 single problem with the reasoning that when water is scarce temperatures tend to be high
558 and that it is reduced water levels in ponds that allow temperature to have an impact on
559 cultured organisms as there is little chance for them to move to cooler deeper water.

560 The present assessment associates reduced water availability, in terms of precipitation
561 change and current water balance, with vulnerability for inland aquaculture. An accepted
562 limitation of the model is that these variables are considered on a per grid square basis with
563 no mechanism for lateral flow between cells and thus flow accumulation within water
564 courses. Parish et al. (2012) has argued that the use of a simple per grid cell approach to
565 water availability as opposed to more complex routed runoff models can be valid as it
566 allows use of easily available data sources, such as runoff values, taken directly from
567 AOGCMs. A similar point of view is adopted here in terms of the use of MAGICC/SCENGEN
568 where only precipitation, surface air temperature, and air pressure data are available. While
569 a significant amount of aquaculture will rely on ground and surface water that will be
570 involved in inter-cell drainage, there is also much, possibly belonging to poorer smaller scale
571 aquaculture producers, that is at least partially dependent on localised runoff and rainfall.

572 The range of indicators of exposure to climate change that were available at the global scale
573 for marine aquaculture were more limited with only ocean surface air temperature change
574 and cyclone data being used. Changes in primary productivity may also become significant,
575 and as previously highlighted in relation to increased temperatures, both positive and
576 negative consequences may result depending on area, current patterns, and local
577 ecosystems (Blanchard et al., 2012, Brown et al., 2010, Chassot et al., 2010). With this in
578 mind areas indicated as being most vulnerable in the current assessment should be viewed
579 as high priorities for more detailed investigation where it is possible that both positive and
580 negative implications for aquaculture may be found depending on the species and culture
581 system being considered. Accurate modelling of potential impacts on marine culture
582 systems may need to take place at a more localised scale using high resolution data to try to
583 account for variables such as local variations in current, temperature and primary

584 productivity. In some areas there are significant inter-annual variations associated with
585 processes such as El Niño/La Niña–Southern Oscillation which will also need to be
586 considered by extending investigations over longer time periods and / or for a range of
587 scenarios.

588 A further significant potential impact for marine aquaculture related directly to increasing
589 atmospheric carbon dioxide levels as opposed to changing climate is ocean acidification.
590 From an aquaculture perspective the most obvious threat is to growth and survival rates for
591 species forming calcareous structures such as the shells of bivalve molluscs (Gazeau et al.,
592 2007, Narita et al., 2012). Cooley et al. (2012) assessed vulnerability of nations to ocean
593 acidification impacts on mollusc production, both wild and aquacultured, based on:
594 contributions to the economy and dietary protein (sensitivity), time until a modelled
595 transient decade where water conditions are significantly altered so that current levels of
596 mollusc harvest cannot be guaranteed (exposure), and adaptive capacity. While not
597 addressed specifically in the present model, ocean acidification is a global issue where the
598 extent of impacts for aquaculture will be strongly related to culture species as well as
599 localised ecosystems and water conditions. Future research could potentially apply the
600 approach used in the current assessment but with the sensitivity component adjusted to
601 focus on species most likely to be affected by lowered pH and the exposure component
602 adjusted to indicate areas where pH is already lower.

603 With reference to all three culture environments the current study, being global in scope,
604 was significantly constrained in terms of data availability but can be considered as a strong
605 starting point for understanding the spatial distribution of aquaculture related vulnerability
606 to changing climate at the global scale. Further work within this area should certainly be
607 encouraged. The investigation of the interaction of individual climate variables with

608 aquaculture production may be valuable but is likely to be best suited to more localised
609 studies where specific aquaculture practices, species, and localised environmental
610 conditions can be considered. There is likely to be significant scope for the application of
611 spatial data when modelling climate change interactions at the national and sub-national
612 scale where a greater variety of data may exist with improved accuracy and resolution.

613 There have been a number of attempts to model aquaculture pond temperature in relation
614 to climate variables either through energy balance approaches (Cathcart & Wheaton, 1987;
615 Losordo & Piedrahita, Nath, 1996) or via regression (Wax & Pote, 1990). The refinements of
616 such approaches in combination with the application of data generated by future climate
617 modelling community is another potentially valuable research area along with efforts to
618 predict likely changes in water availability, salinity and quality for aquaculture.

619 While direct effects of climate change on aquaculture are obvious targets for investigation
620 future efforts to understand less direct interactions should also be strongly encouraged with
621 changes to feed supplies, the supply of other goods and services, and competition with
622 other users of resources such as water being possible areas of importance.

623 Finally while understanding the mechanisms and locations of aquaculture related
624 vulnerability to climate change is vitally important there will also be areas of opportunity
625 and adaptation if appropriate species and culture systems can be matched to a changing
626 pattern of environmental conditions. In this respect future modelling using spatial data
627 should be seen as especially valuable.

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632 **Conclusion:**

633 The current assessment improves on the only previous global evaluation of vulnerability of
634 aquaculture related livelihoods to climate change (Handisyde et al., 2006). A notable
635 advancement is the application of a more sophisticated set of climate change projections in
636 the form of a multi-model ensemble of data obtained using the MAGICC/SCENGEN package.
637 Improvements are also made in along with changes in data processing via the use of a
638 geometric rather than arithmetic mean to reduce the likelihood of countries with very small
639 aquaculture sectors (low sensitivity) being considered as highly vulnerable in situations
640 where metrics for exposure and adaptive capacity scored highly. To complement this
641 approach the impacts of exposure and adaptive capacity were also considered in isolation to
642 provide insight into where vulnerability may exist irrespective of national aquaculture
643 industry size. Such a view may be especially useful when considering areas with emerging
644 aquaculture industries that may be expected to develop significantly in the future.

