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The impact of climate change on existing and emerging microbial threats across the food chain: an island of Ireland perspective

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24 **Abstract**

25 The Agri-Food and aquaculture industries are vital to the economy of the island of
26 Ireland with a gross annual output that is expected to double in the future.

27 Identifying and understanding the potential influences of the anticipated climate
28 variables on microorganisms that cause foodborne diseases, and their impact on
29 these local industries, are essential. Investigating and monitoring foodborne
30 pathogens and factors that influence their growth, transmission, pathogenesis and
31 survival will facilitate assessment of the stability, security and vulnerability of the
32 continuously evolving and increasing complex local food supply chain.

33 **Introduction**

34 Climate change in the 21st century is a global phenomenon and although it is a
35 worldwide recognised issue its effects vary by geographic location making regional
36 studies of potential impact of high importance. In general, weather conditions have
37 become more variable with extreme weather events increasing in regularity and
38 intensity (IPCC5, 2013). The consequences of climate change have been described
39 as an increase in temperature, unusual regional weather patterns, more severe
40 storms, heat waves, rising sea levels, thawing permafrost, more frequent droughts,
41 acidification of oceans, change in nutrient loads, and altered ocean circulation
42 (Solomon et al., 2007; Miraglia et al., 2009).

43 The archetypical mild climate and rich soil has contributed to the agri-food industry
44 becoming the largest indigenous industry on the island of Ireland (IoI), playing a vital
45 role in the local economy, environment and society. As such it is essential to
46 understand what impacts changes in physical processes and other climate variables
47 may have on the stability and security of the local food supply. Local climatic
48 conditions influence local vegetation and so, as the climate changes, growing
49 seasons may change and biological consequences will be inevitable with variations
50 in the crops that are cultivated and animals farmed. This could lead to changes in
51 plant and animal epidemiology and transformations in entire ecosystems (Lennon,
52 2014). Extinctions and invasions into new territories will influence these changes
53 and the outcomes will be unpredictable and dependent on the resistance and
54 resilience of organisms and the environment, resulting in numerous factors which will
55 influence the emergence of new and/or the re-emergence or exacerbation of existing

56 foodborne pathogens. A equilibrium must be achieved between minimising food
57 safety risks to consumers while contributing to the production of enough food to
58 satisfy a global population that is expected to reach nine billion by the year 2050
59 (Royal Society, 2009; Godfray et al., 2010). Achieving this balance will be
60 challenging in a world of increased competition for depleting resources coupled with
61 the inability of the environment to cope with increasing anthropogenic influences and
62 climate change (Vermeulen et al., 2012).

63 Many systems are in place, particularly in Europe, to safeguard food safety along the
64 production chain, however, numerous influences both inside and outside the chain,
65 such as human behaviour, trade, climate, regulation and technology, may directly or
66 indirectly influence the emergence and development of foodborne hazards (Marvin et
67 al., 2009). The susceptibility of the complex, modern food production systems to
68 microbiological agents is evident from the large number of food safety incidents
69 reported (Westrell et al., 2009; Scallan et al., 2011, EFSA/ECDC 2015) and, in the
70 future, as demographics shift the number of people at risk from foodborne illness
71 may increase (Gamble et al., 2013). In the USA the economic burden of foodborne
72 illness has been estimated to be \$14 billion/year (Batz et al., 2012) and when the
73 etiological agents of foodborne outbreaks have been identified, bacteria have been
74 found to be responsible for 39%, viruses 59% and parasites 2% of the outbreaks
75 with the majority of the economic cost associated with five pathogens: *Salmonella*
76 *sp*, *Campylobacter sp*, *Listeria monocytogenes*, *Toxoplasma gondii* and norovirus
77 (Scallan et al., 2011) with *Salmonella* being the most commonly reported bacterial
78 pathogen. In England and Wales the economic burden in 2006 was estimated to be
79 £1.5 billion (FAO, 2008) with *Campylobacter sp*. being the most common bacterial
80 cause of food poisoning (EFSA/ECDC 2015).

