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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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Abstract

The Agri-Food and aquaculture industries are vital to the economy of the island of Ireland with a gross annual output that is expected to double in the future. Identifying and understanding the potential influences of the anticipated climate variables on microorganisms that cause foodborne diseases, and their impact on these local industries, are essential. Investigating and monitoring foodborne pathogens and factors that influence their growth, transmission, pathogenesis and survival will facilitate assessment of the stability, security and vulnerability of the continuously evolving and increasing complex local food supply chain.

Introduction

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

The archetypical mild climate and rich soil has contributed to the agri-food industry becoming the largest indigenous industry on the island of Ireland (IoI), playing a vital role in the local economy, environment and society. As such it is essential to understand what impacts changes in physical processes and other climate variables may have on the stability and security of the local food supply. Local climatic conditions influence local vegetation and so, as the climate changes, growing seasons may change and biological consequences will be inevitable with variations in the crops that are cultivated and animals farmed. This could lead to changes in plant and animal epidemiology and transformations in entire ecosystems (Lennon, 2014). Extinctions and invasions into new territories will influence these changes and the outcomes will be unpredictable and dependent on the resistance and resilience of organisms and the environment, resulting in numerous factors which will influence the emergence of new and/or the re-emergence or exacerbation of existing foodborne pathogens. A equilibrium must be achieved between minimising food safety risks to consumers while contributing to the production of enough food to satisfy a global population that is expected to reach nine billion by the year 2050 (Royal Society, 2009; Godfray et al., 2010). Achieving this balance will be challenging in a world of increased competition for depleting resources coupled with the inability of the environment to cope with increasing anthropogenic influences and climate change (Vermeulen et al., 2012).

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

In response to global warming the seasonality and geographic range of foodborne disease pathogens is expected to expand and additional foodborne outbreaks are expected to occur as a results of extreme weather events. Correlations between meteorological parameters and the behaviour of foodborne pathogens have been made (Rose et al., 2001) and these can be used as a basis to speculate on the potential impact of climate change on future patterns at a more local level. This review considers the climate change predicted for the IoI and investigates possible pertinent microbiological food safety issues that are likely to be impacted by these changes with the aim of improving our understanding and ability to control the identified microbiological hazards. The review deliberates the potential impact of climate change on foodborne pathogens associated with two economically important sectors in Ireland, poultry and seafood. Campylobacteriosis is associated with the poultry industry and is the most commonly reported foodborne illness in Ireland and so the potential impact of climate change on this warrants further investigation. If climate change predictions manifest then *Vibrio vulnificus*, could emerge as a potential threat to the lucrative Irish shellfish industry. Also discussed is the potential impact on waterborne pathogens and transmission of pathogens along the food chain. Effective food safety management requires an understanding of the microbiological hazards and how their presence in foods can be prevented or maintained within tolerable levels. Areas of concern such as incomplete data on the pathogen epidemiology, poor understanding of mechanisms of disease and immunity, and gaps in our knowledge of virulence, survival and transmission mechanisms of the selected foodborne pathogens are highlighted. Steps are recommended to ameliorate these impacts and opportunities for future research highlighted to enable more effective and efficient prevention, detection and control of local foodborne illnesses.

Local Climate Change Predictions

Changes to the climate on the IoI are in general expected to be similar with those being experienced in the global context with summers becoming warmer and drier, heavier rainfalls in winter and more extreme events such as storms and floods. The impacts of gradual changes such as increasing temperature and precipitation are more predictable than the impacts of the more damaging extreme events. Regional climate model predictions published by the Environmental Protection Agency (Dunne et al., 2008) have indicated that by the year 2050 the annual precipitation will remain relatively unchanged; however, more rain is predicted for the winter months and less in the summer months. The temperature is predicted to increase by 1.5˚C during January and 2.5˚C during July, and summer rainfall is expected to be reduced by 25-40% with winter rainfall anticipated to increase by 10-25%. These changes are not expected to be uniform across the IoI resulting in regional differences. The greatest temperature increase is predicted for South-east and East of Ireland whereas the West of the country is more likely to experience increased flooding. It is expected that the more temperate winter conditions currently experienced on the south coast of Ireland will move northwards, which may influence the availability and quality of water putting pressure on water supply infrastructures. Water resource management may become an issue with increased flooding interlinked with periods of drought. Longer term projections indicate a rise in sea levels as the rising global temperature results in ice-cap melting and possible thermal expansion of oceans. The warmer sea water and effects of coastal erosion may disrupt ecosystems, influence biodiversity and introduce new potential microbiological threats.