645 Due to their substantial aquaculture industries a number of Asian countries, Vietnam, Laos,
646 Bangladesh, and to a lesser extent China, were considered most vulnerable to impacts on
647 freshwater aquaculture production. Vietnam along with Ecuador was also considered highly
648 vulnerable in terms of brackish water production. Norwegian mariculture was indicated as
649 most vulnerable to climate change despite being one of the world's most highly developed
650 countries. Chile, another nation with relatively high levels of development also scored
651 highly. The results in the case of Norway and Chile were influenced by the extremely high
652 *per capita* levels of production compared with other nations. Other notable areas with
653 indicated mariculture vulnerability include: China, Vietnam, the Philippines, Thailand,

654 Greece, and Madagascar. Vietnam is notable in achieving high vulnerability scores across all
655 three culture environments.

656 To date the potential interactions of changing climate with the aquaculture sector have
657 been significantly under-researched. The current assessment provides a highly valuable
658 indication of where aquaculture related vulnerability to climate change may occur and
659 where further research is likely warranted. There would appear to be significant scope for
660 further investigation at a more localised level where specific aquaculture practices and
661 environmental conditions can be considered. While gaining an understanding of potential
662 negative impact is certainly important, focused regional studies should also aim to evaluate
663 potential positive impacts of changing climate on specific aquaculture practices. Such an
664 approach would be valuable in guiding future development and adaptation within the
665 sector.

666

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839

840 **Tables:**

841 Table 1. Potential impacts of climate change on aquaculture systems(farmed species and
842 surrounding ecosystems) and production. (Adapted from: Handisyde et al., 2006).

Drivers of change	Impacts on culture systems, both positive (+) and negative (-). Likely pathway: ^d = direct impacts, ⁱ = indirect impacts, ^{di} = both direct and indirect impacts.	Operational impacts, both positive (+) and negative (-).
Sea surfacetemperature changes	<ul style="list-style-type: none"> • Increase in harmful algal blooms that release toxins in the water and produce fish kills (-)^d • Decreased dissolved oxygen (-)^d • Increased incidents of disease and parasites (-)^d • Enhanced growing seasons (+)^d • Change in the location and/or size of the suitable range for a given species (- or +)^d • Lower natural winter mortality (+)^d • Enhanced growth rates and feed conversions (metabolic rate) (+)^d • Enhanced primary productivity (photosynthetic activity) to benefit production of filter-feeders (+)^d • Altered local ecosystems - competitors and predators (- or +)^{di} • Competition, parasitism and predation from exotic and invasive species (-)^{di} • Damage to coral reefs that may have helped protect shore from wave action – may combine with sea level rise to further increase exposure (-)ⁱ 	<ul style="list-style-type: none"> • Changes in infrastructure and operation costs (- or +) • Increased infestation of fouling organisms, pests, nuisance species and/or predators (-) • Expanded geographic distribution and range of aquatic species for culture (+) • Changes in production levels (- or +) • Increased chance of damage to infrastructure from waves or flooding of inland coastal areas due to storm surges where protective reefs have been damaged by increasing sea surface temperatures (-)
Change in other oceanographic variables (variations in wind velocity, currents and wave action)	<ul style="list-style-type: none"> • Changes in flushing rate that can affect food availability to shellfish (- or +)^d • Alterations in water exchanges and waste dispersal (- or +)^d • Change in abundance and/or range of capture fishery species used in the production of fishmeal and fish oil (- or + most likely -)ⁱ 	<ul style="list-style-type: none"> • Changes in rate of accumulation of waste under pens (- or +) • Changes in operational costs (- or +)
Sea level rise	<ul style="list-style-type: none"> • Loss of areas available for aquaculture (-)^d • Loss of areas such as mangroves that may provide protection from 	<ul style="list-style-type: none"> • Damage to infrastructure (-) • Changes in aquaculture zoning (most likely -) • Competition for space with

<p>Increase in frequency and/or intensity of storms</p>	<p>waves/surges and act as nursery areas that supply aquaculture seed (-)ⁱ</p> <ul style="list-style-type: none"> • Sea level rise combined with storm surges may create more severe flooding (-)^d • Salt intrusion into ground water^d • Large waves (-)^d • Storm surges (-)^d • Flooding from intense precipitation (-)^d • Structural damage (-)^d • Salinity changes (- or +)^d • Introduction of disease or predators during flood episodes (-)^d 	<p>ecosystems providing costal defence services (i.e. mangroves) (-)</p> <ul style="list-style-type: none"> • Increased insurance costs (-) • Reduced freshwater availability (-) • Loss of stock (-) • Damage to facilities (-) • Higher capital costs, need to design cages moorings, jetties etc. that can withstand events (-) • Negative effect on pond walls and defences (-) • Increased insurance costs (-)
<p>Higher inland water temperatures (Possible causes: changes in air temperature, intensity of solar radiation and wind speed)</p>	<ul style="list-style-type: none"> • Reduced water quality especially in terms of dissolved oxygen (-)^d • Increased incidents of disease and parasites (-)^d • Enhanced primary productivity may benefit production (+)^d • Change in the location and/or size of the suitable range for a given species (- or +)^d • Increased metabolic rate leading to increased feeding rate, improved food conversion ratio and growth provided water quality and dissolved oxygen levels are adequate otherwise feeding and growth performance may be reduced (- or +)^d 	<ul style="list-style-type: none"> • Changes in level of production (- or +) • Changes in operating costs (- or +) • Increase in capital costs e.g. aeration, deeper ponds (-) • Change of culture species (- or +)
<p>Floods due to changes in precipitation (intensity, frequency, seasonality, variability)</p>	<ul style="list-style-type: none"> • Salinity changes (-)^d • Introduction of disease or predators (-)^d • Structural damage (-)^d • Escape of stock (-)^d 	<ul style="list-style-type: none"> • Loss of stock (-) • Damage to facilities (-) • Higher capital costs involved in engineering flood resistance (-) • Higher insurance costs (-)
<p>Drought (as an extreme event, as opposed to a gradual reduction in water availability)</p>	<ul style="list-style-type: none"> • Salinity changes (-)^d • Reduced water quality (-)^d • Limited water volume (-)^d 	<ul style="list-style-type: none"> • Loss of stock (-) • Loss of opportunity – limited production (probably hard to insure against) (-)
<p>Water stress (as a gradual reduction in water availability due to increasing evaporation rates)</p>	<ul style="list-style-type: none"> • Decrease water quality leading to increased diseases (-)^d • Reduce pond levels (-)^d • Altered and reduced freshwater supplies – greater risk of impact by drought if operating close to 	<ul style="list-style-type: none"> • Costs of maintaining pond levels artificially (-) • Conflict with other water user • Loss of stock (-) • Reduced production capacity • Increased per unit production