81 In response to global warming the seasonality and geographic range of foodborne
82 disease pathogens is expected to expand and additional foodborne outbreaks are
83 expected to occur as a results of extreme weather events. Correlations between
84 meteorological parameters and the behaviour of foodborne pathogens have been
85 made (Rose et al., 2001) and these can be used as a basis to speculate on the
86 potential impact of climate change on future patterns at a more local level. This
87 review considers the climate change predicted for the lol and investigates possible
88 pertinent microbiological food safety issues that are likely to be impacted by these

89 changes with the aim of improving our understanding and ability to control the
90 identified microbiological hazards. The review deliberates the potential impact of
91 climate change on foodborne pathogens associated with two economically important
92 sectors in Ireland, poultry and seafood. Campylobacteriosis is associated with the
93 poultry industry and is the most commonly reported foodborne illness in Ireland and
94 so the potential impact of climate change on this warrants further investigation. If
95 climate change predictions manifest then *Vibrio vulnificus*, could emerge as a
96 potential threat to the lucrative Irish shellfish industry. Also discussed is the potential
97 impact on waterborne pathogens and transmission of pathogens along the food
98 chain. Effective food safety management requires an understanding of the
99 microbiological hazards and how their presence in foods can be prevented or
100 maintained within tolerable levels. Areas of concern such as incomplete data on the
101 pathogen epidemiology, poor understanding of mechanisms of disease and
102 immunity, and gaps in our knowledge of virulence, survival and transmission
103 mechanisms of the selected foodborne pathogens are highlighted. Steps are
104 recommended to ameliorate these impacts and opportunities for future research
105 highlighted to enable more effective and efficient prevention, detection and control of
106 local foodborne illnesses.

107 **Local Climate Change Predictions**

108 Changes to the climate on the lol are in general expected to be similar with those
109 being experienced in the global context with summers becoming warmer and drier,
110 heavier rainfalls in winter and more extreme events such as storms and floods. The
111 impacts of gradual changes such as increasing temperature and precipitation are
112 more predictable than the impacts of the more damaging extreme events. Regional
113 climate model predictions published by the Environmental Protection Agency (Dunne
114 et al., 2008) have indicated that by the year 2050 the annual precipitation will remain
115 relatively unchanged; however, more rain is predicted for the winter months and less
116 in the summer months. The temperature is predicted to increase by 1.5°C during
117 January and 2.5°C during July, and summer rainfall is expected to be reduced by 25-
118 40% with winter rainfall anticipated to increase by 10-25%. These changes are not
119 expected to be uniform across the lol resulting in regional differences. The greatest
120 temperature increase is predicted for South-east and East of Ireland whereas the
121 West of the country is more likely to experience increased flooding. It is expected

122 that the more temperate winter conditions currently experienced on the south coast
123 of Ireland will move northwards, which may influence the availability and quality of
124 water putting pressure on water supply infrastructures. Water resource management
125 may become an issue with increased flooding interlinked with periods of drought.
126 Longer term projections indicate a rise in sea levels as the rising global temperature
127 results in ice-cap melting and possible thermal expansion of oceans. The warmer
128 sea water and effects of coastal erosion may disrupt ecosystems, influence
129 biodiversity and introduce new potential microbiological threats.

130 **Potential Impacts of Climate Change on foodborne microorganisms**

131 *Direct impact on pathogens.* The microflora of food comprises microorganisms
132 associated with raw materials, those acquired during handling and processing and
133 those surviving preservation and storage. Climatic conditions will determine the
134 establishment and growth of a microorganism and climate can impact on each of the
135 three sectors of the classic epidemiologic triangle, the host, the organism, and the
136 environment. The potential impacts of climate change on foodborne and waterborne
137 diseases is evidenced by (i) the changing patterns of disease when temperatures
138 vary, with higher temperatures increasing the risk of bacterial contamination of food
139 and water (Lake et al. 2009); (ii) the historical links between extreme weather events
140 and increased occurrence of food and waterborne disease (Hall et al., 2002); and (iii)
141 the fact that many foodborne and diarrhoeal diseases are seasonal (Rose et al.,
142 2001; Hall et al., 2002; Koelle et al., 2005).