Potential Impacts of Climate Change on foodborne microorganisms

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

Bacterial pathogens found in food are ubiquitous and can adapt not only to persist but to proliferate in the environment. Spread of these pathogens is reliant on their capability to survive (FAO, 2008), and meteorological factors such as temperature and humidity will influence the growth and survival and therefore the distribution of foodborne pathogens, as well as the emergence of new pathogens or the number of outbreaks of known pathogens (D'Souza et al., 2004; Kovats et al., 2004; Ukuku and Sapers, 2007; Lake et al., 2009; Miraglia et al., 2009; Tirado et al., 2010). Climate change will have the most impact on pathogens such as *Campylobacter* sp and Enterohaemorrhagic *E. coli* which have low-infective doses, can survive in the environment, and can adapt well to stress factors such as temperature and pH (FAO, 2008). The survival rates of many enteric pathogens such as *Salmonella*, *Campylobacter* and *E coli* O157 have been linked to temperature (Hall et al., 2002; Lake et al., 2009) with temperature having the most noticeable effect on salmonellosis, where 30% of reported cases have been attributed to warm temperatures. For each degree increase in weekly temperature above 5°C a 5-10% increase in the number of notifications of salmonellosis has been detected (Bentham and Langford, 1995; D'Souza et al., 2004; Kovats et al., 2004). Although some of this increase can be attributed to increased rate of food spoilage and some to changes in human social behaviours, such as camping, barbeques and picnics, which are connected with a higher risk of foodborne illness; some of this seasonal increase is directly associated with the rise in temperature. Studies have indicated that the incidence of foodborne disease can be linked to temperatures in the month previous to the onset of illness (Bentham and Langford, 1995) and some diseases have been found to be distinctly seasonal (Naumova et al., 2007; Koelle et al., 2005). As higher ambient temperatures and temperature spikes associated with extreme weather events could increase both the prevalence of specific pathogenic organisms in animals and the replication cycles of foodborne pathogens leading to a higher degree of contamination (Kendrovski and Gjorgjev, 2012) it is important to determine the epidemiology of infectious diseases and to explore what effect climate change may have on disease patterns and pathogen survival and transmission (McMichael et al., 2004).

Indirect impacts on pathogens (a) environmental factors. The sources of foodborne infections can be infected animals, food directly contaminated by human or animal faecal matter, or food contaminated indirectly by the use of contaminated water for irrigation or washing purposes (Rose et al., 2001; Wachtel et al., 2002; Hall et al., 2002; Nichols et al., 2009). The impacts of global climate change on food systems are expected to be extensive and complex and influenced by geography and socioeconomic conditions (Schmidhuber and Tubiello, 2007). It is anticipated that an altered climate will result in the production of food under different environmental conditions and adaptation to and mitigation against climate change leading to the introduction of alternative crops and livestock species adapted to survive in these different environments (Nichols and Lake, 2012; Lake et al., 2012). Analyses of epidemiological data indicate a relationship between certain pathogens and environmental conditions for example, an increase in the frequency and severity of extreme rainfall and flooding influences the distribution and transmission of many diarrhoeal diseases in humans (Ahern et al., 2005), and changing the topography or use of land has been found also to influence the emergence or resurgence of numerous infectious and vector borne diseases (Patz et al., 2008). Historical studies and climate assessment models suggest that climate change is expected to impact on agriculture, prices, delivery, quality and safety of food (Vermeulen et al., 2012; Lake et al., 2012). Globalisation of the world's food supply has already changed patterns of food consumption and climate change is expected to lead to shifting food belts resulting in a broad, worldwide selection of foods for consumers. However, global sourcing minimises geographic barriers to traditional, emerging and re-emerging pathogens exacerbating their spread and resulting in an increase in foodborne illnesses as growing conditions and food safety management practises may be different at source (Adak et al., 2005). In addition, as technologies such as next generation sequencing, DNA microarray, PCR and mass spectrometry evolve, and isolation and identification techniques improve, new pathogens will be recognised and known pathogens will be more efficiently and effectively detected.