and decreasing
rainfall)

the limit in terms of water supply
(-)^d

costs (-)
• Change of culture species (- or +
likely -)

843

844 Table 2. Data used to model the spatial distribution of vulnerability of aquaculture to the
845 effects of climate change at the global scale.

846

Variable (units)	Data format (original resolution)	Source (reference)
Aquaculture production quantities (tonnes)	National level production statistics	FAO FishstatJ (FishStatJ, 2013)
Aquaculture production value (USD)	National level production statistics	FAO FishstatJ (FishStatJ, 2013)
Population density (persons per km ²)	Raster grid (30 arcseconds)	LandScan 2008 data (Oak_Ridge_National_Laboratory, 2008)
Actual evapotranspiration (mm per year)	Raster grid (30 arcminutes)	(Fisher et al., 2008)
Precipitation (mm per year)	Raster grid (10 arcminutes)	CRU CL2 (New et al., 2002)
Projected change in local surface air temperatures under global warming(°C)	Raster grid (2.5 degrees)	MAGICC/SCENGEN version 5.3 (Wigley, 2008)
Projected change in local precipitation under globalwarming (percent)	Raster grid (2.5 degrees)	MAGICC/SCENGEN version 5.3 (Wigley, 2008)
Flood frequency based on historic data	Vector Polygon (sub national resolution)	Aqueduct Global Maps 2.0 (Gassert et al., 2013)
Drought frequency based on historic data	Vector Polygon (sub national resolution)	Aqueduct Global Maps 2.0 (Gassert et al., 2013)
Cyclone frequency based on historic data	Vector line	International Best Track Archive for Climate Stewardship (IBTrACS) (Knapp et al., 2010)
Human development index (HDI)	Online database (national)	HDI 2012 (Malik, 2013)
Country borders polygons	Vector Polygon	TM_WORLD_BORDERS-0.3 (thematicmapping.org, 2013)
Marine Exclusive EconomicZones (EEZ) polygons	Vector Polygon	World EEZ v7 (Marine_Regions, 2013)

National population estimates (total population)	Data table	United Nations Population Division (UN_Population, 2013)
National GDP estimates (USD)	Data table	World Bank GDP data (World_Bank, 2013)

847

848 Table 3. Weightings used for combining indicators in the vulnerability assessment for
849 freshwater aquaculture systems.

850

Inputs	Weight (arithmetic mean)	Sub-model	Weight (arithmetic mean)	Sub-model	Geometric mean	Output
Temperature change	0.175					
Water balance	0.175					
Population density	0.175					
Precipitation change	0.175	Exposure sub-model	0.333			
Flood risk	0.125					
Drought risk	0.125					→
Cyclone risk	0.05					
						Exposure and adaptive capacity sub-model
Human development index	→	Adaptive capacity sub-model	0.666			Vulnerability
Aquaculture production (kg per capita)	0.666					
Aquaculture value (percent GDP)	0.333	→	→	Sensitivity sub-model	→	

851

852

853 Table 4. Weightings used for combining indicators in the vulnerability assessment for
 854 brackish water aquaculture systems.

855

Inputs	Weight (arithmetic mean)	Sub-model	Weight (arithmetic mean)	Sub-model	Geometric mean	Output
Temperature change	0.175					
Water balance	0.175					
Population density	0.175	Exposure sub-model	0.333			
Precipitation change	0.175					
Flood risk	0.05					
Drought risk	0.05					→
Cyclone risk	0.2					
Human development index	→	Adaptive capacity sub- model	0.666			Vulnerability
Aquaculture production (kg per capita)	0.666					
Aquaculture value (percent GDP)	0.333	→	→	Sensitivity sub-model	→	

856

857

858 Table 5. Weightings used for combining indicators in the vulnerability assessment for marine
 859 aquaculture systems.

860

Inputs	Weight (arithmetic mean)	Sub-model	Weight (arithmetic mean)	Sub-model	Geometric mean	Output
Temperature change	0.6	Exposure sub-model	0.333	Exposure and adaptive capacity sub-model	→	Vulnerability
Cyclone risk	0.4					
Human development index	→	Adaptive capacity sub-model	0.666			
Aquaculture production (kg per capita)	0.666	→	→	Sensitivity sub-model	→	
Aquaculture value (percent GDP)	0.333					