143 Bacterial pathogens found in food are ubiquitous and can adapt not only to persist
144 but to proliferate in the environment. Spread of these pathogens is reliant on their
145 capability to survive (FAO, 2008), and meteorological factors such as temperature
146 and humidity will influence the growth and survival and therefore the distribution of
147 foodborne pathogens, as well as the emergence of new pathogens or the number of
148 outbreaks of known pathogens (D'Souza et al., 2004; Kovats et al., 2004; Ukuku and
149 Sapers, 2007; Lake et al., 2009; Miraglia et al., 2009; Tirado et al., 2010). Climate
150 change will have the most impact on pathogens such as *Campylobacter* sp and
151 Enterohaemorrhagic *E. coli* which have low-infective doses, can survive in the
152 environment, and can adapt well to stress factors such as temperature and pH (FAO,
153 2008). The survival rates of many enteric pathogens such as *Salmonella*,

154 *Campylobacter* and *E coli* O157 have been linked to temperature (Hall et al., 2002;
155 Lake et al., 2009) with temperature having the most noticeable effect on
156 salmonellosis, where 30% of reported cases have been attributed to warm
157 temperatures. For each degree increase in weekly temperature above 5°C a 5-10%
158 increase in the number of notifications of salmonellosis has been detected (Bentham
159 and Langford, 1995; D'Souza et al., 2004; Kovats et al., 2004). Although some of this
160 increase can be attributed to increased rate of food spoilage and some to changes in
161 human social behaviours, such as camping, barbeques and picnics, which are
162 connected with a higher risk of foodborne illness; some of this seasonal increase is
163 directly associated with the rise in temperature. Studies have indicated that the
164 incidence of foodborne disease can be linked to temperatures in the month previous
165 to the onset of illness (Bentham and Langford, 1995) and some diseases have been
166 found to be distinctly seasonal (Naumova et al., 2007; Koelle et al., 2005). As higher
167 ambient temperatures and temperature spikes associated with extreme weather
168 events could increase both the prevalence of specific pathogenic organisms in
169 animals and the replication cycles of foodborne pathogens leading to a higher
170 degree of contamination (Kendrovski and Gjorgjev, 2012) it is important to determine
171 the epidemiology of infectious diseases and to explore what effect climate change
172 may have on disease patterns and pathogen survival and transmission (McMichael
173 et al., 2004).

174 *Indirect impacts on pathogens (a) environmental factors.* The sources of foodborne
175 infections can be infected animals, food directly contaminated by human or animal
176 faecal matter, or food contaminated indirectly by the use of contaminated water for
177 irrigation or washing purposes (Rose et al., 2001; Wachtel et al., 2002; Hall et al.,
178 2002; Nichols et al., 2009). The impacts of global climate change on food systems
179 are expected to be extensive and complex and influenced by geography and
180 socioeconomic conditions (Schmidhuber and Tubiello, 2007). It is anticipated that an
181 altered climate will result in the production of food under different environmental
182 conditions and adaptation to and mitigation against climate change leading to the
183 introduction of alternative crops and livestock species adapted to survive in these
184 different environments (Nichols and Lake, 2012; Lake et al., 2012). Analyses of
185 epidemiological data indicate a relationship between certain pathogens and
186 environmental conditions for example, an increase in the frequency and severity of

187 extreme rainfall and flooding influences the distribution and transmission of many
188 diarrhoeal diseases in humans (Ahern et al., 2005), and changing the topography or
189 use of land has been found also to influence the emergence or resurgence of
190 numerous infectious and vector borne diseases (Patz et al., 2008). Historical studies
191 and climate assessment models suggest that climate change is expected to impact
192 on agriculture, prices, delivery, quality and safety of food (Vermeulen et al., 2012;
193 Lake et al., 2012). Globalisation of the world's food supply has already changed
194 patterns of food consumption and climate change is expected to lead to shifting food
195 belts resulting in a broad, worldwide selection of foods for consumers. However,
196 global sourcing minimises geographic barriers to traditional, emerging and re-
197 emerging pathogens exacerbating their spread and resulting in an increase in
198 foodborne illnesses as growing conditions and food safety management practises
199 may be different at source (Adak et al., 2005). In addition, as technologies such as
200 next generation sequencing, DNA microarray, PCR and mass spectrometry evolve,
201 and isolation and identification techniques improve, new pathogens will be
202 recognised and known pathogens will be more efficiently and effectively detected.