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

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

Effect of climate change on:

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

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

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

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

(iii) Transmission of microbiological pathogens

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

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

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

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

Although improved detection methods have contributed to the upsurge in fruit and vegetables as the sources of foodborne disease outbreaks other factors have been implicated. Pre-cut foods have been found to have higher proportions of contaminants (Berger et al., 2010) and cutting is thought to transfer pathogens from the coating of the produce onto the edible part where they can then multiply in the absence of proper cold storage (Ukuku and Sapers, 2007). In addition, some bacteria such as *Salmonella* sp have been found to be particularly attracted towards cut leaves (Kroupitski et al., 2009) with studies indicating the involvement of type III secretions system, flagella and the pilus curli of *E. coli* O157 in the colonisation of lettuce leaves and additional studies indicating a sero-specific association of *Salmonella* with fresh produce (Berger et al., 2010). Information on pathogen colonisation and survival on fresh produce as well as where along the food chain contamination occurs needs to be obtained. A better understanding of the factors that predispose or facilitate contamination and consumer education in relation to washing of raw produce before eating will enable development of procedures and technologies which will decrease the risk of bacterial contamination of produce consumed raw and the impact climate change could have on this.

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

Conclusions and recommendations

The adverse effects of climate change on food safety are now becoming evident. Globalisation of the food chain continuum has resulted in a diverse, extensive and easily accessible system which is vulnerable to the introduction of contaminants which can compromise food safety. In this review we highlighted the potential impact of climate change on microbiological aspects of two highly lucrative and economically important industries on the IoI, the poultry and aquaculture sectors. *Campylobacter* related illness is on the increase in Ireland and if not brought under control could, under the influence of climate change, continue to increase. The lack of knowledge on its transmission, survival and virulence determinants were highlighted as areas of concern and topics for future research. *Vibrio vulnificus* was identified as a pathogen which, under the changes in climate predicted for the IoI could be a foodborne threat of the future with possible economic influence. The effect of extreme weather events on pathogen transmission and how this could be mitigated was also discussed. The objective is, using the predicted change to the local climate, to identify possible future microbiological threats in order to prevent, detect and control foodborne illnesses. This is challenging because of the complex and continually evolving production and processing developments and the extensive food distribution network involved. Food traceability and consumer preferences and activities also compound the challenge. Detection, identification and control of food problems at an early stage in the food chain will facilitate targeted interventions and reduce the need for food product recall. To improve food safety we need to understand the behaviour of foodborne pathogens. Research to better understand microbial interactions, pathogen survival, colonisation, attachment, stress adaptation and proliferation of foodborne pathogens in food, crops, livestock and the environment was recommended. We also need to enhance our knowledge of pathogen behaviour and activity in food, understand the influence of pathogen numbers and dose response, and elucidate factors that increase and decrease the virulence of foodborne pathogens. Assessing the pathogenicity of foodborne organisms, including differences between serotypes, and characterisation of the dynamics of microbial populations throughout the food chain and how these will be impacted or influenced by climate change will be important for employing novel monitoring and intervention approaches. Research is also required on how the predicted altered climate will influence the emergence of new pathogens such as *Vibrio vulnificus,* and the transmission of known pathogens, such as *Cryptosporidium*, in order to decrease potential risks as crop irrigation, heavy rainfalls, flooding and overflows are expected to be more frequent in parts of Ireland in the future. The structure and capability of local water treatment plants and the aging water infrastructure on the IoI will need to be assessed to evaluate their capability to alleviate the effects of extreme weather events.

The food industry along with other stakeholders on the IoI need to work together to gather information on the projected climate variability, relate these to food safety and develop action plans to identify adaption and mitigation measures. There is a need for continual vigilance and to improve the detection, identification and under-reporting of many pathogens (Nichols and Lake, 2012). Rapid, sensitive and cost effective technologies are required to detect multiple pathogens, to enable differentiation of pathogenic from non-pathogenic organisms, and to predict and identify emerging or re-emerging pathogens. Many structures and policies are in place to regulate food production, however, these must be maintained, expanded and strengthened in order to monitor the quality and safety of food, and to expedite responses to safety issues that arise. Information sharing of surveillance data between industry and governmental agencies is essential. An expanded and co-ordinated surveillance system incorporating animal health, environmental health, public health and food safety will enable a broader view of pathogens across the food chain and help with risk assessment analysis and the development of risk management strategies. Co-operation, interagency collaboration and standardisation of methods and procedures between public health, veterinary health, crop health and food safety, international surveillance and scientific research would facilitate rapid detection of and response to foodborne outbreaks and disease prevention and control programmes.

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

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