861

862 Table 6. Details of data standardisation to a common 0 – 1 scoring system.

863

Variable	Standardisation details
Aquaculture production quantity (kg per capita)	Aquaculture production data were standardised to values ranging from 0 to 1 using a linear relationship where 0 represents areas with no aquaculture production and 1 equates to the area with highest production. The one exception was for mariculture where the Faroe islands which are the largest per capita producers of mariculture products were excluded as complete data needed for other areas of the model were not available.
Aquaculture production value (percentage of GDP)	As above
Human Development Index (HDI)	All values were standardised over the range 0 to 1 using an inverse linear relationship so that the country with the lowest HDI value receives a new value of 1 and the one with the highest HDI value receives a new value of 0.
Population density	Population density data were standardised using a linear relationship so that areas averaging more than 1000 people per square km were given a value of 1 and areas indicated as having no population were given a value of 0.
Projected temperature change	Temperature change data were standardised to values ranging from 0 to 1 based on a linear relationship between 3 standard deviations below and above the mean increase. For the fresh and brackish water models the mean value was derived from all land areas between 60°S and 60°N. For the marine model the average increase was obtained using a 20km buffer around all land areas between 60°S and 60°N. The 60° north and southcut off was applied to exclude high latitude areas that are projected to warm significantly more than other areas but are generally insignificant in aquaculture terms.
Projected precipitation change	Projected precipitation change data were standardised to values ranging from 0 to 1 based on a linear relationship between 3 standard deviations above and below the mean value that was calculated over all land areas used in the assessment. This results in areas with the greatest projected decrease in precipitation being given the highest score and thus making the greatest contribution to vulnerability.

Cyclone risk	International Best Track Archive for Climate Stewardship (IBTrACS) data describing the number of cyclones that have occurred in a given area over the last 40 years were standardised to values ranging from 0 to 1 using a linear relationship with a value of 0 being assigned to areas with no recorded cyclones and 1 being assigned to the area with the highest number of recorded cyclones.
Flood risk	The Aqueduct Global Maps 2.0 flood occurrence data were already scaled from 0 to 5 with 5 representing areas with highest occurrence of flood events. The data were rescaled using a linear relationship over the range 0 to 1.
Drought risk	The Aqueduct Global Maps 2.0 drought occurrence data were already scaled from 0 to 5 with 5 representing areas with highest occurrence of drought events. The data were rescaled using a linear relationship over the range 0 to 1.
Water balance	Water balance was calculated as precipitation minus actual evaporation. Water balance values were standardised using a linear relationship so that areas with a water balance of 0mm per year receive a score of 1 while areas with 1000mm or more per year received a value of 0.

864

865

866 Table 7. Average vulnerability values (highest to lowest) for the top 20 most vulnerable
 867 countries in relation to the freshwater, brackish and marine environments. Vulnerability
 868 values obtained via the combination of the sensitivity, exposure and adaptive capacity sub-
 869 model outputs.

870

Freshwater ¹		Brackish ²		Marine ³	
Vietnam**	0.690	Ecuador	0.558	Norway	0.307
Lao People's Democratic Republic	0.561	Vietnam**	0.557	Chile	0.273
Bangladesh*	0.544	Belize*	0.524	China**	0.160
Myanmar	0.514	Egypt	0.483	Madagascar	0.156
China**	0.504	Taiwan*	0.460	Vietnam**	0.123
Taiwan*	0.404	Thailand**	0.457	Malta	0.112
Uganda	0.342	Nicaragua	0.358	Peru	0.111
Cambodia	0.334	Philippines**	0.332	Philippines**	0.096
Thailand**	0.322	Honduras*	0.325	Greece	0.095
India	0.293	Indonesia*	0.308	Korea, Republic of	0.095
Indonesia*	0.268	Iceland*	0.265	Seychelles	0.090
Belize*	0.253	Malaysia*	0.241	New Zealand	0.085
Honduras*	0.241	Guatemala	0.222	Thailand**	0.077
Philippines**	0.239	Bangladesh**	0.207	Croatia	0.069
Costa Rica*	0.224	Panama	0.171	Japan	0.069
Nepal	0.213	Finland	0.142	Cyprus	0.068
Malaysia*	0.213	Costa Rica*	0.125	Turkey	0.066
Republic of Moldova	0.206	China**	0.111	Iceland*	0.064
Nigeria	0.199	Guam	0.109	Canada	0.063
Iran	0.195	Brunei Darussalam	0.103	Mozambique	0.061

871

872 ¹For freshwater gridded vulnerability values were averaged over the entire land area of each
 873 country.

874 ²For brackish water vulnerability values were a averaged over land area within 50km of the
 875 coast.

876 ³For mariculture vulnerability values were average over each countries coastal waters for an
 877 area extending 50km offshore.

878 ** = countries appearing in the top 20 for all three culture environments.

879 * = countries appearing in the top twenty for two of the three culture environments.

880 **Figure Legends:**

881

882 Figure 1. Schematic representation of vulnerability model applied in the assessment of the
883 effects of climate change on aquaculture at the global scale.

884 Figure 2. Global vulnerability of aquaculture to climate change in freshwater systems based
885 on exposure, adaptive capacity and sensitivity.

886 Figure 3. Global vulnerability of aquaculture to climate change in Brackishwater systems
887 based on exposure, adaptive capacity and sensitivity.

888 Figure 4. Global vulnerability of aquaculture to climate change in marine systems based on
889 exposure, adaptive capacity and sensitivity.