203 *(b) Human behaviour.* Weather conditions such as temperature and sunshine affect
204 human behaviour (Agnew and Palutikof, 1999) and the altering climate will change
205 the conditions under which food is produced and the choice of food consumed (Lake
206 et al., 2012). It is therefore reasonable to assume that in the future patterns of food
207 consumption will be influenced by the changes in temperature and precipitation.
208 Food safety risks may change as foods carry different risks of foodborne illness, for
209 example, eating poultry or seafood instead of meat might increase foodborne
210 illnesses (Adak et al., 2005). Climate change will result in emerging pathogens,
211 alternative crop and livestock species, altered use of pesticides, fertilizers and
212 veterinary medicines and may possibly influence how contaminants transfer and
213 interchange from the environment to food impacting on food safety (Lake et al.,
214 2012, Cooper et al., 2014). Agricultural adaptation to climate change may involve
215 increased use of irrigation water and, although irrigation on the lol is currently
216 minimal, it may become necessary in the future in some areas and using wastewater
217 for irrigation could increase pathogen risks for consumers (WHO, 2006).

218 Throughout the food chain continuum continuous refrigeration is required to extend
219 the shelf life of fresh and processed foods. With increasing temperatures the food

220 cooling chain will become harder to manage and heat waves and power cuts related
221 to either high energy demands or adverse weather conditions could cause cold
222 storage failure during food processing and storage, compromising food safety
223 (Vermeulen et al ., 2012). As temperatures increase the perishability and therefore
224 safety of fresh foods will be compromised. The storage life of food will be halved for
225 each 2-3°C rise in temperature (Vermeulen et al ., 2012) as bacterial growth rates
226 approximately double with every 10°C rise in temperature above 10°C (James and
227 James, 2010). The risks of food handling mistakes occurring will increase in
228 prolonged periods of warm weather and more outbreaks may occur as a result of
229 food handling mistakes caused by poor hygiene conditions and or lack of hand-
230 washing (Kendrovski and Gjorgjev, 2012). Incorrect food handling is also a factor
231 with “temperature misuse”, either by cooled storage or heat processing, considered
232 to be a contributing factor in 32% of foodborne outbreaks in Europe (Tirado and
233 Schmidt, 2001). The longer, hotter summers predicted for the future will extend the
234 time period associated with these higher risk behaviours contributing to an overall
235 higher occurrence of disease. The result will be that summer foodborne disease
236 outbreaks will affect more people and last longer. In the UK it has been predicted
237 that an average air temperature increase of 1°C could increase the burden of
238 foodborne disease could increase by 4.5% (DOH/HPA, 2008). Bentham and
239 Langford (1995) calculated that in England and Wales by the year 2050 the annual
240 food poisoning incidents in England and Wales could increase by almost 200,000
241 cases. When calculated on a pro rata basis using population numbers for the lol, and
242 assuming similar changes in climate and effect of foodborne pathogens, this would
243 equate to an annual increase of 20,000 food poisoning incidents during the same
244 period in Ireland.

245 **Effect of climate change on:**

246 *(i) Campylobacteriosis* – The poultry industry has a long tradition in Northern Ireland
247 and represents almost 20% of the total gross turnover of food and drink processing.
248 Poultry is a highly efficient and sustainable protein increasingly chosen by health
249 conscious consumers. The most important microbiological threat to this industry is
250 campylobacteriosis, which is the most commonly reported foodborne illness in
251 Ireland and Europe (Westrell et al., 2009). A recent annual report has indicated that
252 although outbreak figures across Europe have stabilised, this is not the case in

253 Ireland as incidents continue to rise (EFSA/ECDC, 2015). *Campylobacteriosis* is
254 caused by *Campylobacter* sp. bacteria which contaminate and survive on food,
255 although they are not thought to multiply on it. There is a vast reservoir of
256 *Campylobacter* in nature (Kovats et al., 2005), however, the prevalent sources of
257 infections are broiler and fresh poultry meat (EFSA/EDC 2015). Relatively little is
258 known about the survival mechanisms used by *Campylobacter* as it passes through
259 the food chain or how and why its pathogenicity changes. Previous studies have
260 suggested associations between environmental factors such as seasonality and
261 geography on the carriage of campylobacters by poultry (Jorgensen et al., 2011). As
262 such, the potential impact of climate factors on the incidence and prevalence of
263 *Campylobacter* sp. warrants further investigation. Colonisation of broiler-chicken
264 flocks is expected to increase as ambient temperatures rise so the incidence of
265 campylobacter is predicted to increase in the future as a result of climate change
266 (Allard et al., 2011). *Campylobacter* sp. have a number of stress response
267 mechanisms enabling them to adapt quickly to environmental conditions although
268 they are sensitive to desiccation (Murphy et al., 2006). They are considered to be a
269 seasonal foodborne pathogen they not as strongly linked to temperature fluctuations
270 as other pathogens (Kovats et al., 2005; D'Souza et al., 2004). Many vectors and
271 routes have been suggested as vehicles for spread of *Campylobacter* (Skelly and
272 Weinstein, 2003; Kovats et al., 2005). Among these flies have been suggested to be
273 a source of contamination of broiler flocks (Hald et al., 2004) and have been
274 proposed as vectors for transmission (Nichols, 2005). Flies emerge in the spring time
275 around the same time as campylobacteriosis cases begin to increase and fly activity
276 has been found to be closely related to environmental temperatures (Goulson et al.,
277 2005). So foodborne illnesses caused by *Campylobacter* could increase as a result
278 of global warming influencing fly activity. In addition, modern food processing
279 stresses may increase the incidence of *Campylobacter*, for example, the increasing
280 use of modified atmosphere packaging of food to protect and prolong the shelf life of
281 food products may influence growth of *Campylobacter* as the reduced oxygen
282 conditions within the packaged product may predispose to the more favourable
283 microaerophilic conditions for *Campylobacter* growth. Future research on
284 *Campylobacter* is needed to; (i) identify new virulence factors and the dynamics that
285 influence their expression; (ii) determine how *Campylobacter* survives; (iii) clarify its
286 stress adaptation mechanisms and triggers and; (iv) expose factors required, or

287 which influence, its transmission along the food chain. Understanding these
288 biological mechanisms will provide a better understanding of the roles of season and
289 climatic factors and their relative impacts on broiler flock colonization and enable
290 more accurate predictions of the effects of climate change and could indicate
291 alternative means of pathogen control.

292 *(ii) Non-cholera vibrios - A potential emerging pathogen.* The clean, unpolluted
293 waters around Ireland's coastline are rich in aquatic life and form an exceptional
294 environment for seafood. Global consumption of seafood is on the increase with the
295 result that Ireland's seafood sector is worth over €800 million to the economy. The
296 potential impact of climate change on potential microbiological threats to this local
297 industry therefore warrants further investigation. By 2050, there is expected to be
298 between a 2-4°C increase in seawater temperature in the UK and Ireland (Hulme et
299 al., 2002; Hiscock et al., 2004) depending on the region. This could have implications
300 for the aquaculture industry in Ireland which is currently estimated to be worth €131
301 million annually and is anticipated to expand in the future leading to more intense
302 aquaculture practises. Shallow, estuarine environments are more suitable for bivalve
303 aquaculture but this environment may be more readily influenced by climate change
304 than oceans. This in turn may favour a group of potentially emerging microbiological
305 pathogens, the marine vibrios, which are a genus of thermo dependent bacteria
306 which thrive naturally in warm, low salinity sea water. *Vibrio vulnificus* and *Vibrio*
307 *parahaemolyticus* are contaminants that have been associated with seafood
308 consumption (Oliver, 2006) with *V. parahaemolyticus* being the most prevalent
309 bacterial pathogen associated with seafood (Joseph et al., 1982). Climate change
310 has been linked to foodborne outbreaks caused by non-cholerae vibrios (Paz et al.,
311 2007) with temperature having a strong influence over the seasonal distribution of
312 *V. vulnificus* (Lipp and Rose, 1997). In both Europe and the USA although reported
313 incidents of both *V. vulnificus* and *V. parahaemolyticus* are currently low they are on
314 the increase and typically follow periods of warm weather (Rangdale and Baker-
315 Austin, 2010). In the US, it is estimated that infections with vibrios increased by 47%
316 between 1996 and 2005 with a 41% increase globally in the same time period (Bross
317 et al., 2005). In Europe, *V. vulnificus* infections have originated mainly in
318 Scandinavian countries probably because of the lower salt concentrations of their
319 sea water and to date, in the UK, there are no reported indigenously acquired