890 Figure 5. Results of sensitivity sub-model for freshwater systems.

891 Figure 6. Results of sensitivity sub-model for brackish water systems.

892 Figure 7. Results of sensitivity sub-model for marine systems.

893 Figure 8. Results of exposure sub-model for freshwater systems.

894 Figure 9. Results of exposure sub-model for brackish water systems.

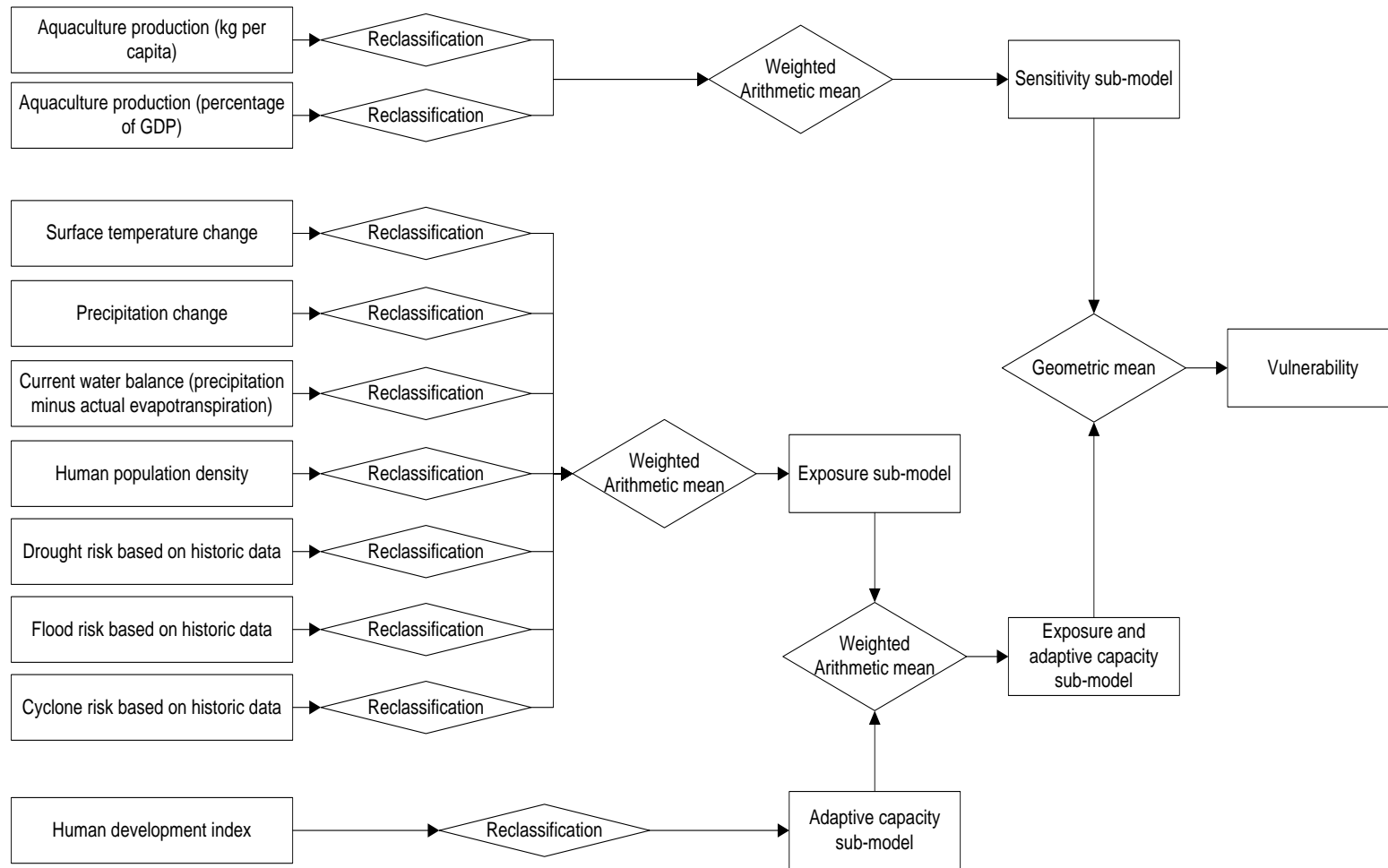
895 Figure 10. Results of exposure sub-model for marine systems.

896 Figure 11. Results of adaptive capacity sub-model - used for freshwater, brackish and marine
897 systems.

898 **Figures:**

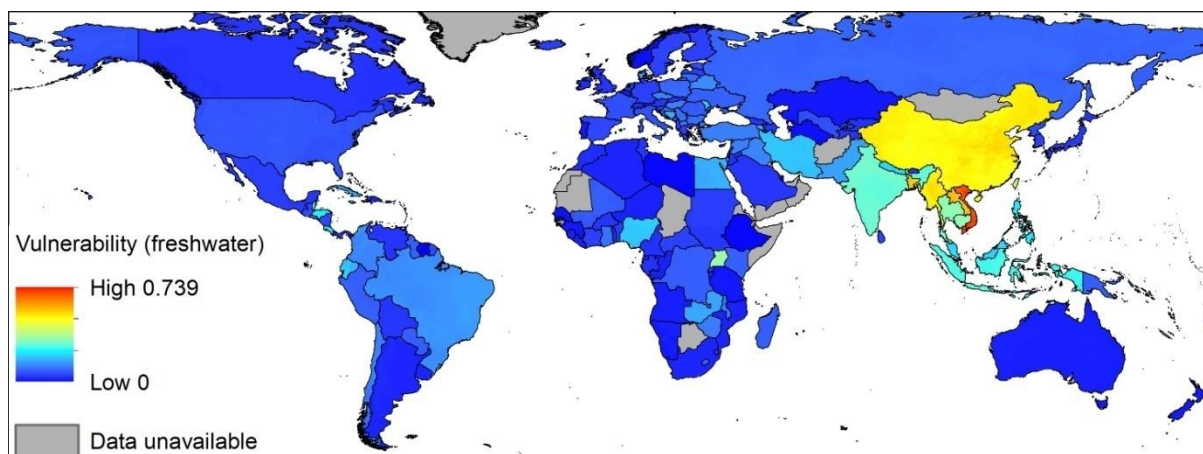
899 Fig. 1.