320 infections of *V. vulnificus* (Rangdale and Baker-Austin, 2010). Marine temperatures
321 of 15°C and above and lower water salinity may predispose to *V. vulnificus*
322 infections, however, *V. parahaemolyticus* can tolerate higher salinity levels so the
323 increase in sea water temperature, rising sea levels and regional reduction in salinity
324 predicted to occur around lol under climate change (Lowe et al., 2009) are risk
325 factors which could influence non-cholerae vibrio infections. In addition, zooplankton,
326 the vector organism for marine vibrios, is thermo dependant and its geographical
327 distribution is expected to extend as a result of climate change, thereby influencing
328 the distribution of marine vibrios. Testing of seafoods for the presence of pathogenic
329 vibrios is currently not mandatory and as such there are no internationally
330 recognised testing methods (Rangdale and Baker-Austin, 2010). In addition, clinical
331 laboratories do not routinely test faecal samples for marine vibrios unless clinical
332 history indicates consumption of seafood and, as the symptoms caused are similar
333 to norovirus, marine vibrios may currently be underreported. Determination of the
334 prevalence and distribution of marine vibrios currently in both coastal waters and
335 shellfish, understanding their seasonal dynamics, virulence and transmission
336 mechanisms as well as the significance of algal blooms in relation to these bacteria
337 is recommended to predict their future impact within the food industry in relation to
338 climate change

339 *(iii) Transmission of microbiological pathogens*

340 *(a) Waterborne disease.* Waterborne disease outbreaks occur when drinking water is
341 exposed to pathogenic microorganisms and because, on the lol, most drinking water
342 is supplied through water mains using surface water as a source, a waterborne
343 disease outbreak has the potential to affect a large number of people and to contain
344 a mixture of etiological agents. Reservoirs for waterborne pathogens include human
345 and animal waste which can contaminate the water directly, or can be spread as a
346 consequence of agricultural activity or leached from septic tanks or sewage systems.
347 Waterborne disease outbreaks have been found to be seasonal and linked to heavy
348 rainfall (Curriero et al., 2001). Erratic and extreme precipitation events, as predicted
349 for the lol, will increase the risk of waterborne disease and flooding and overflow will
350 potentially flush contaminants into surface and ground waters and possibly
351 overwhelm water treatment plants (Kistemann et al., 2002; Semenza and Nichols,
352 2007; Lake et al., 2005). Pathogens prevalent in the gastrointestinal system such as

353 *Giardia*, *Cryptosporidium*, *Campylobacter*, *Shigella* and verotoxigenic *E.coli* are the
354 most common waterborne disease hazards (Mac Kenzie et al., 1994; Charron et al.,
355 2004; Westrell et al., 2009, EFSA/ECDC, 2015) and many outbreaks associated with
356 these organisms have been as a result of adverse weather conditions (Atherholt et
357 al., 1998; Hrudehy et al., 2003; Lake et al., 2005). Increased ambient temperatures
358 and lower precipitation levels will lead to drought conditions where there will be an
359 increased demand for water but at the same time the water supply will be reduced
360 and vulnerable as any microorganisms present may survive better in the warmer
361 temperatures and be more concentrated in the reduced volume of water. In addition,
362 heavy rainfall following drought conditions can lead to increased risk of water
363 contamination (Charron et al., 2004).

364 *Cryptosporidium* is an intracellular parasite which causes gastrointestinal infections
365 which can be life threatening to immuno-compromised individuals and in Western
366 Europe they are a major waterborne disease associated with the public water supply.
367 They are significant because they can survive for several months in water and are
368 resistant to chemical disinfectants including routinely used water treatment
369 chemicals. Extreme rainfall is thought to play a role in the animal-to-human
370 transmission pathway (Kovats et al., 2005; Curriero et al., 2001) and studies have
371 indicated a positive correlation between maximum river flows and cases of
372 *Cryptosporidium* (Lake et al., 2005) and heavy rainfall preceded by low levels of
373 precipitation (Nichols et al., 2009). Some outbreaks are related to maintenance
374 failures, with rainfall as an additional causative factor, such as the *Cryptosporidium*
375 outbreak in Milwaukee (MacKenzie et al., 1994). Data has shown that of three recent
376 outbreaks of *Cryptosporidium* reported two of these were in Ireland (EFSA/ECDC,
377 2015). Currently on the IOL the presence of *Cryptosporidium* in potable water is
378 tested for during routine water quality testing only in certain sites considered to be at
379 high risk (EHS, 2002; EPA 2011). In the future, with the increased risk of heavy
380 rainfall, the frequency of testing and the number of sites tested may need to be
381 reviewed and expanded. In addition, the presence of *Cryptosporidium* is not routinely
382 tested for in clinical microbiological laboratories but with the expectancy of more
383 frequent extreme precipitation events and therefore a greater risk of cryptosporidium
384 contamination in water this practice may also need reviewed.

385 (b) *Alternative pathogen transmission routes.* Traditionally the main sources and
386 transmission vehicles of foodborne disease outbreaks were considered to be foods
387 of animal origin, however, recent investigations of global foodborne outbreaks have
388 identified fruits and vegetables as important sources, particularly as most are
389 consumed raw (Berger et al., 2010). Consumption of fruit and vegetables is actively
390 promoted as part of a balanced diet; however, studies in the USA have indicated
391 increases in foodborne outbreaks and foodborne outbreak-associated illnesses as a
392 result of contaminated raw produce (Sivapalasingam et al., 2004). Investigations of
393 the occurrence of pathogenic bacteria in fruits and vegetables in Europe have
394 indicated that pathogens are present on foods. Microbiologically compromised water
395 used for irrigation has been found to be a source of contamination facilitating the
396 establishment of pathogens on raw produce (Wachtel et al., 2002) and as climate
397 change is expected to increase the need for irrigation this could be an area for
398 concern in the future. In addition insects have also been suggested as a potential
399 transmission route for contamination. Studies have shown that flies; can transfer
400 bacteria to plant leaves or fruits (Sela et al., 2005); can carry *E. coli* O157:H7 when
401 found in fields next to cattle (Iwasa et al., 1999); and have been implicated in the
402 transmission of *E. coli* O157:H7 to leaves (Talley et al., 2009). Climate change has
403 impacted on insect behaviour and survival (Gregory et al., 2009) and the movement
404 of insect populations (Cannon, 1998) wild birds (Vedder et al., 2013), plant (Walther
405 et al., 2002) and wild animal populations which may introduce new or different
406 foodborne pathogens and raise new biosecurity concerns on the lol.

407 Although improved detection methods have contributed to the upsurge in fruit and
408 vegetables as the sources of foodborne disease outbreaks other factors have been
409 implicated. Pre-cut foods have been found to have higher proportions of
410 contaminants (Berger et al., 2010) and cutting is thought to transfer pathogens from
411 the coating of the produce onto the edible part where they can then multiply in the
412 absence of proper cold storage (Ukuku and Sapers, 2007). In addition, some
413 bacteria such as *Salmonella* sp have been found to be particularly attracted towards
414 cut leaves (Kroupitski et al., 2009) with studies indicating the involvement of type III
415 secretions system, flagella and the pilus curli of *E. coli* O157 in the colonisation of
416 lettuce leaves and additional studies indicating a sero-specific association of
417 *Salmonella* with fresh produce (Berger et al., 2010). Information on pathogen

418 colonisation and survival on fresh produce as well as where along the food chain
419 contamination occurs needs to be obtained. A better understanding of the factors
420 that predispose or facilitate contamination and consumer education in relation to
421 washing of raw produce before eating will enable development of procedures and
422 technologies which will decrease the risk of bacterial contamination of produce
423 consumed raw and the impact climate change could have on this.

424 As approximately 75% of foodborne diseases are zoonotic the effect of climate
425 change on livestock must be considered. Heatwaves during the summer may cause
426 livestock to become stressed (Miraglia et al., 2009), and therefore more likely to
427 become ill and possibly discharge larger numbers of pathogens (Keen et al., 2003;
428 Humphrey et al., 2007). During the processing stage there may be a greater risk of
429 contaminating the meat (Elder et al., 2000) or there may be an increase in the use of
430 antimicrobials to treat these animals (Cooper et al., 2014) which in turn could
431 contribute to the development of antimicrobial resistance (EFSA, 2006). The
432 introduction of standardised subtyping techniques for commonly isolated pathogens
433 across food, veterinary and clinical laboratories with the results deposited in a
434 central, easy accessible, electronic bank could improve the ability to detect, predict
435 and prevent outbreaks.