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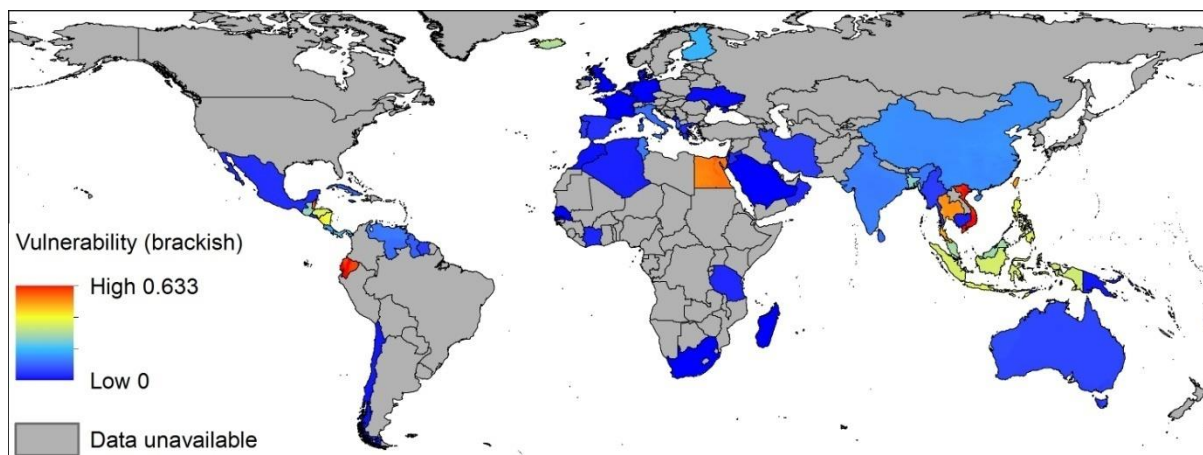
902 Fig.2.



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904

905 Fig. 3.



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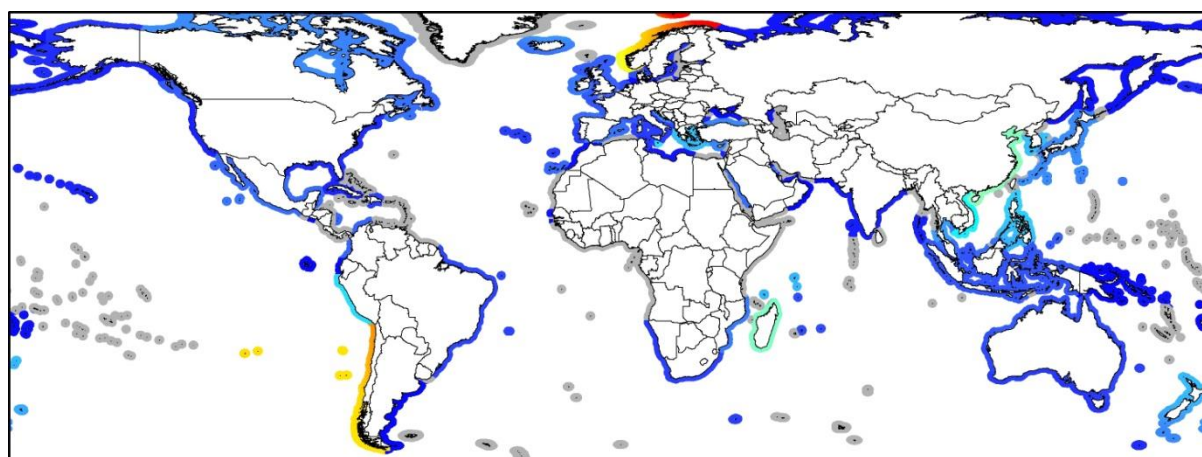
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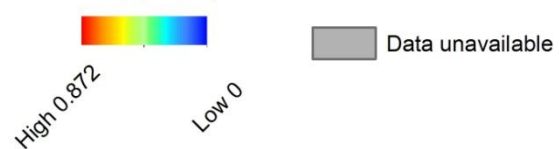
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911 Fig. 4.



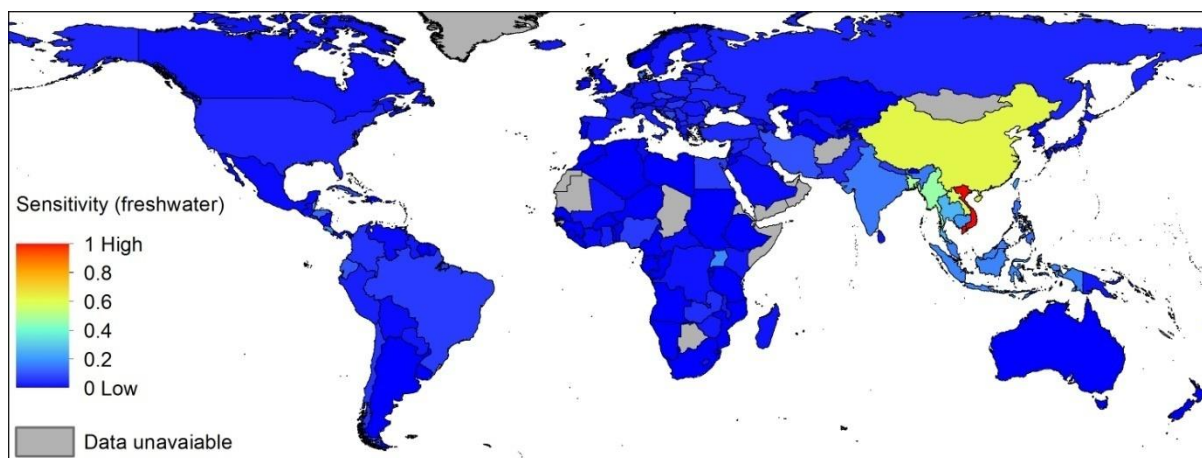
Vulnerability (marine)



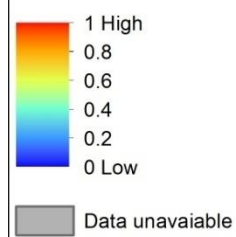
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914 Fig. 5.