436 **Conclusions and recommendations**

437 The adverse effects of climate change on food safety are now becoming evident.
438 Globalisation of the food chain continuum has resulted in a diverse, extensive and
439 easily accessible system which is vulnerable to the introduction of contaminants
440 which can compromise food safety. In this review we highlighted the potential impact
441 of climate change on microbiological aspects of two highly lucrative and
442 economically important industries on the IOL, the poultry and aquaculture sectors.
443 *Campylobacter* related illness is on the increase in Ireland and if not brought under
444 control could, under the influence of climate change, continue to increase. The lack
445 of knowledge on its transmission, survival and virulence determinants were
446 highlighted as areas of concern and topics for future research. *Vibrio vulnificus* was
447 identified as a pathogen which, under the changes in climate predicted for the IOL
448 could be a foodborne threat of the future with possible economic influence. The
449 effect of extreme weather events on pathogen transmission and how this could be

450 mitigated was also discussed. The objective is, using the predicted change to the
451 local climate, to identify possible future microbiological threats in order to prevent,
452 detect and control foodborne illnesses. This is challenging because of the complex
453 and continually evolving production and processing developments and the extensive
454 food distribution network involved. Food traceability and consumer preferences and
455 activities also compound the challenge. Detection, identification and control of food
456 problems at an early stage in the food chain will facilitate targeted interventions and
457 reduce the need for food product recall. To improve food safety we need to
458 understand the behaviour of foodborne pathogens. Research to better understand
459 microbial interactions, pathogen survival, colonisation, attachment, stress adaptation
460 and proliferation of foodborne pathogens in food, crops, livestock and the
461 environment was recommended. We also need to enhance our knowledge of
462 pathogen behaviour and activity in food, understand the influence of pathogen
463 numbers and dose response, and elucidate factors that increase and decrease the
464 virulence of foodborne pathogens. Assessing the pathogenicity of foodborne
465 organisms, including differences between serotypes, and characterisation of the
466 dynamics of microbial populations throughout the food chain and how these will be
467 impacted or influenced by climate change will be important for employing novel
468 monitoring and intervention approaches. Research is also required on how the
469 predicted altered climate will influence the emergence of new pathogens such as
470 *Vibrio vulnificus*, and the transmission of known pathogens, such as
471 *Cryptosporidium*, in order to decrease potential risks as crop irrigation, heavy
472 rainfalls, flooding and overflows are expected to be more frequent in parts of Ireland
473 in the future. The structure and capability of local water treatment plants and the
474 aging water infrastructure on the lol will need to be assessed to evaluate their
475 capability to alleviate the effects of extreme weather events.

476 The food industry along with other stakeholders on the lol need to work together to
477 gather information on the projected climate variability, relate these to food safety and
478 develop action plans to identify adaption and mitigation measures. There is a need
479 for continual vigilance and to improve the detection, identification and under-
480 reporting of many pathogens (Nichols and Lake, 2012). Rapid, sensitive and cost
481 effective technologies are required to detect multiple pathogens, to enable
482 differentiation of pathogenic from non-pathogenic organisms, and to predict and

483 identify emerging or re-emerging pathogens. Many structures and policies are in
484 place to regulate food production, however, these must be maintained, expanded
485 and strengthened in order to monitor the quality and safety of food, and to expedite
486 responses to safety issues that arise. Information sharing of surveillance data
487 between industry and governmental agencies is essential. An expanded and co-
488 ordinated surveillance system incorporating animal health, environmental health,
489 public health and food safety will enable a broader view of pathogens across the
490 food chain and help with risk assessment analysis and the development of risk
491 management strategies. Co-operation, interagency collaboration and standardisation
492 of methods and procedures between public health, veterinary health, crop health and
493 food safety, international surveillance and scientific research would facilitate rapid
494 detection of and response to foodborne outbreaks and disease prevention and
495 control programmes.

496 Surveillance to appreciate the current extent of foodborne diseases, to monitor
497 developing trends in foodborne disease outbreaks and to identify the specific foods
498 involved is also important. An integrated, efficient and interdisciplinary approach
499 combining microbiology, epidemiology, genomics, proteomics and bioinformatics will
500 facilitate an understanding of the ability of foodborne pathogens to adapt and evolve.
501 This information will strengthen the design and development of risk assessments,
502 evidence-based policies, procedures, and technologies aimed at improving the
503 safety of food using control and intervention strategies introduced at critical periods
504 of production and processing (Berger et al., 2010), leading to better control and
505 validation processes and facilitating the development of new innovative production
506 processes and products. Foodborne diseases will need monitored and reviewed as
507 ecosystems, food belts, human behaviours and contact patterns between wild and
508 domestic animals, especially during extreme weather conditions, change.
509 Assessment of the costs of foodborne illness and the benefits and effectiveness of
510 research strategies will help policy makers rank risks, determine prevention
511 strategies, focus policy and prioritise spending which could ultimately improve
512 veterinary and public health, and the viability of the food industry.

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