Sensitivity (freshwater)



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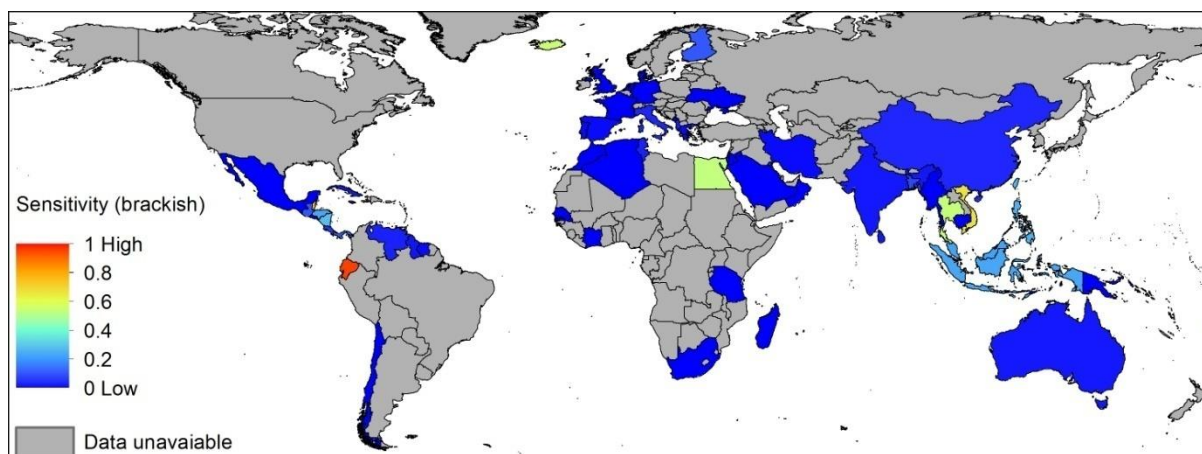
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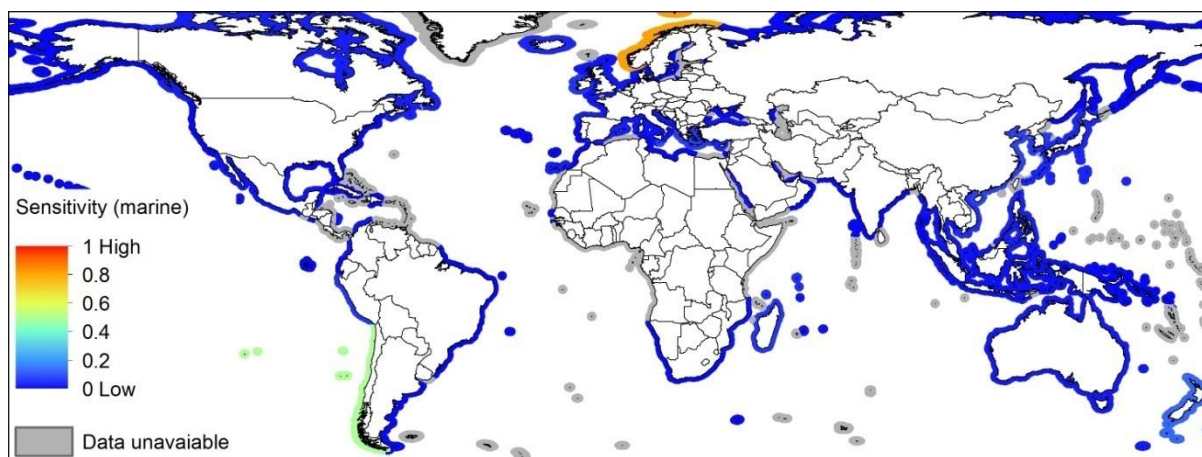
923 Fig. 6.



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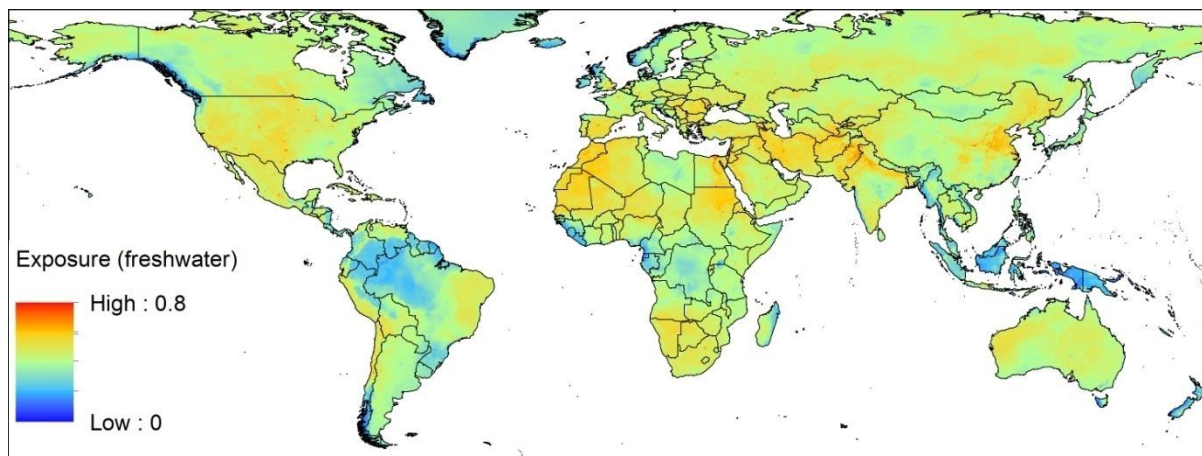
926 Fig. 7.



927

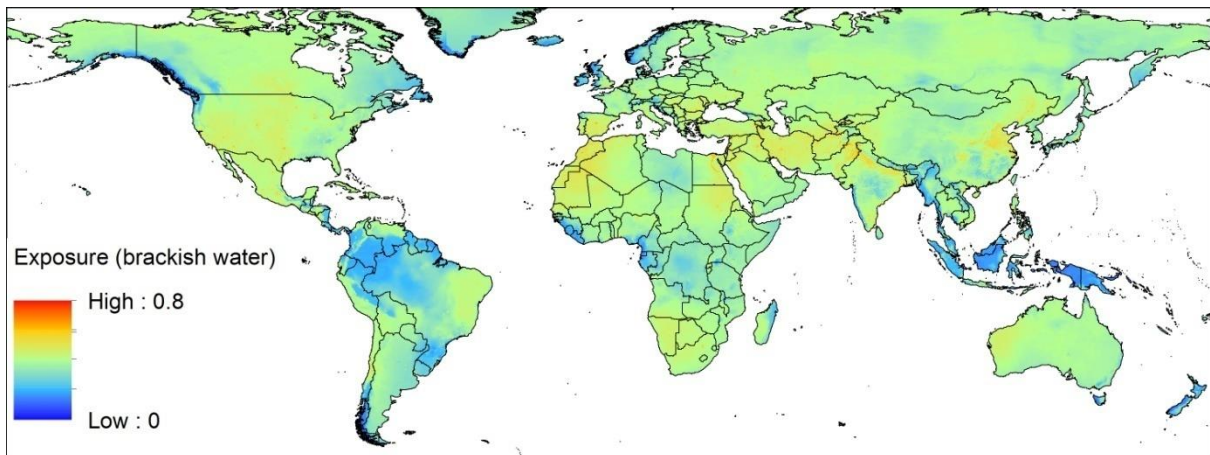
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929 Fig. 8.



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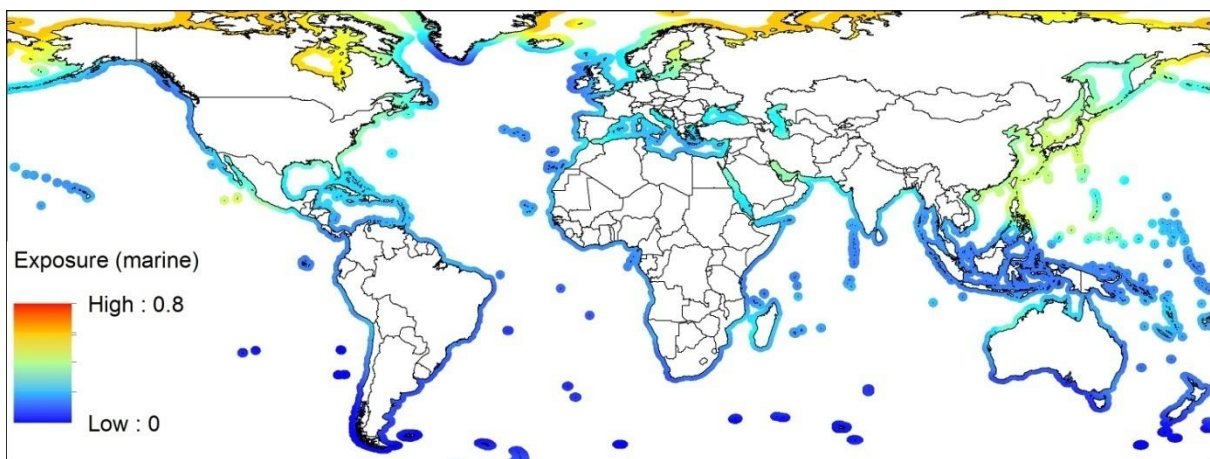
931 Fig. 9.



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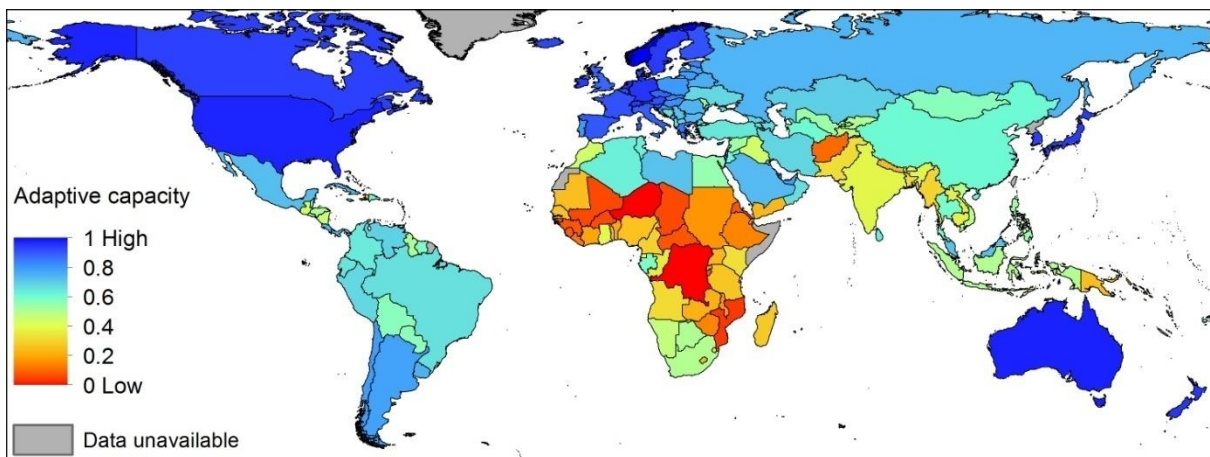
934 Fig. 10.



935

936

937 Fig. 11.



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